

Direct Adaptive Neural Network-Based Sliding Mode Control of a High-Speed, Ultratall Building Elevator

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Declaration

I declare that this dissertation is my own, unaided work, except where otherwise acknowledged. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other university.

Signed this 18th day of August 2021

A handwritten signature in black ink that reads "M. Mangera". The letters are cursive and slightly slanted to the right.

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Abstract

The aim of this dissertation was to design and compare various controllers in the control of three separate high-speed, supertall/ultratall elevators. The three models differed in building height, non-linear cable dynamics, override height and the motor used for actuation. Following verification of the models in an uncontrolled state, seven different control architectures were developed – a conventional proportional-integral-derivative (CPID) controller, a conventional pseudo-derivative feedback (CPDF) controller, a nonlinear proportional-integral-derivative (NPID) controller, a nonlinear pseudo-derivative feedback (NPDF) controller, a full sliding mode control (FSMC) system, a simplified sliding mode control (SSMC) system and a direct adaptive neural network-based sliding mode control (RBFNN-SMC) system. The parameters of each of the controllers were tuned using genetic algorithm (GA) optimisation. The control systems were evaluated on the ability to efficiently track the setpoint signal, ensure prompt arrival of the cabins, maintain ride comfort by limiting the experienced acceleration and jerk, and reduce the power consumption of the system. Following extensive simulations, it was observed that the NPDF controller exhibited the best all-round performance, being the only control system to obtain at least acceptable performance (i.e., arrival accuracy ≤ 0.3 m, experienced jerk ≤ 1.7 m/s³, etc.) for each of the cabin masses, travel distances and travel directions considered throughout this dissertation. In addition to superior robustness in operation, the NPDF controller displayed a high level of flexibility in design; being the most effective control scheme at prioritising comfort and energy efficiency, while effectively re-levelling the cabin to within 1 mm of the target floor when performance was given precedence. Notable improvements were observed in the NPID controller responses, compared with those of the CPID control architecture, particularly in terms of sensitivity to parameter variations. The implementation of a simplified mathematical model in the SSMC control law resulted in noticeable reductions in run time, compared with the FSMC. The drawbacks associated with the need to explicitly define the model in the SMC control laws were overcome following the introduction of the RBFNN-SMC, with comparable control recorded despite the system dynamics being approximated. Although the RBFNN-SMC was able to suitably account for external disturbances, with the connection weights of the hidden layer neurons being adapted on-line in order to maintain control; problematic chattering was observed following rapid changes to the system states due to sensor noise. It was concluded that in order to be viable in practice, the RBFNN-SMC must be coupled with a noise-attenuating filter.

Scope and Contribution

Novelty in this dissertation exists in:

1. The development of two 1000 m tall roped building elevator mathematical models, accounting for nonlinear cable dynamics.
2. An evaluation of direct adaptive neural network-based sliding mode control (RBFNN-SMC), sliding mode control (SMC), nonlinear pseudo-derivative feedback (NPDF) control and conventional pseudo-derivative feedback (CPDF) control of various roped elevator systems.
3. An analysis of genetic algorithm (GA)-optimisation of initial RBFNN-SMC parameters.
4. An investigation into the effects of designing a SMC system using a simplified version of the system to be controlled.
5. The design and GA-optimisation of a NPDF controller.
6. An investigation into the validity and performance of an NPDF controller across a range of control criteria.
7. An examination of the effects of cable stiffness, damping and free rope length on the controllability of supertall and ultratall elevator systems.

Published Work

Aspects of this dissertation have been published in the following references:

- **M. Mangera, A. Panday and J. O. Pedro**, "GA-Based Nonlinear Pseudo-Derivative Feedback Control of a High-Speed, Supertall Building Elevator," *The Third IEEE Conference on Control Technology and Applications*, Hong Kong, IEEE, pp. 982–987, 2019.
- **I-L. R. Hill, M. Mangera, D. S. Parshotam, A. Panday and J. O. Pedro**, "Genetic algorithm based design of PID and PDF controllers for velocity tracking of a high-rise building elevator," *SICE International Symposium on Control Systems*, Tokyo, IEEE, pp. 136–143, 2018.
- **M. Mangera, D. S. Parshotam and I-L. R. Hill, A. Panday, J. O. Pedro**, "Velocity tracking of a high-rise building elevator using PDF control," *11th Asian Control Conference*, Gold Coast, IEEE, pp. 2310–2315, 2017.

The following titles for potential journal publications are proposed:

- **M. Mangera, J. O. Pedro and A. Panday**, "Direct Adaptive Neural Network-Based Sliding Mode Control of a High-Speed, Ultratall Building Elevator Using Genetic Algorithm."
- **M. Mangera, J. O. Pedro and A. Panday**, "GA-Optimised Nonlinear Pseudo-Derivative Feedback Control of a Sustainable, High-Speed, Ultratall Building Elevator."

Nomenclature

Symbol	Description	Units
A	Cross-sectional area of the main hoisting cable	m^2
a_d	Acceleration setpoint signal	m/s^2
a_{d-r}	Adaptive acceleration re-levelling setpoint signal	m/s^2
A_f	Constant in the FSMC equation representing $\frac{1}{m_c+p_c}$	kg^{-1}
A_s	Constant in the SSMC equation representing $\frac{k_c}{m_c+p_c}$	N/m.kg
b	Spread of all radial centres of the RBFNN hidden layer neurons	-
B_f	Constant in the FSMC equation representing $\frac{r}{m_c+p_c}$	m/kg
B_s	Constant in the SSMC equation representing $\frac{c_c r}{m_c+p_c}$	N.s/kg
C_{0r}	Basic static radial load rating of the sheave bearings	N
c_1	Radial centre of the first RBFNN hidden layer neuron	-
c_{b_d}	Sheave bearing damping constant	N.m.s/rad
c_{b_l}	Frictional torque as a function of load of the sheave bearings	N.mm
c_{b_s}	Frictional torque as a function of speed of the sheave bearings	N.mm
c_c	Damping coefficient of the main cabin-side hoisting cable	N.s/m
C_f	Constant in the FSMC equation representing $\frac{1}{m_c+p_c}$	kg^{-1}
c_j	Radial centre of the j^{th} RBFNN hidden layer neuron	-
c_m	Motor friction damping as experienced on the sheave	N.m.s/rad
C_s	Constant in the SSMC equation representing $\frac{c_c}{m_c+p_c}$	N.s/m.kg
c_w	Damping coefficient of the main counterweight-side hoisting cable	N.s/m
D_b	Outer diameter of the sheave bearings	mm
d_b	Bore diameter of the sheave bearings	mm
d_c	Displacement of the elevator cabin	m
$d_{centres}$	Distance between RBFNN hidden layer neuron radial centres	-
D_f	Constant in the FSMC equation representing $\frac{r}{J_p}$	$\text{kg}^{-1}\text{m}^{-1}$
d_{mb}	Mean bearing diameter of the sheave bearings	mm
D_s	Constant in the SSMC equation representing $\frac{c_w r}{J_p}$	N.s/kg.m^2
d_w	Displacement of the counterweight	m
E	Young's modulus of elasticity	Pa
e_0	SMC tracking error signal	V
E_f	Constant in the FSMC equation representing $\frac{r}{J_p}$	$\text{kg}^{-1}\text{m}^{-1}$
E_s	Constant in the SSMC equation representing $\frac{c_w r}{J_p}$	N.s/kg.m^2
F	Fitness function	-
f_0	Sheave bearing factor as a function of speed	-
f_1	Sheave bearing factor as a function of load	-

$F_{combined}$	A weighted combination of multiple fitness functions	-
F_f	Constant in the FSMC equation representing $\frac{r^2}{J_p}$	kg^{-1}
F_s	Constant in the SSMC equation representing $\frac{(c_c+c_w)r^2}{J_p}$	N.s/m.kg
g	Acceleration due to gravity	m/s^2
G_f	Constant in the FSMC equation representing $\frac{r}{J_p}$	$\text{kg}^{-1}\text{m}^{-1}$
G_s	Constant in the SSMC equation representing $\frac{k_c r}{J_p}$	N/kg.m^2
H_f	Constant in the FSMC equation representing $\frac{r}{J_p}$	$\text{kg}^{-1}\text{m}^{-1}$
h_j	Activation function of the j^{th} RBFNN radial centre	-
H_s	Constant in the SSMC equation representing $\frac{k_w r}{J_p}$	N/kg.m^2
I_f	Constant in the FSMC equation representing $\frac{nK_T}{J_p}$	-
i_m	Perturbation current through the motor	A
i_{m0}	Current through the motor at rest	A
I_s	Constant in the SSMC equation representing $\frac{nK_T}{J_p}$	-
J	Cost function	-
$J_{combined}$	A weighted combination of multiple cost functions	-
$\dot{j}_d$	Jerk setpoint signal	m/s^3
$\dot{j}_{d-r}$	Adaptive jerk re-levelling setpoint signal	m/s^3
J_f	Constant in the FSMC equation representing $\frac{n}{J_p}$	$\text{kg}^{-1}\text{m}^{-2}$
J_p	Polar moment of inertia of the traction machine	kg.m^2
J_s	Constant in the SSMC equation representing $\frac{n}{J_p}$	$\text{kg}^{-1}\text{m}^{-2}$
k_c	Spring stiffness of the main cabin-side hoisting cable	N/m
k_{c_f}	Final cabin-side hoisting cable stiffness after travel	N/m
k_{c_i}	Initial cabin-side hoisting cable stiffness before travel	N/m
K_D	Derivative gain of the CPID/CPDF/NPID/NPDF controller	-
K_e	Back EMF constant of the motor	V.s/rad
K_f	Constant in the FSMC equation representing $\frac{c_{b_d}}{J_p}$	N.s/rad.kg
k_{GA}	Number of iterations within the GA	-
$k_{GA_{max}}$	Maximum allowable iterations within the GA	-
$k_{GA_{min}}$	Minimum iterations within the GA before convergence can be assumed	-
K_I	Integral gain of the CPID/CPDF/NPID/NPDF controller	-
K_P	Proportional gain of the CPID/CPDF/NPID/NPDF controller	-
K_R	Reaching law gain of the FSMC/SSMC/RBFNN-SMC system	-
K_s	Constant in the SSMC equation representing $\frac{c_{b_d}}{J_p}$	N.s/rad.kg
K_T	Torque constant of the motor	Nm/A
k_{tach}	Constant of the tachometer sensor	V.s
k_w	Spring stiffness of the main counterweight-side hoisting cable	N/m
L	Inductance of the motor	mH
l_{cc}	Length of a single cabin-side compensation rope	m
l_{cc_i}	Initial length of a single cabin-side compensation rope before travel	m
l_{ch}	Length of a single cabin-side hoisting cable	m
l_{ch_f}	Final length of a single cabin-side hoisting cable after travel	m
l_{ch_i}	Initial length of a single cabin-side hoisting cable before travel	m
l_{cT}	Combined length of a cabin-side hoisting cable and compensation rope	m
L_f	Constant in the FSMC equation representing $\frac{c_m}{J_p}$	N.s/rad.kg
l_{ground}	Distance from the starting floor to the lowest floor served by the elevator	m
$l_{override}$	Free rope length above the elevator cabin when stopped at the top floor	m
l_R	Ratio of l_{ch_f} to l_{ch_i}	-

L_s	Constant in the SSMC equation representing $\frac{c_m}{J_p}$	N.s/rad.kg
l_{top}	Distance from the starting floor to the highest floor served by the elevator	m
l_{wc}	Length of a single counterweight-side compensation rope	m
l_{wc_i}	Initial length of a single counterweight-side compensation rope before travel	m
l_{wh}	Length of a single counterweight-side hoisting cable	m
l_{wh_i}	Initial length of a single counterweight-side hoisting cable before travel	m
l_{wT}	Combined length of a counterweight-side hoisting cable and compensation rope	m
m_c	Combined mass of the elevator cabin and all occupants	kg
M_f	Constant in the FSMC equation representing r	m
M_{GA}	Number of individuals within each population in the GA	-
M_s	Constant in the SSMC equation representing r	m
m_w	Mass of the elevator counterweight	kg
n	Gear ratio of the traction machine	-
N_f	Constant in the FSMC equation representing $\frac{1}{L}$	mH ⁻¹
n_n	Number of hidden layer neurons in the RBFNN	-
N_s	Constant in the SSMC equation representing $\frac{1}{L}$	mH ⁻¹
O_f	Constant in the FSMC equation representing $\frac{nK_e}{L}$	V.s/rad.mH
O_s	Constant in the SSMC equation representing $\frac{nK_e}{L}$	V.s/rad.mH
P_{0r}	Equivalent static radial load rating of the sheave bearings	N
P_1	Decisive load for frictional torque of the sheave bearings	N
p_c	Combined mass of all cabin-side cables and compensation ropes	kg
P_f	Constant in the FSMC equation representing $\frac{R}{L}$	Ω/mH
P_{GA_c}	Probability of crossover occurring in the GA	-
P_{GA_m}	Probability of mutation occurring in the GA	-
$P_{m_{tot}}$	Total power consumption to hold the cabin at and perturb it from rest	kW
P_R	Rated power consumption of the motor	kW
P_s	Constant in the SSMC equation representing $\frac{R}{L}$	Ω/mH
p_w	Combined mass of all counterweight-side cables and compensation ropes	kg
q	Total mass per meter of the cables and compensation ropes	kg/m
R	Resistance of the motor	Ω
r	Radius of the sheave	m
r_{gov}	Radius of the governor wheel of the tachometer	m
s	Sliding mode function of the FSMC/SSMC/RBFNN-SMC system	-
s_d	Snap setpoint signal	m/s ⁴
s_{d-r}	Adaptive snap re-levelling setpoint signal	m/s ⁴
t	Time	s
T_A	Torque applied by the sheave	N.m
$t_{arrival}$	Actual arrival time of the elevator cabin	s
T_b	Resisting torque caused by the sheave bearings	N.m
T_d	Torque disturbance of the motor	N.m
T_m	Perturbation torque applied by the motor	N.m
T_{m_0}	Torque applied by the motor to hold the cabin at rest	N.m
T_R	Combined resisting torque of the motor and sheave bearings	N.m
t_{sched}	Scheduled arrival time of the elevator cabin	s
t_{sim}	Simulation run time	s
U	Control signal out of the controller	V
U_d	Setpoint velocity signal post-conversion to a voltage signal	V
U_e	Tracking error signal for the CPID/CPDF/NPID/NPDF controller	V

U_m	Perturbation voltage through the motor	V
U_{m_0}	Voltage through the motor at rest	V
U_s	Feedback sensor signal for the CPID/CPDF/NPID/NPDF controller	V
U_{tach}	Voltage signal from the tachometer	V
V	Lyapunov function	-
v_c	Velocity of the elevator cabin	m/s
$\dot{v}_{c_L}$	Ideal maximum acceleration	m/s ²
$\dot{v}_{c_{max}}$	Absolute maximum acceleration	m/s ²
$\ddot{v}_{c_L}$	Ideal maximum jerk	m/s ³
$\ddot{v}_{c_{max}}$	Absolute maximum jerk	m/s ³
v_d	Velocity setpoint signal	m/s
v_{d-r}	Adaptive velocity re-levelling setpoint signal	m/s
v_{r-h}	h^{th} velocity re-levelling sub-operation	m/s
v_w	Velocity of the elevator counterweight	m/s
W^*	Ideal RBFNN connection weight value	-
w_0	Initial RBFNN connection weight value	-
x_c	Extension of the cabin-side cable	m
x_w	Extension of the counterweight-side cable	m
α_D	Derivative nonlinear α term of the NPID/NPDF controller	-
α_I	Integral nonlinear α term of the NPID/NPDF controller	-
α_P	Proportional nonlinear α term of the NPID/NPDF controller	-
β_J	Velocity tracking weighting factor of the cost function	-
γ	Adaptive law parameter of the RBFNN	-
γ_J	Displacement tracking weighting factor of the cost function	-
δ_D	Derivative nonlinear δ term of the NPID/NPDF controller	-
δ_I	Integral nonlinear δ term of the NPID/NPDF controller	-
δ_P	Proportional nonlinear δ term of the NPID/NPDF controller	-
ϵ	Approximation error of the RBFNN	-
ϵ_J	Acceleration minimisation weighting factor of the cost function	-
ζ	Damping ratio of the main hoisting cable	-
η_J	Jerk minimisation weighting factor of the cost function	-
θ_{GA}	Convergence criteria of the GA	-
κ_J	Power consumption minimisation weighting factor of the cost function	-
λ_i	i^{th} λ term of the FSMC/SSMC/RBFNN-SMC system	-
ν_b	Kinematic viscosity of the lubricant for the sheave bearings	mm/s ²
ρ	Saturation function parameter of the FSMC/SSMC/RBFNN-SMC system	-
Φ_D	Derivative nonlinear function of the NPID/NPDF controller	-
Φ_I	Integral nonlinear function of the NPID/NPDF controller	-
Φ_P	Proportional nonlinear function of the NPID/NPDF controller	-
ψ_x	Search space for parameter x within the GA	-
ω_{gov}	Angular velocity of the governor wheel of the tachometer	rad/s
ω_m	Angular velocity of the motor	rad/s
ω_{rpm}	Angular velocity of the sheave in revolutions per minute	rpm
ω_s	Angular velocity of the sheave	rad/s

Acronyms

Acronym	Meaning
ABS	Anti-lock braking system
ACO	Ant colony optimisation
ANN	Artificial neural network
CPDF	Conventional pseudo-derivative feedback control
CPID	Conventional proportional-integral-derivative control
CTBUH	Council on Tall Buildings and Urban Habitat
DE	Differential evolution
EJ	End jerk (experienced jerk starting 5 seconds after t_{sched})
EMF	Electromotive force
FSMC	Full sliding mode control
GA	Genetic algorithm
MPL	Minimum parameter learning
MVAWT	Maglev vertical axis wind turbine
NPDF	Nonlinear pseudo-derivative feedback control
NPID	Nonlinear proportional-integral-derivative control
PAA	Parameter adaption algorithm
PSO	Particle swarm orientation
PWM	Pulse width modulation
RBFNN	Radial basis function neural network
RBFNN-SMC	Direct adaptive neural network-based sliding mode control
SSMC	Simplified sliding mode control
UAV	Unmanned aerial vehicle
VSC	Variable structure control
VVVF	Variable-voltage/variable-frequency

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1 Introduction

1.1 Research Background and Motivation

An elevator, sometimes referred to as a lift, is a mechanism which makes use of a mechanically-powered pulley system to transport people and/or cargo in a vertical direction. With one elevator for every 344 individuals in the United States, averaging over 18 billion passenger trips in the country per year; it is evident that the elevator has come to play a vital role in the modern world. Despite the wide-spread nature of elevators and years of advancements in lift design, the ever-changing skylines of modern cities demand new developments in elevator design and control. As buildings continue to rise to greater heights, consequently requiring faster elevators; ensuring passenger safety and ride comfort becomes an ever-more challenging task. While the parameters of elevator cables for low lifting heights and velocities can be assumed to be constant, such a model cannot be used when designing an elevator for an ultratall building, such as the upcoming 1 km tall Jeddah Tower in Saudi Arabia. At great lifting heights and velocities, the effect of the changing free rope length on the dynamic behaviour of the cables must be considered. The resulting oscillations due to the continuously changing cable stiffness and damping coefficient are highly nonlinear and, subsequently, difficult to control [1].

In control engineering, it is customary to assume that a system may be defined by a set of linear equations within a certain range of interest, as demonstrated in the following equation [2]:

$$\dot{x}(t) = Ax(t) + BU(t) \quad (1.1)$$

where $x(t)$ represents the system state vector, A and B are time-invariant matrices and $U(t)$ denotes the system input vector. Assuming that Equation 1.1 accurately describes the dynamics of the system in question, linear control theory can be applied to control the system [2].

Linear control has a long history, with several control methods being developed and successfully implemented for numerous industrial applications. In the late 1980s/early 1990s, however, researchers from certain industries (such as aerospace, biomedical, etc.) began showing an interest in the development and introduction of nonlinear control into their respective fields. There were several reasons for this, such as the limited operating range of a linear controller, the prevalence of hard nonlinearities

in the systems, the reality of constantly changing and/or completely uncertain model parameters and the fact that, perhaps paradoxically, a good nonlinear controller may be simpler and more intuitive to design than a corresponding linear controller [3]. Unstable parameters are particularly relevant regarding the case of an ultratall, high-speed elevator system; where drastic cable stiffness changes occur during lifting due to the diminishing free rope length [4], in addition to the constantly varying cabin load.

Intelligent and adaptive nonlinear control has been successfully implemented in various applications where similar nonlinearities appear due to varying system dynamics. Examples of intelligent adaptive control in the elevator industry have not been found in existing literature, however such control could potentially be ideal for a system where the cable dynamics, car loads, travel distances, etc., are never constant.

1.2 Problem Statement

Despite being a central, long-standing component of modern civilization, the elevator remains a subject of research within many different studies. The dynamic behaviour of the hoisting cables during operation is a problem that remains unsatisfactorily solved, with the highly-nonlinear responses only being exacerbated by increased lifting heights and velocities [5]. As technology advances and humanity continues building towards the sky – increasing moving masses, travel velocities and lifting heights in the process; the subsequent control problems that arise must be dealt with effectively. Although linear control is commonplace in many nonlinear systems, it relies on the assumption of a relatively small range of operation [3]. Such an assumption cannot be made for the case of an ultratall elevator due to the aforementioned nonlinearities; in addition to parameters such as cabin mass, position of the cabin, travel direction, etc., being ever-changing. As such, a nonlinear control system is required that is able to successfully maintain efficient and safe elevator operation in spite of the nonlinearities and uncertainties inherent to the system.

1.3 Literature Review

1.3.1 Elevator nomenclature

1.3.1.1 Elevator/building lifting height criteria

At the time of submission of this dissertation, the Burj Khalifa in Dubai, standing at a height of 828 m [6], is the current tallest building in the world. Following its completion, the term "supertall" (i.e.,

a building with a height greater than or equal to 300 m) was no longer deemed sufficient for defining skyscrapers based on height. As such, the Council on Tall Buildings and Urban Habitat (CTBUH) officially introduced the term "megatall" to describe buildings that are greater than or equal to 600 m tall [7]. While not officially recognised by the CTBUH, as such a building is yet to be completed, the term "ultratall" has been used to define buildings with a structural height of at least 900 m [8]. For the purposes of this dissertation, elevators are defined by lifting height using the aforementioned criteria. Hence, an elevator with a lifting height between 300 m and 600 m is defined as a supertall elevator; whilst an elevator with a lifting height greater than 900 m is defined as an ultratall elevator.

1.3.1.2 Express and local elevators

One method of ensuring efficient passenger transport through a high-rise building is for the elevator systems to mimic that of a high-speed railway service; whereby the elevators are divided into two variants – express and local elevators. Express elevators operate at high speeds and only serve a limited number of floors within the building. Passengers will travel on an express elevator to reach the closest floor to their final destination, before transferring to a local elevator for the final leg of the journey. Local elevators typically operate at much lower speeds, with multiple cabins utilising the same shaft to serve different zones within the building [9]. This minimises the amount of valuable real estate space wasted by elevator shafts, while maintaining efficient movement of occupants through the building.

1.3.2 Elevator model

1.3.2.1 Industry standard elevator drives and drive control

For the current research to be relevant, existing methods for elevator control used in industry must be examined and taken into account. Otis Elevator Company describes the Otis4000 as a "high performance, gearless solution for prestigious high buildings." A variable-voltage/variable-frequency (VVVF) drive system is used, with the control system able to ensure efficient operation for elevator speeds up to 4 m/s [10]. While not explicitly stated within the brochure, patents assigned to Otis [11], as well as various publications on VVVF drives [12] [13] [14], suggests that the speed control is most likely performed by a proportional-integral (PI) controller. Naturally, no company would allow their design to enter into the public space, however it is safe to assume that the VVVF closed-loop vector control drive design used by Otis is not too dissimilar to a typical VVVF drive, which is illustrated in [Figure 1.1](#) [13].

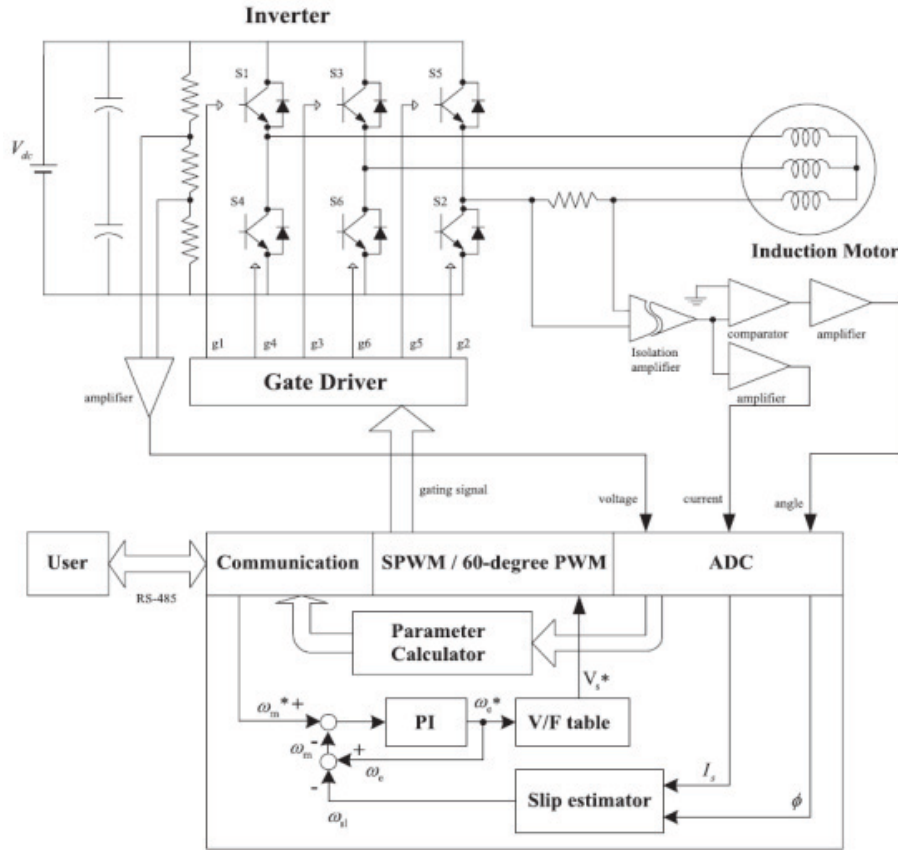


Figure 1.1: Variable-voltage/variable-frequency drive schematic [13]

According to the brochure for the Otis4000 [10], this control system is said to:

- Deliver exceptional ride quality, irrespective of cabin load.
- Monitor the car speed and travel distance throughout the journey and compare these parameters to a speed profile generated online, making fine adjustments to the voltage and frequency to provide a smooth commute.
- Obtain the optimum torque from the drive through the use of pulse width modulation (PWM), thereby decreasing wait time and maximising energy efficiency.
- Ensure that the elevator car arrives within 3 mm of its final destination, regardless of the payload.

In-depth modelling of the driving moment for an elevator is a complicated procedure, as the performance is heavily-dependent on the features of the motor, such as electromagnetic flux, motor inertia, method of control, etc. The most common method is to approximate the driving force in the operating regime based on the start-up process of the motor, as described by the following set of equations [5]:

$$F(t) = F_0 - \text{constant force} \quad (1.2)$$

$$F(t) = F_0 \left(1 - \frac{t}{t_a}\right) - \text{soft drive regime} \quad (1.3)$$

$$F(t) = F_0 \left(1 - \frac{t^2}{t_a^2}\right) - \text{medium drive regime} \quad (1.4)$$

$$F(t) = F_0 \left(1 - \frac{t^4}{t_a^4}\right) - \text{rigid drive regime} \quad (1.5)$$

where F_0 is the pulled force [N] and t_a is the acceleration time [s].

The driving moment (M_m) can be more accurately defined by using the static characteristic of an electric motor in the velocity function as follows [1]:

$$M_m = \frac{q_m}{2\pi f_m} U_{m_{tot}}^2 p_m \frac{\frac{R'_r}{s_m}}{\left(R_s + \frac{R'_r}{s_m}\right)^2 + \left(X_{\gamma s} + X'_{\gamma rk}\right)^2} \quad (1.6)$$

where q_m is the number of phases, f_m is the network frequency [Hz], $U_{m_{tot}}$ represents the total voltage through the motor [V], p_m denotes the number of pole pairs, R'_r is the rotor resistance [Ω], s_m is the motor slip, R_s is the stator resistance [Ω], $X_{\gamma s}$ is the stator leakage reactance [Ω] and $X'_{\gamma rk}$ is the rotor leakage reactance [Ω].

In related research [16], the variability of the driving torque of high-speed, high-rise elevators is underlined as a reason behind the complexity of such a system. Disturbance torque values of approximately 1% of the peak torque have been reported in technical brochures [17], with such a seemingly miniscule disturbance having a significant influence on the system dynamics. As such, the effects of torque disturbance within the actuator cannot be ignored and must be suitably attenuated by the controllers. Wang et al., [18] achieved effective disturbance rejection by coupling a sliding mode control (SMC) system with a disturbance torque observer (DTO) during speed control of a permanent magnet synchronous motor (PMSM). It was reported that the combined SMC+DTO was more effective at handling disturbances than an isolated SMC system.

1.3.2.2 DC drum braking

In addition to maintaining efficient elevator operation, the braking system of an elevator must ensure the safety of occupants within the cabin. The brake should guarantee that the car will not move for payloads up to and including 125% of the rated load [15]. Drum brakes are the most commonly used variation within the elevator industry, with electromagnetic drum brakes generally being the design of choice [19] [20] [21]. An electromagnetic drum brake consists of a spring assembly, a magnet and two brake shoes which clamp down on the elevator sheave by means of compression springs in order to induce a braking torque. The brake is released by powering the electromagnet, thereby causing the brake coil to push the brake shoes apart due to the generated electromagnetic force. This design ensures that, in the case of a loss of power, the brakes will engage [15] [19]. An example of a typical DC-operated elevator brake is shown in Figure 1.2 [19].

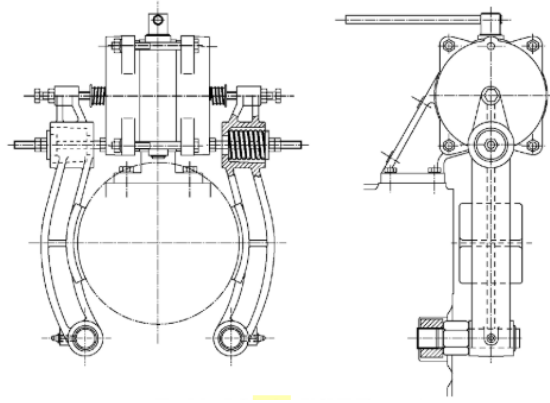


Figure 1.2: DC drum brake (KONE Elevators) [19]

Accounting for braking performance when developing an elevator control system is of utmost importance. For example, even a minor error in determining the time taken for the brake to engage could significantly affect the final position of the elevator car. An error of only 100 milliseconds for an elevator travelling at 2.5 m/s would result in an error of 0.25 m, while an elevator travelling at 10 m/s would arrive a full meter away from the desired destination [20].

1.3.2.3 Counter-current braking

Counter-current braking (commonly referred to as plugging) is a method of braking whereby the polarity of the supply voltage is reversed, subsequently reversing the flow of current and applying a braking torque opposite to the rotation of the rotor. Although a fast braking response can be obtained, counter-current braking is highly inefficient, as the supply power is wasted in resistance [22]. Additionally, should the supply voltage not be disconnected once zero speed is reached, reverse motoring is initiated [23]. Counter-current braking is regularly implemented in multiple applications, including elevator braking [24].

1.3.2.4 Fail-safe braking

In addition to the main elevator braking system, a number of secondary fail-safe braking systems exist in order to further guarantee passenger safety. One such method involves the use of an over-speed governor connected to the elevator car by a separate cable. Within the governor are spring loaded flyweights, which are extended outwards by centrifugal force should the elevator exceed its maximum allowable velocity. The hooked flyweights then lock onto the stationary inner rim of the governor, immediately bringing the elevator cabin to an abrupt halt [25].

Another safety brake, developed specifically for high-speed elevators, is capable of safely bringing an elevator falling at 20 m/s to rest, without exceeding the industry standards for maximum allowable deceleration. The device consists of a wedge which clamps down on the guide rails to apply a braking force, with the laminated ceramic material ensuring that the wedge is able to withstand the heat and wear due to the high frictional forces involved [26].

1.3.2.5 Elevator cables

For an ultratall elevator, the significant change in free rope length causes substantial fluctuations in the cable parameters, which may lead to unstable elevator movement and cable failure. According to Vladić et al., [1], a suitable dynamic model of an elevator without a machine room, that may be used as a basis for developing a set of differential equations, is illustrated in Figure 1.3 [1].

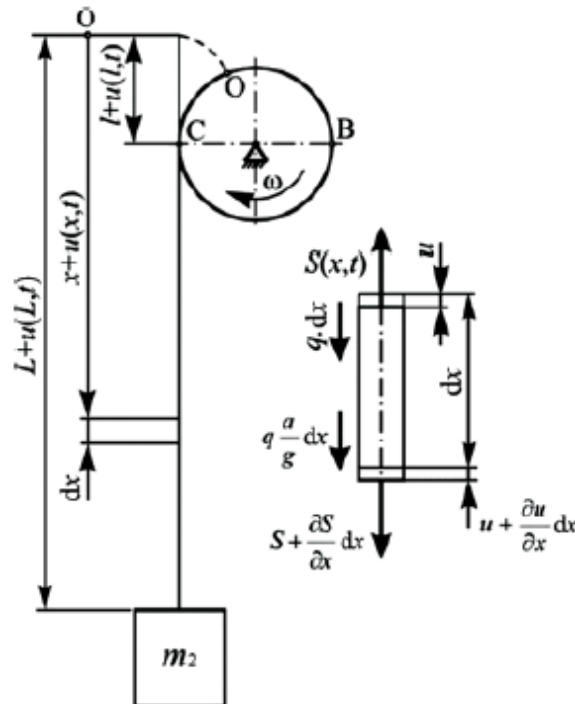


Figure 1.3: Elevator model with boundary conditions [1]

Two elevator models were developed from the derived differential equations, one travelling at 10 m/s to a height of 100 m, with the other travelling at 20 m/s for a distance of 500 m. For both elevators, simulations were performed for cases of varying and constant cable stiffness. The resulting acceleration responses and corresponding cable stiffness changes for both elevators are provided in Figures 1.4 and 1.5, respectively [1].

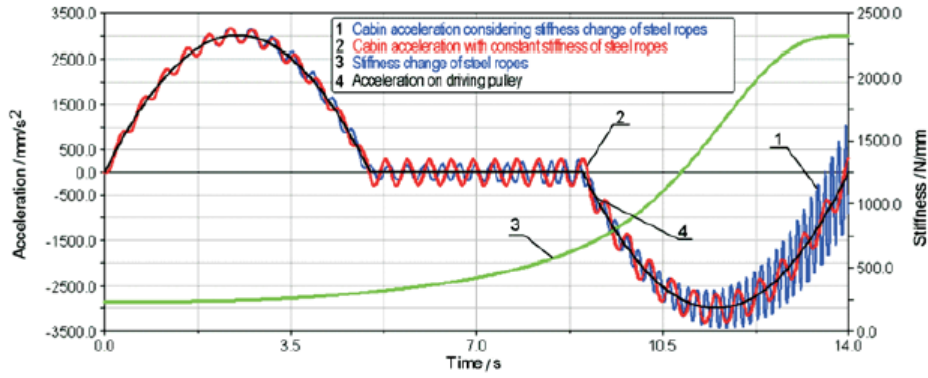


Figure 1.4: Acceleration response and change in cable stiffness for a 10 m/s elevator with a lifting height of 100 m [1]

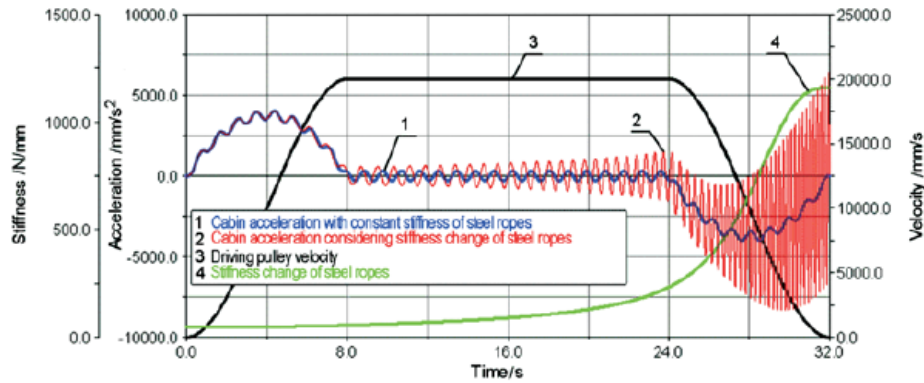


Figure 1.5: Acceleration response and change in cable stiffness for a 20 m/s elevator with a lifting height of 500 m [1]

From these figures, it is clear that the nonlinear change in cable stiffness has a significant effect on cabin acceleration, with an increase in travel velocity and lifting height causing massive oscillations during the braking procedure. Such movement would pose a serious risk to passengers within the cabin due to the excessive acceleration and jerk experienced, in addition to potentially damaging elevator components. Additional complexity is introduced when considering the effects of damping within the cables. Cable damping is a component of the dynamic behaviour that has not been sufficiently examined, as it is dependent on a number of factors such as stress within the rope, inner friction, lubrication, etc., [16]. It is clear that an effective control system is required to ensure safe and efficient high-speed, ultratall elevator operation despite the associated uncertainties and nonlinearities.

For the case of ultratall buildings, it is a commonly accepted fact within the elevator industry that traditional steel-cabled elevators are not a practical solution [27], with the lifting height for such elevators limited to approximately 500 m. The two main reasons for this are the impractical weight of steel cables that would be required, as well as the susceptibility of the ropes to building sway [28].

This is evident in the Burj Khalifa, which requires three separate groups of elevators travelling to the 43rd, 76th and 123rd floors, respectively [1]. This significantly increases the power consumption of the building, wastes valuable retail space and limits innovative architectural designs. In order to solve this problem, two separate solutions have been developed by ThyssenKrupp and KONE.

MULTI, the first rope-free elevator developed in the industry, utilises linear motors to transport the elevator car by making use of magnetic levitation. According to the manufacturer, the advantages associated with this system are:

- Shorter wait times for passengers.
- Increased elevator capacity.
- Reduced power consumption as a result of the removal of heavy cables, low-friction movement, etc.

Additionally, the ability of MULTI to travel horizontally as well as vertically is claimed to significantly reduce traffic within the building [27].

KONE, rather than removing cables completely, developed a new rope specifically for ultratall buildings. UltraRope®, consisting of a carbon-fibre core and high-friction coating, is extremely lightweight, lasts twice as long as conventional steel cables and is less sensitive to building sway; as the resonance frequency of carbon-fibre differs from steel and most other structural materials. A comparison between the moving masses of conventional steel-cabled elevators and equivalent UltraRope® elevators is provided in Table 1.1, with the weight difference plotted in Figure 1.6 [28].

Table 1.1: Steel cable vs UltraRope® moving masses [28]

Lifting Height [m]	Steel Cable Moving Mass [kg]	KONE UltraRope® Moving Mass [kg]
100	13000	11800
200	15100	12000
300	17900	12200
400	22400	12400
500	29000	12800
600	39500	13200
700	60700	13600
800	108600	13900

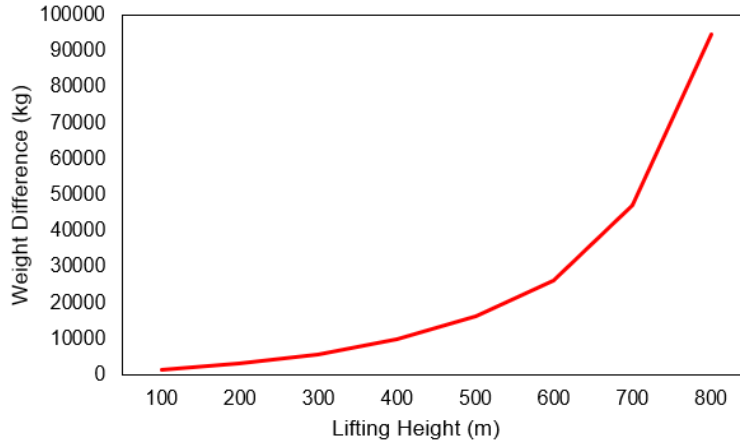


Figure 1.6: Difference in moving masses between elevators using Steel Cables and UltraRope® [28]

As shown in Figure 1.6, UltraRope® offers a significant reduction in the lifting load, growing exponentially with increasing building heights. The coating is highly resistant to abrasion and requires no lubrication, further reducing environmental impact [28]. UltraRope® is set to be installed in the upcoming Jeddah Tower, which would result in the highest elevator rise in the world.

1.3.3 Nonlinear control

1.3.3.1 Gain scheduling

Gain scheduling, considered to be the simplest nonlinear control technique [29], is a method of utilising linear control procedures to oversee nonlinear systems with a theoretical guarantee of stability and performance [30]. Gain-scheduled conventional proportional-integral-derivative (CPID) controllers have been effectively implemented in a number of nonlinear control problems, with Qiao et al., [31] successfully applying the strategy for the control of a multivariable nonlinear unmanned aerial vehicle (UAV). It was concluded that the gain-scheduled CPID controller ensured improved setpoint tracking, in addition to increasing the fault-tolerant capability of the vehicle. The robust properties, straightforward design and simple implementation were highlighted as benefits of the control system.

In previous work [32] [33], it was found that effective elevator control was achieved through the use of a conventional pseudo-derivative feedback (CPDF) controller, successfully meeting all system requirements and constraints in terms of passenger safety, ride comfort, elevator performance, sensitivity to load variations and disturbance rejections. While the cable stiffness was assumed constant in these investigations, the successful implementations of gain-scheduled CPID controllers by Qiao et al., [31], Santoso et al., [34] and Shao et al., [35] suggests that a gain-scheduled CPDF controller could be able to efficiently control a similar system with varying cable dynamics. Two potential

issues regarding the implementation of gain scheduling are that the changing system dynamics must be predictable [31] and must vary slowly [36], which may not necessarily be true for an ultratall, high-speed elevator.

1.3.3.2 Nonlinear proportional-integral-derivative control

CPID control remains the most commonly utilised control architecture for industrial purposes, due to its robustness, relatively simple algorithm and effectiveness at controlling linear systems [32]. Most industrial processes, however, are nonlinear; meaning that conventional PID controllers are only effective within a limited operating range for such systems. In order to more effectively modulate nonlinear systems using PID control, a nonlinear PID (NPID) controller has been developed and is defined in Equation 1.7 [37]:

$$U = K_P \Phi_{P-NPID}(U_e, \alpha_P, \delta_P) + K_I \Phi_{I-NPID}\left(\int U_e dt, \alpha_I, \delta_I\right) + K_D \Phi_{D-NPID}(\dot{U}_e, \alpha_D, \delta_D) \quad (1.7)$$

where U_e , $\int U_e dt$, and $\dot{U}_e$ represent the error signal, integration of the error signal with respect to time and the error signal rate, respectively. K_P , K_I and K_D are the respective proportional, integral and derivative gains, while U denotes the controller output. α_P , δ_P , α_I , δ_I , α_D and δ_D are parameters of the nonlinear functions (Φ_{P-NPID} , Φ_{I-NPID} and Φ_{D-NPID}), which are defined in Equation 1.8 [37]:

$$\Phi(x, \alpha, \delta) = \begin{cases} |x|^\alpha \cdot \text{sign}(x), & |x| > \delta \\ \delta^{\alpha-1} \cdot x, & \text{otherwise} \end{cases} \quad (1.8)$$

An alternative to gain-scheduling, the concept of NPID control is to pass each of the signals: U_e , $\int U_e dt$ and $\dot{U}_e$ through the three nonlinear functions that modify the respective signals before they are seen by the controller [37]. Two examples of nonlinear functions employed on the proportional mode of a NPID controller are illustrated in Figure 1.7, alongside the profile of a CPID controller function for comparison. The subsequent adaptations of the proportional control signals are displayed in Figure 1.8.

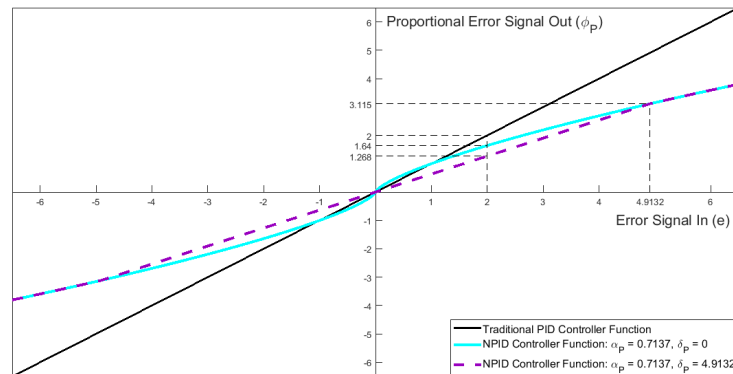


Figure 1.7: NPID and CPID controller proportional mode functions

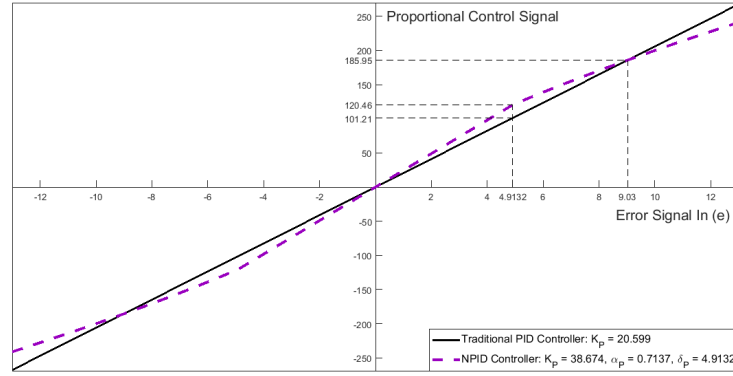


Figure 1.8: NPID and CPID controller proportional mode control signals

As seen in Figure 1.7, for a nonlinear function having parameters $\alpha_P = 0.7137$ and $\delta_P = 0$, lower proportional action occurs at higher errors when compared with a CPID controller having the same proportional gain. For errors below $e = 1$, on the other hand, higher proportional action occurs than can be achieved by an equivalent CPID controller. While this may ensure effective control in certain scenarios, it can often result in an excessively high response to small errors, leading to inefficient control and/or numerical problems. In order to overcome this issue, δ_P can be increased to introduce a linear area within the nonlinear function between errors of 0 and δ_P , thereby preventing an unacceptably high response to low errors. The subsequent proportional control signal response of a NPID controller with parameters $K_P = 38.674$, $\alpha_P = 0.7137$ and $\delta_P = 4.9132$ is compared with that of a CPID controller having a gain of $K_P = 20.599$ in Figure 1.8. As can be seen, the ability to adapt the α and δ terms within each of the three nonlinear functions offers far more flexibility than a traditional CPID controller, with the parameters able to be tuned in a multitude of ways to obtain the required responses to specific errors. Naturally, this comes at the cost of a more difficult tuning process compared with a CPID controller, with six extra parameters that must be carefully optimised to obtain the desired control response.

Jiang et al., [37] found that for control of the anti-lock braking system (ABS) of a truck, a NPID controller performed better than its conventional equivalent, while simultaneously retaining the intuitions and simplicity of tuning of a CPID controller. An improved robustness to uncertainties was reported, with the NPID controller displaying no variations in performance following a 25% change in parameters compared with the CPID controller, which exhibited a substantial decline in control performance following the change. As mentioned, previous work on elevator control [32] [33] found that highly effective control was achieved through the use of a CPDF controller, greatly surpassing the performance of a CPID controller for the same system. These results, as well as the successful implementation of NPID control to nonlinear systems by Jiang et al., [37] and Zaidner et al., [38],

suggest some value in investigating the possibility of applying nonlinear pseudo-derivative feedback (NPDF) control to an elevator system.

1.3.3.3 Feedback linearisation-based control

Feedback linearisation is a method for controlling nonlinear systems by transforming the model dynamics into an equivalent linear system, either partly or wholly, allowing for the implementation of linear control techniques [39]. This method differs from Jacobian linearisation, as exact state transformations occur, as opposed to approximating the nonlinear dynamics [3]. There are two types of feedback linearisation, namely input-state feedback linearisation and input-output feedback linearisation. Input-state feedback linearisation is a two-step method. Firstly, state transformation is utilised to convert the nonlinear system into a linear one. Secondly, a linear controller is designed and implemented as required [39]. Input-output feedback linearisation is performed by first developing a linear relationship between the system inputs and outputs before applying a linear control methodology [3].

Hamouda et al., [40] applied input-state feedback linearisation to control two-stage matrix converters interfaced with high-speed microturbine generators. One of the main benefits reported following simulation was the absence of oscillations in the input current waveforms during the transient stage. Li et al., [41] combined input-output feedback linearisation with sliding mode control for the stabilisation of the rudder of a ship. The combination of the two control schemes ensured good robustness and accurate course control under a number of different ocean conditions. Such a combination could be highly effective for control of an elevator system, where sufficient robustness is required to account for uncertainties and varying parameters such as cabin occupancy, cable stiffness, etc.

1.3.3.4 Sliding mode control

SMC is a specific branch of variable structure control (VSC), whereby the controller is designed to drive the system state onto a particular surface in the state space, referred to as the sliding surface. Once the sliding surface has been reached, the SMC constrains the states within the area of the sliding surface. This surface is sometimes referred to as the switching surface, due to the fact that the system has a specific gain if the state trajectory is located on one side of the surface, switching to a different gain should the trajectory traverse to the opposite side [42].

The two main advantages associated with SMC are that the dynamic behaviour of the system may be tailor-made by the particular choice of the sliding function and that the closed-loop response is insensitive to specific uncertainties within the model. This insensitivity makes SMC an appropriate option for the implementation of robust control [42].

Consider a generic system defined as:

$$\begin{aligned}
x_1 &= h(x) \\
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= x_3 \\
&\vdots \\
\dot{x}_{(z-1)} &= x_z \\
\dot{x}_{(z)} &= f(x) + g(x)U + \Delta b(x)
\end{aligned} \tag{1.9}$$

where z is the relative degree of the system, $f(x)$ and $g(x)$ are known, $b(x)$ represents external disturbances and $h(x)$ is the controlled variable.

The sliding mode function (s) is defined as [43]:

$$s = \frac{d^{(z-1)}e_0}{dt} + \lambda_{(z-2)}\frac{d^{(z-2)}e_0}{dt} + \dots + \lambda_0 e_0 \tag{1.10}$$

with the tracking error (e_0) and derivative values calculated using:

$$e_0 = x_1 - x_d$$

and

$$\frac{d^{(i)}e_0}{dt} = \frac{d^{(i)}x_1}{dt} - \frac{d^{(i)}x_d}{dt}$$

where x_d is the setpoint signal. Additionally, the SMC coefficients (λ_i) must satisfy the Hurwitz condition, ensuring that the polynomial $p^{(z-1)} + \lambda_{(z-2)}p^{(z-2)} + \dots + \lambda_0$ has stable roots, where p is a Laplace operator.

From Equation 1.10, it can be seen that the errors will tend to zero exponentially if the trajectory is confined to the sliding surface. An appropriate sliding surface will ensure that any trajectory originating on the surface will remain there, while any trajectory starting elsewhere will tend towards the surface asymptotically.

The sliding mode control law is designed as [43]:

$$U = \frac{1}{\mathcal{L}_g \mathcal{L}_f^{(z-1)} h(x)} \left(\frac{d^{(z)}x_d}{dt} - \mathcal{L}_f^z h(x) - \lambda_{(z-2)} \frac{d^{(z-1)}e_0}{dt} - \dots - \lambda_0 \dot{e}_0 - 1.1K_R \text{sign}(s) \right) \tag{1.11}$$

where the sign function is defined as:

$$\text{sign}(s) = \begin{cases} 1, & s > 0 \\ 0, & s = 0 \\ -1, & s < 0 \end{cases} \tag{1.12}$$

The reaching law gain (K_R) must be selected to ensure the following bound on the magnitude of the disturbances:

$$K_R \geq |\Delta b(x)| \quad (1.13)$$

with the constant value of 1.1 being a randomly selected value, with any number greater than 1 being a suitable option to aid in ensuring the bound on the disturbance.

In order to prove that $s \rightarrow 0$ as $t \rightarrow \infty$, consider the time derivative of the sliding surface defined in Equation 1.10 [43]:

$$\begin{aligned} \dot{s} &= \frac{d^{(z)}e_0}{dt} + \lambda_{(z-2)} \frac{d^{(z-1)}e_0}{dt} + \dots + \lambda_0 \dot{e}_0 \\ &= \frac{d^{(z)}x_1}{dt} - \frac{d^{(z)}x_d}{dt} + \lambda_{(z-2)} \frac{d^{(z-1)}e_0}{dt} + \dots + \lambda_0 \dot{e}_0 \\ &= \left(\mathcal{L}_f^z h(x) + \mathcal{L}_g \mathcal{L}_f^{(z-1)} h(x) U + \mathcal{L}_{\Delta f}^{(z-1)} h(x) \right) - \frac{d^{(z)}x_d}{dt} + \lambda_{(z-2)} \frac{d^{(z-1)}e_0}{dt} + \dots + \lambda_0 \dot{e}_0 \end{aligned} \quad (1.14)$$

By rearranging Equation 1.11 and introducing it into Equation 1.14, the expression becomes:

$$\begin{aligned} \dot{s} &= \left(\left(\frac{d^{(z)}x_d}{dt} - \lambda_{(z-2)} \frac{d^{(z-1)}e_0}{dt} - \dots - \lambda_0 \dot{e}_0 - 1.1 K_R \text{sign}(s) \right) + \mathcal{L}_{\Delta f}^{(z-1)} h(x) \right) \\ &\quad - \frac{d^{(z)}x_d}{dt} + \lambda_{(z-2)} \frac{d^{(z-1)}e_0}{dt} + \dots + \lambda_0 \dot{e}_0 \end{aligned}$$

which simplifies to:

$$\dot{s} = -1.1 K_R \text{sign}(s) + \mathcal{L}_{\Delta f}^{(z-1)} h(x) \quad (1.15)$$

where:

$$\mathcal{L}_{\Delta f}^{(z-1)} h(x) = \Delta b(x)$$

Noting the relationship defined in Equation 1.13, it can be shown that when $s > 0$, Equation 1.15 becomes:

$$\dot{s} \leq -0.1 K_R \quad (1.16)$$

and when $s < 0$:

$$\dot{s} \geq 0.1 K_R \quad (1.17)$$

indicating that s tends to zero in finite time. This can be proven by rewriting Equation 1.16:

$$\frac{d}{dt} s(x, t) \leq -0.1 K_R$$

and integrating both sides between 0 and t :

$$s(x, t) - s(x, 0) \leq -0.1 K_R t$$

An upper bound for the time (t_0) at which $s(x, t_0) = 0$ can be computed as follows:

$$t_0 \leq \frac{s(x, 0)}{0.1 K_R}$$

where $s(x, 0) > 0$. By rewriting Equation 1.17 and integrating both sides between 0 and t , an upper bound for t_0 at which $s(x, t_0) = 0$ can be calculated as:

$$t_0 \leq -\frac{s(x, 0)}{0.1K_R}$$

where $s(x, 0) < 0$. Therefore, the upper bound on t_0 can be expressed by:

$$t_0 \leq \frac{|s(x, 0)|}{0.1K_R}$$

indicating that $s(x, t)$ approaches 0 in finite time. Once the sliding surface has been reached, assuming appropriate choices of the SMC λ coefficients, the tracking error (e_0) will tend to 0 asymptotically. With regards to Equations 1.16 and 1.17, it can be shown that the design of the control law must guarantee that $s\dot{s} < 0$.

Defining the Lyapunov function (V) as:

$$V = \frac{1}{2}s^2 \quad (1.18)$$

the time derivative can be obtained:

$$\dot{V} = s\dot{s} \quad (1.19)$$

Since $V \geq 0$ and $\dot{V} \leq 0$, it can be seen that V is limited as $t \rightarrow \infty$.

Referring to the control law given in Equation 1.11, it can be seen that it is a discontinuous function due to the instantaneous switch associated with the sign function. This raises a number of issues, both practical and theoretical. In terms of theory, a discontinuous function cannot be Lipschitz continuous, thereby breaking the central condition of the Picard-Lindelöf Existence and Uniqueness theorem. As a result, it is not possible to infer the uniqueness and existence of solutions [44]. In terms of realisability of an SMC in a real-world system, it is impossible to induce an instantaneous response, as there will always be some delay within the actuator. This delay may cause the state trajectory to overshoot the sliding surface, resulting in chattering as illustrated in Figure 1.9 [45].

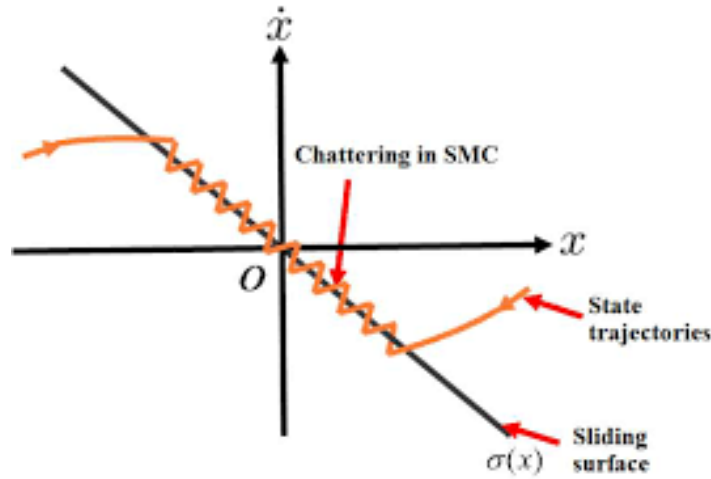


Figure 1.9: Sliding mode control chattering behaviour [45]

The reduction of chattering is an important consideration in SMC design, as it may induce high heat losses within the electronic circuits, cause damage to the actuator, excite high-frequency dynamics, degrade the controller performance and potentially lead to instability of the system. Two possible ways to reduce chattering are to avoid an unnecessarily high value of K_R [42] and/or to replace the sign function with a high-slope saturation function, as defined in Equation 1.20 and illustrated in Figure 1.10 [46]:

$$\text{sat}(s, \rho) = \begin{cases} 1, & s > \rho \\ s, & -\rho \leq s \leq \rho \\ -1, & s < -\rho \end{cases} \quad (1.20)$$

where $\rho > 0$ and has a small value.

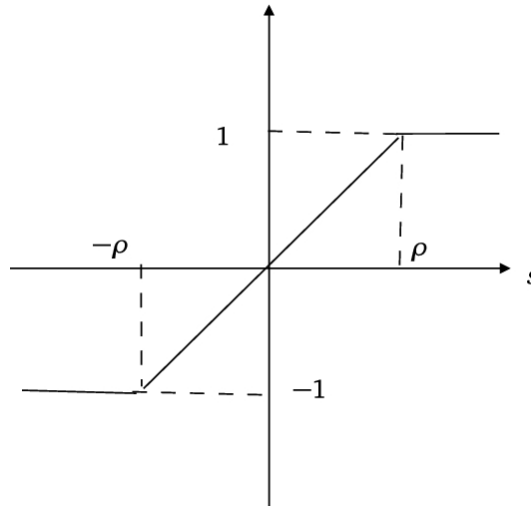


Figure 1.10: SMC saturation function to reduce chattering [46]

Control of an elevator system using SMC is reported in literature, with Alipour et al., [47] utilising a parallel CPID-SMC to ensure the smooth operation of a ropeless elevator. While simulations indicated that a stand-alone CPID controller was able to maintain an efficient transient response, system performance was heavily influenced by external disturbances during steady-state operation. This issue was solved by introducing an SMC, which is robust at the expense of slower performance. The combined CPID-SMC made use of the advantages of both controllers, with the CPID controlling the transient period of operation before switching to the SMC once the response settled. As a result, a fast and robust response was obtained, while overshoot and oscillations were simultaneously minimised.

In terms of comparing SMC and feedback linearisation; Eltayeb et al., [48] compared both architectures for control of a quadrotor UAV. Although both systems were reported to have achieved effective control, the SMC exhibited superior disturbance rejection capabilities.

1.3.3.5 Adaptive control

Adaptive control involves automatic controller adjustments in real time with the aim of maintaining efficient control when parameters of the plant model are unknown and/or constantly changing over time. This is performed by collecting input and output data from the system and tuning the controller accordingly in order to obtain the desired performance, as shown in Figure 1.11 [49].

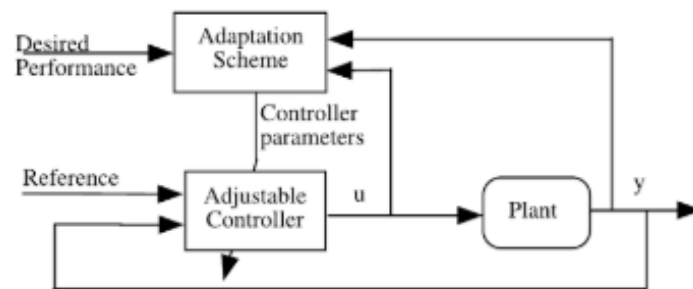


Figure 1.11: Adaptive control system architecture [49]

There are two types of adaptive control, direct and indirect adaptive control. Direct adaptive control involves updating the controller based on the adaptation error, which is the difference between actual performance and desired performance. Direct adaptive control structures are generally developed in one of two ways [49]:

1. Define an adaptation error equation that is a function of the difference between the tuned-controller parameters and the existing controller parameters. Use the adaptation error to establish a parameter adaptation algorithm (PAA) for the controller.
2. Use an indirect adaptive control scheme in conjunction with an adaptive predictor of the system output that is re-parametrised in terms of the controller parameters. The output of the adaptive predictor should then be forced to accurately follow the setpoint.

The basic premise of indirect adaptive control is that an appropriate controller can be developed online if a plant model is estimated online based on input-output data. The method is "indirect," as the adaptation is split into two stages [49]:

1. The plant parameters are estimated online.
2. The controller parameters are selected online based on the estimated plant model.

Pop et al., [50] developed an adaptive controller to regulate the operation of a mining elevator, concluding that the estimation algorithm and adaptation strategy were sufficiently precise under simulation. The effectiveness of the adaptation scheme was highlighted as significant, as it suggested that a similar adaptive control scheme could be implemented into real-world mining elevator systems.

1.3.3.6 Adaptive backstepping control

Adaptive backstepping is an approach to the design of adaptive controllers and is based on Lyapunov stability specifically for strict feedback systems. For plant models that are transformable into strict feedback form, global or regional tracking properties are guaranteed. One advantage of using backstepping to design an adaptive controller is the step-by-step procedure, making the development of the feedback control laws and Lyapunov functions a logical undertaking. Additionally, the inherent flexibility of the method allows it to avoid the cancellation of useful nonlinearities within the system [51].

Patel et al., [52] applied adaptive backstepping control for trajectory tracking of mobile manipulators. In addition to guaranteeing system stability, perfect trajectory tracking was also obtained. Similarly, Eddahmani et al., [53] were able to achieve global system stability for control of a variable wind speed turbine as a result of the Lyapunov functions. The adaptive backstepping controller achieved significantly better tracking of the setpoint than a linear PI controller, with the control scheme being highlighted as ideal for an application requiring robustness, stability and good tracking performance. Control of an ultratall, high-speed elevator is such an application, with speed control in existing elevators generally performed by a PI controller (refer to Figure 1.1), implying that the implementation of an adaptive backstepping controller could provide better elevator performance than the control systems currently in use.

1.3.3.7 Neural network-based control

Artificial neural networks (ANNs) are computing systems inspired by biological neural networks. They comprise of several interconnected units referred to as neurons, usually organised into multiple layers in a feedforward/feedback arrangement. Neural networks are an attractive option for the modelling and control of nonlinear systems for a number of reasons [54] [55]:

1. ANN controllers are able to learn from experimental data using specialised training methods that can be either offline/online-based;
2. ANNs are particularly useful in cases where conventional design techniques fail to develop an appropriate system model and/or controller;

3. ANNs are able to tolerate faults and uncertainties within the model;
4. ANNs are universal approximators, meaning that any continuous nonlinear function can be approximated arbitrarily well over a compact interval by an ANN consisting of one or more hidden layers;
5. ANNs are able to perform massive parallel processing, with the network having a highly-parallel structure consisting of many simple processing elements.

Both static and dynamic ANNs exist, with the former consisting of a static map between the model inputs and outputs, while the latter relates an input vector and its derivative to an output. ANN control may be classed as either direct or indirect, depending on the role of the ANN in the control strategy. Direct ANN control indicates that the network acts as the controller, while indirect ANN-based control implies that the network serves as the dynamic model of the system, predicting either the output or complete state vector [43] [55].

An example of elevator speed control is found in the work by Yu et al., [56], where a neural network was used to adjust the gains of a CPID controller in order to achieve optimal control of a linear elevator system. The control scheme was particularly effective at controlling the system following a sudden load disturbance, with the ANN adjusting the CPID controller gains to quickly and effectively mitigate the disturbance in a way that an isolated CPID controller could not.

1.3.3.8 Radial basis function neural networks

Radial basis function neural networks (RBFNNs) are a popular variant of neural networks due to the relative simplicity of having a single hidden layer, as well as the ability of the network to quickly and accurately approximate any nonlinear function [42] [57] [58]. The structure of a generic RBFNN is illustrated in Figure 1.12 [58].

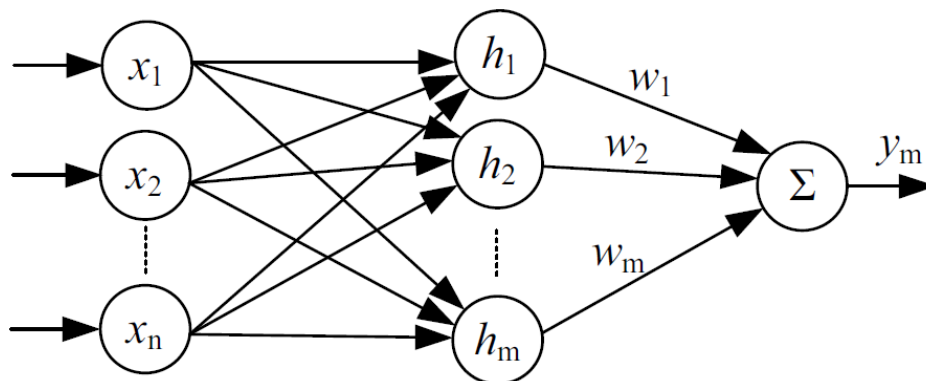


Figure 1.12: Radial basis function neural network (RBFNN) [58]

As can be seen in [Figure 1.12](#), the architecture of the network consists of three layers – namely the input layer ($\mathbf{x} = [x_1, x_2, \dots, x_n]$), the hidden layer and the output layer. The hidden layer performs a nonlinear transformation of the input, whereas the transformation from the hidden space to the output space is linear. The hidden units are defined as radial centres ($\mathbf{c} = [c_1, c_2, \dots, c_m]$), where m is the number of neurons within the hidden layer. A centre is activated when the input $\mathbf{x}$ lies within its receptive field, producing a non-zero response. The target output (y_m) is then obtained as follows:

$$y_m = \sum_{j=1}^m h_j w_j \quad j = 1, 2, \dots, m \quad (1.21)$$

where w_j is the connection weight from the j^{th} node to the output and h_j is the activation function of the j^{th} radial centre.

Typically, this activation function takes the form of a Gaussian radial function, defined in [Equation 1.22](#) [42]:

$$h_j = \exp\left(-\frac{\|\mathbf{x} - \mathbf{c}_j\|^2}{2b_j^2}\right) \quad (1.22)$$

where $\|\mathbf{x} - \mathbf{c}_j\|$ is the Euclidean distance between $\mathbf{x}$ and $\mathbf{c}_j$, while b_j is the spread of the j^{th} radial centre ($b_j > 0$).

Training of an RBFNN consists of optimal selection of $\mathbf{c}_j$ and w_j , with common learning techniques including the gradient-descent and pseudo-inverse procedures. Adaptive RBFNN control is possible through online adjustments of the weight values, with such an architecture easily derived through the Lyapunov stability analysis due to the linear relationship between the hidden and output layers [57].

Application of RBFNN to adaptive control problems is well documented in existing literature, with Qing et al., [59] developing an adaptive RBFNN to estimate the unknown disturbances on a quadrotor landing on a moving vehicle. The adaptive RBFNN was applied to the controller using a backstepping technique, successfully guaranteeing good landing performance by restricting the tracking error to small values.

Wang et al., [60] highlighted that for improving the performance of a wind turbine generator system, a neural network alone is incapable of eliminating steady-state error. An adaptive RBFNN-CPID controller was developed as a result, effectively achieving improved control accuracy and general system performance. Additionally, it was concluded that the designed control method is easily extendable to other nonlinear systems.

Haiyang et al., [61] designed an adaptive RBFNN-CPID controller to control temperature for vacuum thermal tests, with the control system able to adjust the network weights and CPID controller gains online in order to reduce the tracking overshoot. The adaptive RBFNN-CPID controller was able to ensure good reference tracking, improved temperature predictability and efficiently adaptive control capabilities.

Considering the numerous examples of nonlinear control problems wherein an adaptive RBFNN-CPID control was able to successfully manage the system in question, it could prove to be an effective control system for a high-speed, ultratall elevator.

1.3.3.9 Direct adaptive neural network-based sliding mode control

A further example of adaptive control based on RBFNN relates to feedback linearisation/sliding mode control problems wherein the nonlinear functions $f(x)$ and/or $g(x)$ are unknown. The universal approximation capabilities of an RBFNN allows the network to estimate these functions, with the weight values being adjusted online to ensure that control is achieved irrespective of any uncertainties in the system. This gives the design an advantage over the traditional SMC system detailed in Section 1.3.3.4, wherein $f(x)$ and $g(x)$ are required to be explicitly defined.

For the case of a system where $g(x)$ is known, but $f(x)$ is unknown – $f(x)$ can be written as:

$$f(x) = \mathbf{W}^{*T} \mathbf{h}(x) + \epsilon \quad (1.23)$$

where $\mathbf{W}^*$ is the ideal neural network weight value and ϵ is the neural network approximation error ($\epsilon < \epsilon_N$).

Using an RBFNN to approximate $f(x)$, the network output is calculated:

$$\hat{f}(x) = \hat{\mathbf{W}}^T \mathbf{h}(x) \quad (1.24)$$

Defining $\tilde{\mathbf{W}} = \hat{\mathbf{W}} - \mathbf{W}^*$, it can be seen that:

$$f(x) - \hat{f}(x) = \mathbf{W}^{*T} \mathbf{h}(x) + \epsilon - \hat{\mathbf{W}}^T \mathbf{h}(x) = -\tilde{\mathbf{W}}^T \mathbf{h}(x) + \epsilon \quad (1.25)$$

Equation 1.10, which defines the sliding mode function, is repeated here:

$$s = \frac{d^{(z-1)}e_0}{dt} + \lambda_{(z-2)} \frac{d^{(z-2)}e_0}{dt} + \dots + \lambda_0 e_0$$

Equation 1.15, representing the derivative of the sliding mode function, is rewritten, with $\mathcal{L}_f^r h(x)$, $\mathcal{L}_g \mathcal{L}_f^{(z-1)} h(x)$ and $\mathcal{L}_{\Delta f}^{(z-1)} h(x)$ being replaced by $f(x)$, $g(x)$ and $\Delta b(x)$, respectively:

$$\dot{s} = (f(x) + g(x)U + \Delta b(x)) - \frac{d^{(z)}x_d}{dt} + \lambda_{(z-2)} \frac{d^{(z-1)}e_0}{dt} + \dots + \lambda_0 \dot{e}_0 \quad (1.26)$$

The control law of the direct adaptive RBFNN-based sliding mode controller (RBFNN-SMC) takes the form:

$$U = \frac{1}{g(x)} \left(\frac{d^{(z)}x_d}{dt} - \hat{f}(x) - \lambda_{(z-2)} \frac{d^{(z-1)}e_0}{dt} - \dots - \lambda_0 \dot{e}_0 - 1.1K_R \text{sign}(s) \right) \quad (1.27)$$

The Lyapunov function is defined as:

$$V = \frac{1}{2}s^2 + \frac{1}{2\gamma}\tilde{\mathbf{W}}^T\tilde{\mathbf{W}} \quad (1.28)$$

with the time derivative taking the form:

$$\begin{aligned} \dot{V} &= s\dot{s} + \frac{1}{\gamma}\tilde{\mathbf{W}}^T\dot{\tilde{\mathbf{W}}} \\ &= s\left((f(x) + g(x)U + \Delta b(x)) - \frac{d^{(z)}x_d}{dt} + \lambda_{(z-2)}\frac{d^{(z-1)}e_0}{dt} + \dots + \lambda_0\dot{e}_0\right) + \frac{1}{\gamma}\tilde{\mathbf{W}}^T\dot{\tilde{\mathbf{W}}} \end{aligned} \quad (1.29)$$

where γ is the adaptive law parameter and $\gamma > 0$.

Substituting Equation 1.27 into Equation 1.29, the expression takes the form:

$$\begin{aligned} \dot{V} &= s(f(x) - \hat{f}(x) + \Delta b(x) - 1.1K_R\text{sign}(s)) + \frac{1}{\gamma}\tilde{\mathbf{W}}^T\dot{\tilde{\mathbf{W}}} \\ &= s\left(-\tilde{\mathbf{W}}^T\mathbf{h}(x) + \epsilon + \Delta b(x) - 1.1K_R\text{sign}(s)\right) + \frac{1}{\gamma}\tilde{\mathbf{W}}^T\dot{\tilde{\mathbf{W}}} \\ &= (\epsilon + \Delta b(x))s - 1.1K_R|s| + \tilde{\mathbf{W}}^T\left(\frac{1}{\gamma}\dot{\tilde{\mathbf{W}}} - s\mathbf{h}(x)\right) \end{aligned} \quad (1.30)$$

Hence, the adaptive law can be designed as:

$$\dot{\tilde{\mathbf{W}}} = \gamma s\mathbf{h}(x) \quad (1.31)$$

From Equation 1.30, it can be seen that if the reaching law gain is selected to ensure that $K_R \geq |\epsilon_{max}| + |\Delta b(x)|$, then $\dot{V} = (\epsilon + \Delta b(x))s - 1.1K_R|s| < 0$. As such, a suitable reaching law gain is required in order to overcome the combination of the RBFNN approximation error and external disturbances. For the case where $\dot{V} \equiv 0$, the sliding surface is defined as $s \equiv 0$. Therefore, the system is asymptotically stable based on the La Salle invariance principle ($s \rightarrow 0$ as $t \rightarrow \infty$), with the accuracy of the convergence being heavily dependent on the reaching law gain. As V is restricted as $t \rightarrow \infty$, it can be seen that $\hat{\mathbf{W}}$ is also limited. Additionally, it can be said that $\hat{\mathbf{W}}$ will approach $\mathbf{W}^*$, but will never converge to it, as $\tilde{\mathbf{W}} \equiv 0$ cannot be achieved when $\dot{V} \equiv 0$ [42].

Chen et al., [62] applied a RBFNN-SMC to the maglev system of a maglev vertical axis wind turbine (MVAWT). The RBFNN of the controller was able to effectively approximate the unknown disturbances caused by different types of wind loads. This ensured that the RBFNN-SMC outperformed both a CPID controller and a traditional SMC in terms of speed of response and robustness.

1.4 Gaps in Existing Literature

One of the primary gaps in literature that has been identified relates to CPDF control, with there being relatively little available research into the control scheme, in comparison to CPID control. Apart from

publications stemming directly from this dissertation, there is no mention of CPDF control being applied to the control of an elevator system. Additionally, despite many examples of the implementation of NPID control and optimisation thereof; no publications mention development, or even the concept of a nonlinear PDF (or I-PD) controller. The single exception is work resulting from the current research.

With regards to SMC, no research was found relating to the benefits and drawbacks of developing the control law of the SMC using a simplified model of a system before applying the controller to the full system. Generally, the control law is derived directly from the model to be controlled. While fully defining the system dynamics would likely achieve the best controller performance, simplifying the control law could potentially improve simulation run time, which is an important aspect of any optimisation procedure. Additionally, as with CPDF control, no research relating to RBFNN-SMC of an elevator currently exists.

1.5 Envisaged Contributions to Knowledge

1. The development of two 1000 m tall roped building elevator mathematical models, accounting for nonlinear cable dynamics.
2. An evaluation of RBFNN-SMC, SMC, NPID control and CPDF control of various roped elevator systems.
3. An analysis of GA-optimisation of initial RBFNN-SMC parameters.
4. An investigation into the effects of designing a SMC system using a simplified version of the system to be controlled.
5. The design and GA-optimisation of a NPID controller.
6. An investigation into the validity and performance of a NPID controller across a range of control criteria.
7. An examination of the effects of cable stiffness, damping and free rope length on the controllability of supertall and ultratall elevator systems.

1.6 Research Objectives

The primary aim of this investigation is to design a RBFNN-SMC and evaluate the ability of the controller in ensuring efficient performance of a high-speed, ultratall elevator system; whilst simultaneously maintaining passenger safety and comfort. The secondary goal includes the comparison

of said controller with CPID, CPDF, NPID, NPDF, full SMC (FSMC) and simplified SMC (SSMC) architectures. The tertiary objective is to develop and evaluate the controllability of a wide array of elevator designs. The dissertation objectives, in the order that they are undertaken, are summarised as follows:

- i. Development of Elevator A – a 500 m tall elevator without compensation ropes, having fluctuating lifting cable stiffness, constant lifting cable damping and an override height of 10 m.
- ii. Design, GA-optimisation, simulation and comparison of CPID, CPDF, NPID and NPDF control systems for control of Elevator A.
- iii. Development of Elevator B – a 1000 m tall elevator with compensation ropes, having fluctuating lifting cable stiffness, fluctuating lifting cable damping and an override height of 10 m.
- iv. Design, GA-optimisation, simulation and comparison of CPID, CPDF, NPID, NPDF, FSMC and SSMC architectures for control of Elevator B.
- v. Development of Elevator C – an elevator similar to Elevator B, but having a more powerful motor and the override height reduced to 2 m.
- vi. Design, GA-optimisation, simulation and comparison of NPID, NPDF, FSMC, SSMC and RBFNN-SMC architectures for control of Elevator C.

1.7 Research Methodology

The research methodology is split into four stages, as shown in [Figure 1.13](#).

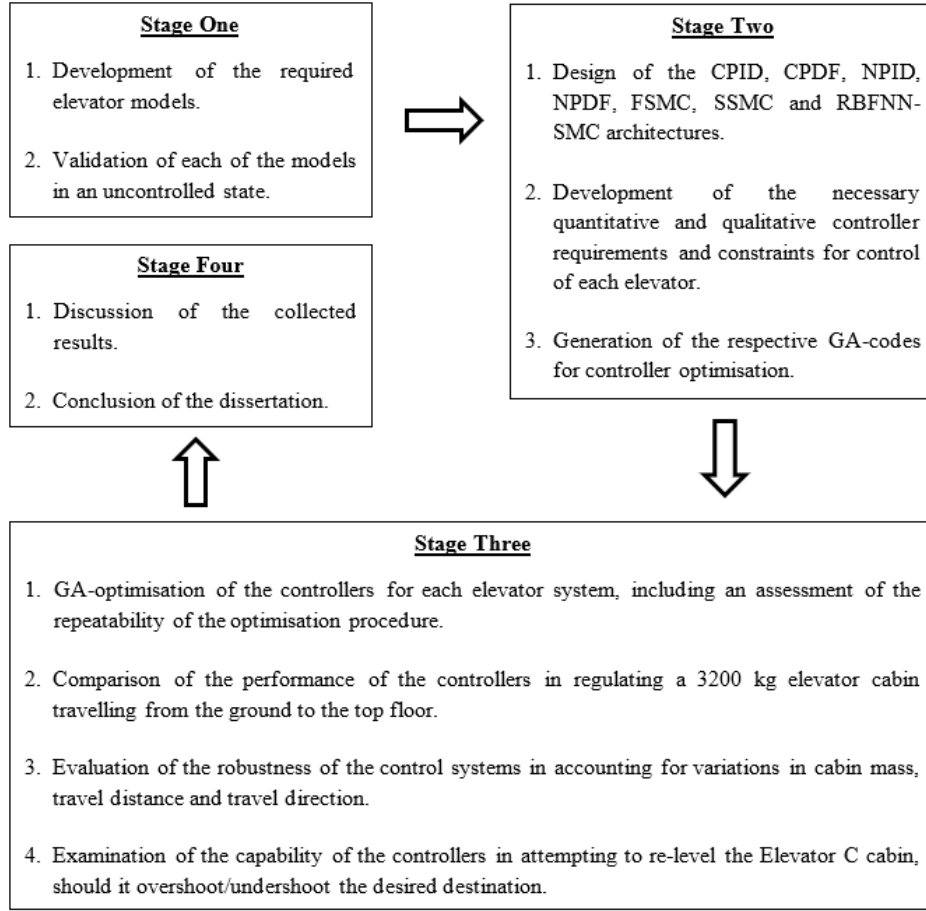


Figure 1.13: Four-stage research methodology

1.8 Dissertation Outline

A baseline elevator model is developed in Chapter 2, following which the model is adapted into three separate elevators. Elevator A is a 500 m tall elevator that does not have any compensation ropes. Cable damping is assumed to be constant (and relatively low towards the end of the journey), while cable stiffness fluctuates throughout operation. Elevator B, a more realistic elevator system, is a 1000 m tall elevator that includes compensation ropes. Both cable stiffness and damping vary during operation. Elevator C is similar in structure to Elevator B, apart from the reduction in the amount of clearance between the traction machine and the roof of the elevator cabin when stopped at the highest floor. This clearance defines the minimum free rope length of the cabin/counterweight side cables and is reduced from 10 m to 2 m in Elevator C, drastically increasing the cable stiffness at higher floors. Additionally, Elevator C is actuated by a more powerful motor to enable more effective RBFNN approximation. Utilising three elevators allows for an analysis of how different aspects of the models affect the controllability of the systems (i.e., an override height of 10 m compared to 2 m, the effects of lower end-of-travel damping in Elevator A, etc.). The models are subsequently summarised

and verified. The various setpoint signals are defined at the end of Chapter 2, including a description as to how adaptive re-levelling is incorporated into the signals for Elevator C.

The control systems are designed in Chapter 3, following which the performance specifications are summarised for control of the elevators. As the control systems must be in an optimised state for a relevant comparison, genetic algorithm (GA)-optimisation is used to tune the parameters of each controller, with the design of the GA-code being provided at the end of Chapter 3.

The control results for Elevators A, B and C are found in Chapters 4, 5 and 6, respectively. Control of Elevator A serves as a comparison between the CPID, CPDF, NPID and NPDF control architectures. FSMC and SSMC are introduced for control of Elevator B, alongside the existing four control architectures. Finally, RBFNN-SMC is applied in the control of Elevator C; with CPID and CPDF control falling away, having been sufficiently examined in the two chapters prior. Each of the elevator systems are controlled by some variant of PID control for a relevant investigation, due to the prevalence of the architecture in industry [32].

The control results for Elevator B in Chapter 5 are given for three different fitness function structures – balanced, comfort-oriented and sustainability-oriented. The control results for Elevators A and C are evaluated using only a performance-oriented fitness function. The sensitivity of the controllers to parameter variations is analysed for all elevator systems; with the controllers for Elevator C also being examined on their ability to execute adaptive re-levelling. The results are discussed in Chapter 7 and the dissertation is concluded in Chapter 8.

2 Elevator Mathematical Modelling

2.1 Chapter Outline

A baseline model of an elevator system is derived in this chapter. In order to fully evaluate the control schemes over a wide array of elevator parameters, this baseline elevator is then adapted into three separate express elevator models for analysis:

- The first model, referred to as Elevator A, is a 500 m tall elevator having no compensation rope system. The damping of the lifting cables is assumed to be constant throughout operation of the system, whilst the fluctuation of the cable stiffness is accounted for. The model has an override height of 10 m,
- The second model, referred to as Elevator B, is a more accurate representation of a real-world elevator system; with compensation ropes being present and both the stiffness and damping of the lifting cables presumed to fluctuate throughout the travel distance of 1000 m. Elevator B also has an override height of 10 m.
- The third model, referred to as Elevator C, has a reduced override height of 2 m and is driven by a more powerful motor to help ensure suitable approximation of the system dynamics during RBFNN-SMC.

The governing equations derived for each of the elevators are then summarised, with a demonstration provided to show that Elevator B is a third-order system. Each of the three models are subsequently verified by applying an impulse perturbation input of 240 V to the systems. The necessary setpoint signals required for control are subsequently designed. Additionally, a description is provided as to how these signals are modified to apply adaptive re-levelling to ensure an accurate arrival of the Elevator C cabin.

2.2 Physical Model of the Baseline Elevator

Elevators are composed of a number of mechanical parts, which are heavily-dependent on the speed rating and maximum loading capacity of the system. The three fundamental components of an elevator system are the traction machine, the elevator cabin and the counterweight. Typically, the machine room housing the actuator and controller is located at the summit of the elevator shaft; however, in recent years machine-room-less elevators have gained popularity due to the development of compact traction machines and control systems [63]. In most cases, the traction machine consists of a traction motor, main lifting sheave and a safety breaker. The counterweight is connected to the traction machine through a moving pulley and is used to balance force of the elevator car [64]. The elevator system to be used as the basis for development of all mathematical models is illustrated in Figure 2.1 [65]. A simplified model of the system to be used for derivation of the equations of motion is illustrated in Figure 2.2.

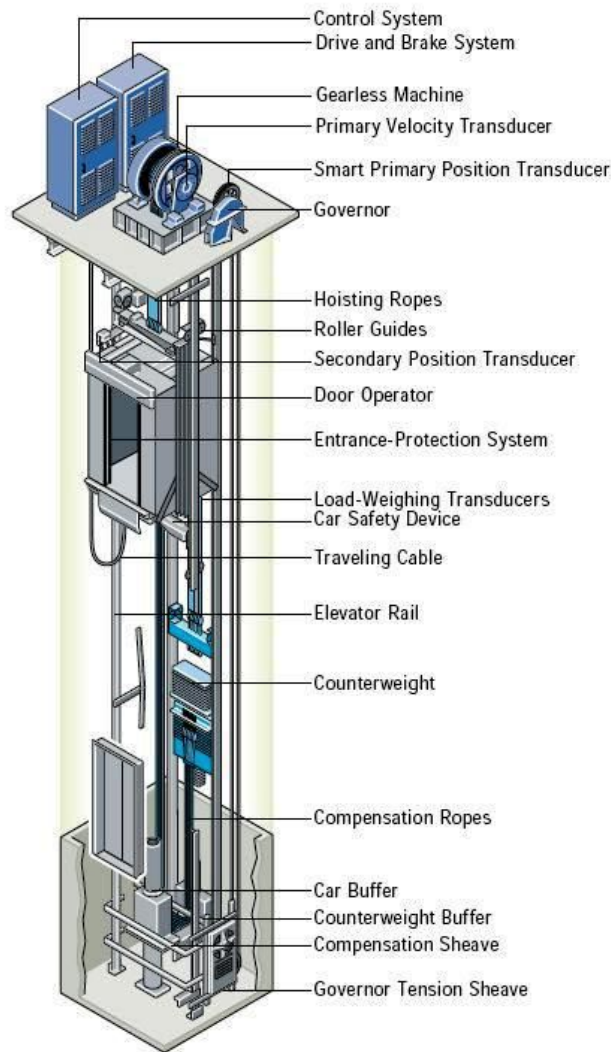


Figure 2.1: Traction elevator schematic [65]

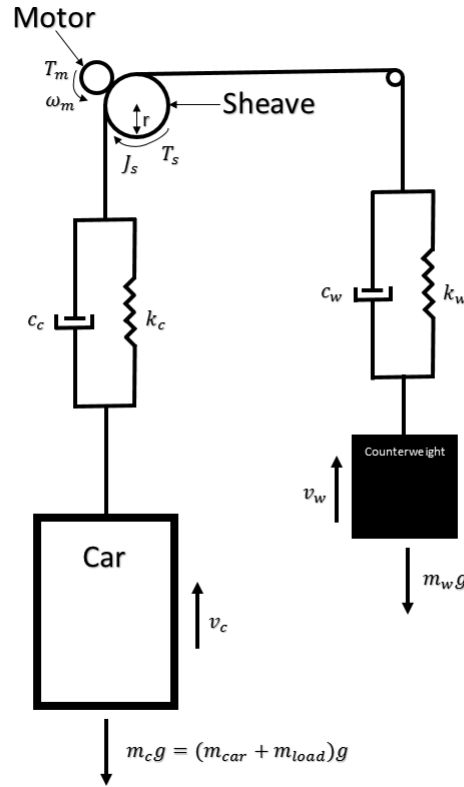


Figure 2.2: Schematic diagram of the elevator system

As can be seen in Figure 2.1, as is the case with the majority of high-rise elevator systems [66], a compensation rope and compensation pulley are present. Compensation ropes are an important component in elevator systems, particularly in high-rise elevators where cables make up the majority of the moving mass [28]. For an elevator cabin positioned on the ground floor of a tall building, the lack of compensation ropes would result in a mass imbalance, due to the majority of the cables being positioned on the cabin side of the sheave. Compensation ropes connect the cabin and counterweight through a compensation pulley located at the base of the shaft, offsetting the mass of the lifting and travelling cables at any given point of operation. As such, the motor would only need to lift the weight difference between the car and counterweight, ensuring that the required force to actuate the elevator is relatively low compared to the loads which are being moved. This allows for a smaller motor to be implemented, as less space and power are required to operate the system [64] [67].

As mentioned in Section 1.3.2.5, due to the fact that steel-cabled elevators are impractical for lifting heights of 500 m and upwards, the hoisting cables for the current system will be modelled as carbon fibre reinforced epoxy composites [68].

The spring stiffness of a single cabin-side lifting cable (k_c) is calculated using:

$$k_c = \frac{EA}{l_{ch}} \quad (2.1)$$

where E is Young's modulus of elasticity [Pa], A is the cross-sectional area of the main hoisting cable [m^2] and l_{ch} is the length of the main cabin-side hoisting cable at any given point of travel [m].

As the elevator travels through the shaft, the length of the cable above the elevator car either increases or decreases depending on the direction of travel. From Equation 2.1, it is seen that a change in the length of the cable above the car will result in a change of the cable stiffness. For an ascending elevator, the percentage change of the cabin-side cable stiffness can be calculated as follows:

$$\begin{aligned}
 \Delta k_c \% &= \frac{k_{cf} - k_{ci}}{k_{ci}} \times 100 \\
 &= \frac{\frac{EA}{l_{chf}} - \frac{EA}{l_{chi}}}{\frac{EA}{l_{chi}}} \times 100 \\
 &= \frac{\frac{1}{l_{chf}} - \frac{1}{l_{chi}}}{\frac{1}{l_{chi}}} \times 100 \\
 &= l_{chi} \times \left(\frac{1}{l_R l_{chi}} - \frac{1}{l_{chi}} \right) \times 100 \\
 &= \left(\frac{1}{l_R} - 1 \right) \times 100
 \end{aligned} \tag{2.2}$$

where k_{cf} is the final stiffness of the cabin-side lifting cable after operation of the elevator [N/m], k_{ci} is the initial stiffness of the cabin-side lifting cable before operation of the elevator [N/m], l_{chf} is the final length of the cabin-hoisting cable after operation of the elevator [m], l_{chi} is the initial length of the cabin-hoisting cable before operation of the elevator [m] and $l_R = \frac{l_{chf}}{l_{chi}}$.

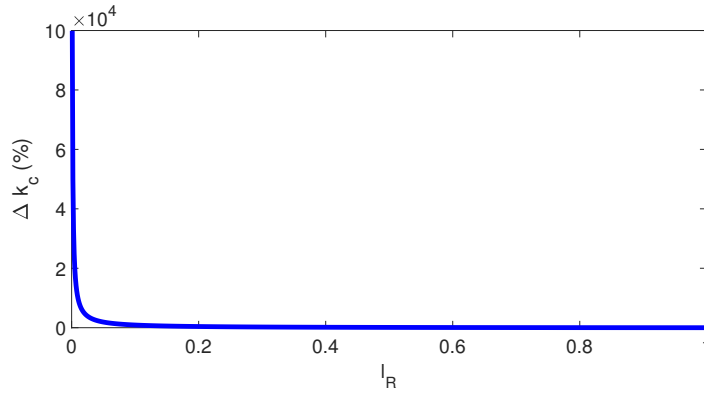


Figure 2.3: Illustration of $\Delta k_c \%$ vs l_R

From Figure 2.3, it can be seen that the percentage change in the spring constant becomes excessive for final cable lengths that are a small fraction of the length at the beginning of the journey. For the case of an ultratall elevator, where the override height will likely be no more than 1% of the total lifting height, the significant change in cable stiffness must be considered.

In order to derive the equations of motion for the system, the following simplifying assumptions were made:

- The inertia of the compensation sheave (should it exist for the specific model) is negligible.
- The dynamic effects of the compensation cables (should they exist for the specific model) are negligible.
- The lifting cables are assumed to have been manufactured to possess desirable dynamic properties.
- The cable masses are assumed to be point loads that can be added to the masses of the cabin and counterweight.
- The flexing of the cables out of the tension axis is negligible.
- Friction effects caused by the car and counterweight moving along the guide rails are negligible.
- Motor torque disturbance and sensor noise are the only external disturbances.

2.3 Mathematical Model of the Baseline Elevator

2.3.1 Elevator sheave

The free-body diagram of the main elevator sheave is given in Figure 2.4.

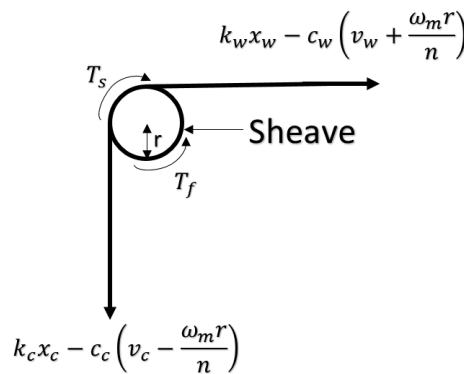


Figure 2.4: Free-body diagram of the sheave

Equation 2.3 is derived from Figure 2.4 as follows:

$$J_p \dot{\omega}_s = -r \left[k_c x_c - c_c \left(v_c - \frac{\omega_m r}{n} \right) \right] + r \left[k_w x_w - c_w \left(v_w + \frac{\omega_m r}{n} \right) \right] + T_A - T_R \quad (2.3)$$

where J_p is the polar moment of inertia of the traction machine [kg.m²], ω_s is the rotational velocity of the sheave [rad/s], r is the radius of the sheave [m], x_c is the extension of the cabin-side cable [m], c_c is the damping coefficient of the cabin-side cable [Ns/m], v_c is the velocity of the cabin [m/s], ω_m is the rotational velocity of the motor [rad/s], n is the gear ratio between the motor and the sheave, k_w is the stiffness of the counterweight-side cable [N/m], x_w is the extension of the counterweight-side cable [m], c_w is the damping coefficient of the cable on the counterweight side [Ns/m], v_w is the velocity of the counterweight [m/s], T_A is the torque applied by the sheave [N.m] and T_R is the combined resisting torque caused by the motor and sheave bearings [N.m].

The resisting torque caused by the bearings (T_b) is given by the following equation [69]:

$$T_b = c_{b_s} + c_{b_l} \quad (2.4)$$

where c_{b_s} is the frictional torque as a function of speed [N.mm] and c_{b_l} is the frictional torque as a function of load [N.mm].

For a high-speed elevator application, deep-groove ball bearings are a suitable choice, due to their robustness and low-maintenance requirements. Additionally, being the most commonly used bearing type in engineering applications, they are widely available in many designs and sizes [70]. Schaeffler 6321-M single row deep-groove ball bearings were selected for the current application, the specifications are provided in Table 2.1 [71].

Table 2.1: Schaeffler 6321-M deep-groove ball bearing specifications [71]

Parameter	Value
Bore Diameter (d_b) [mm]	105
Outer Diameter (D_b) [mm]	225
Width (B_d) [mm]	49
Bearing Mass (m_b) [kg]	9.83
Basic Dynamic Radial Load Rating (C_r) [N]	188000
Basic Static Radial Load Rating (C_{0r}) [N]	150000
Limiting Speed (n_G) [rpm]	5300
Reference Speed (ω_{rpm}) [rpm]	4450
Fatigue Limit Radial Load (C_{ur}) [N]	8100

The frictional torque as a function of speed (c_{b_s}) is given by the following equation [69]:

$$c_{b_s} = f_0 (v_b \omega_{rpm})^{\frac{2}{3}} d_{mb}^3 10^{-7} \quad (2.5)$$

where f_0 is the bearing factor as a function of speed, ν_b is the kinematic viscosity of the bearing lubricant [mm/s²], ω_{rpm} is the rotational velocity of the sheave in revolutions per minute [rpm] and d_{mb} is the mean bearing diameter [mm].

For deep-groove ball bearings experiencing the high loads associated with an elevator application, bearing lubrication having a high kinematic viscosity is required. A kinematic viscosity of 1000 mm/s² is recorded in literature as being suitable for such an application [69]. As a result, mineral oil based lithium soap thickened grease having a kinematic viscosity of 1000 mm/s² [72] at an operating temperature of 40°C was selected [72]. It is assumed that the operating temperature of the current sheave will be kept at approximately 40°C by means of an external cooling device, if cooling is necessary. The design of this cooling device will not be considered in this dissertation. The bearing factor as a function of speed for deep-groove ball bearings lubricated by the selected grease is equal to 1.1, hence the mean bearing diameter can be calculated using the following equation [69]:

$$\begin{aligned} d_{mb} &= \frac{d_b + D_b}{2} \\ &= \frac{105 + 225}{2} = 165 \text{ mm} \end{aligned} \quad (2.6)$$

Therefore, substituting these values for f_0 , ν_b and d_{mb} into Equation 2.5 allows it to be written as:

$$c_{b_s} = 1.1(1000\omega_{rpm})^{\frac{2}{3}}165^3 10^{-7} = 49.41\omega_{rpm}^{\frac{2}{3}} \quad (2.7)$$

The frictional torque as a function of load for deep-groove ball bearings is defined by [69]:

$$c_{b_l} = f_1 P_1 d_{mb} \quad (2.8)$$

where f_1 is the bearing factor as a function of load and P_1 is the decisive load for frictional torque [N].

For deep-groove ball bearings, the bearing factor as a function of load (f_1) is obtained as follows [69]:

$$f_1 = 0.0005 \left(\frac{P_{0r}}{C_{0r}} \right)^{0.5} \quad (2.9)$$

where P_{0r} is the equivalent static radial load [N] and C_{0r} is the basic static radial load rating [N].

For a moving mass of 14500 kg, the equivalent static load (P_{0r}) is calculated as:

$$14500(9.81) = 142245 \text{ N} \quad (2.10)$$

Using the value for the basic static radial load rating (C_{0r}) from Table 2.1, the bearing factor as a function of load (f_1) can be calculated using Equation 2.9:

$$f_1 = 0.0005 \left(\frac{142245}{150000} \right)^{0.5}$$

$$= 481.903 \times 10^{-6} \quad (2.11)$$

As it is assumed that the bearings experience no axial forces during operation, the decisive load for frictional torque (P_1) is equal to the equivalent static radial load (P_{0r}). Hence, the frictional torque as a function of load can be calculated using Equation 2.8 as follows:

$$c_{b_l} = (481.903 \times 10^{-6})(142245)(165) = 11310.468 \text{ N.mm}$$

Finally, Equation 2.4 can be rewritten as:

$$T_b = 49.41\omega_{rpm}^{\frac{2}{3}} + 11310.468 \quad (2.12)$$

By replacing the rotational velocity of the sheave in rpm (ω_{rpm}) with the rotational velocity in rad/s and converting from Newton millimetres to Newton metres, Equation 2.12 becomes:

$$T_b = 0.2224\omega_s^{\frac{2}{3}} + 11.3104 \quad (2.13)$$

As the damping torque acts in the opposite direction to the rotation of the sheave, the absolute value of the angular velocity is used in Equation 2.13. The damping torque is therefore:

$$T_b = 0.2224|\omega_s|^{2/3} + 11.3104 \quad (2.14)$$

Substituting this expression into Equation 2.19 and defining that the direction of viscous damping must always be opposite to the rotation of the sheave gives:

$$\begin{aligned} J_p \dot{\omega}_s = & -rk_c x_c + rc_c v_c - r \frac{\omega_m r}{n} c_c - rc_w v_w - r \frac{\omega_m r}{n} c_w + rk_w x_w + T_A \\ & - \text{sign}(\omega_s) \left(0.2224|\omega_s|^{2/3} + 11.3104 \right) \end{aligned} \quad (2.15)$$

Noting that:

$$T_A = nT_m \quad (2.16)$$

and:

$$\omega_s = \frac{\omega_m}{n} \quad (2.17)$$

Equation 2.15 becomes:

$$\begin{aligned} J_p \dot{\omega}_s = & -k_c x_c r + c_c v_c r - c_c \omega_s r^2 - c_w v_w r - c_w \omega_s r^2 + k_w x_w r + nT_m \\ & - \text{sign}(\omega_s) (0.2224|\omega_s|^{2/3} + 11.3104) \end{aligned} \quad (2.18)$$

Dividing through by J_p and rearranging the governing equation gives:

$$\begin{aligned} \dot{\omega}_s = & \frac{c_c r}{J_p} v_c - \frac{c_w r}{J_p} v_w - \frac{(c_c + c_w) r^2}{J_p} \omega_s - \frac{k_c r}{J_p} x_c \\ & + \frac{k_w r}{J_p} x_w + \frac{n}{J_p} T_m - \text{sign}(\omega_s) \frac{(0.2224|\omega_s|^{2/3} + 11.3104)}{J_p} \end{aligned} \quad (2.19)$$

2.3.2 Elevator cabin

The free-body diagram for the elevator car is illustrated in [Figure 2.5](#).

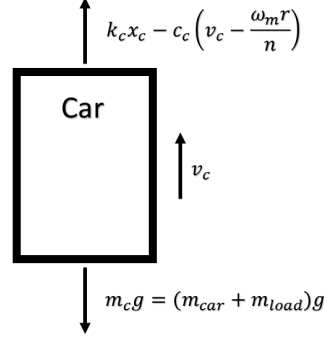


Figure 2.5: Free-body diagram of the cabin

[Equation 2.20](#) is derived from [Figure 2.5](#) and is given as:

$$(m_c + p_c)\dot{v}_c = -(m_c + p_c)g + k_c x_c - c_c \left(v_c - \frac{\omega_m r}{n} \right) \quad (2.20)$$

where m_c is the combined mass of the car and all occupants [kg] and p_c is the total mass of the cables on the cabin-side of the sheave [kg] and g is acceleration due to gravity [9.81 m/s²].

p_c is defined as follows:

$$p_c = l_{cT} q \quad (2.21)$$

where l_{cT} is the combined length of a single cabin-side hoisting cable and compensation rope (should compensation ropes be present) at any given time [m] and q is the total mass per meter of the elevator system cables [kg/m].

Substituting [Equation 2.17](#) into [Equation 2.20](#) gives:

$$(m_c + p_c)\dot{v}_c = -(m_c + p_c)g + k_c x_c - c_c (v_c - \omega_s r) \quad (2.22)$$

Dividing through by the cabin-side moving mass and rearranging, the equation becomes:

$$\dot{v}_c = \frac{k_c}{m_c + p_c} x_c + \frac{c_c r}{m_c + p_c} \omega_s - \frac{c_c}{m_c + p_c} v_c - g \quad (2.23)$$

2.3.3 Elevator counterweight

The free-body diagram of the counterweight is shown in [Figure 2.6](#).

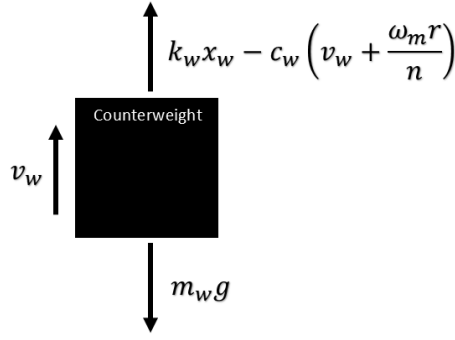


Figure 2.6: Free-body diagram of the counterweight

Equation 2.24 is derived from Figure 2.6:

$$(m_w + p_w)\dot{v}_w = -(m_w + p_w)g + k_w x_w - c_w \left(v_w + \frac{\omega_m r}{n} \right) \quad (2.24)$$

where m_w is the mass of the counterweight [kg] and p_w is the total mass of counterweight-side cables [kg].

p_w is defined as follows:

$$p_w = l_{wT} q \quad (2.25)$$

where l_{wT} is the combined length of a counterweight-side hoisting cable and compensation rope (if compensation ropes are present) at any given moment [m].

Using Equation 2.17 in Equation 2.24 gives:

$$(m_w + p_w)\dot{v}_w = -(m_w + p_w)g + k_w x_w - c_w (v_w + \omega_s r) \quad (2.26)$$

Dividing through by $(m_w + p_w)$, rearranging and multiplying out the terms in parentheses gives:

$$\dot{v}_w = \frac{k_w}{(m_w + p_w)} x_w - \frac{c_w r}{(m_w + p_w)} \omega_s - \frac{c_w}{(m_w + p_w)} v_w - g \quad (2.27)$$

2.3.4 Internal variables

The rate of the extension of the cables on the cabin and counterweight-side of the sheave can be expressed in terms of the velocities of the cabin and counterweight, as well as the rotation of the sheave. Considering the connected bodies and assuming that flexing of the cable out of the tension axis is negligible, the time rate of extension of the cabin-side cable is:

$$\dot{x}_c = \omega_s r - v_c \quad (2.28)$$

Similarly, the time rate of extension of the counterweight-side cable takes the form:

$$\dot{x}_w = -\omega_s r - v_w \quad (2.29)$$

2.3.5 Equilibrium conditions

The governing differential equations, expressed in Equations 2.19, 2.23, 2.27, 2.28 and 2.29 are repeated below:

$$\begin{aligned}\dot{\omega}_s = & \frac{c_c r}{J_p} v_c - \frac{c_w r}{J_p} v_w - \frac{(c_c + c_w) r^2}{J_p} \omega_s - \frac{k_c r}{J_p} x_c \\ & + \frac{k_w r}{J_p} x_w + \frac{n}{J_p} T_m - \text{sign}(\omega_s) \frac{(0.2224 |\omega_s|^{\frac{2}{3}} + 11.3104)}{J_p}\end{aligned}$$

$$\dot{v}_c = \frac{k_c}{m_c + p_c} x_c + \frac{c_c r}{m_c + p_c} \omega_s - \frac{c_c}{m_c + p_c} v_c - g$$

$$\dot{v}_w = \frac{k_w}{m_w + p_w} x_w - \frac{c_w r}{m_w + p_w} \omega_s - \frac{c_w}{m_w + p_w} v_w - g$$

$$\dot{x}_c = \omega_s r - v_c$$

$$\dot{x}_w = -\omega_s r - v_w$$

At equilibrium:

$$\omega_{s_0} = 0 \text{ [rad/s]} \quad (2.30)$$

$$\dot{\omega}_{s_0} = 0 \text{ [rad/s}^2\text{]} \quad (2.31)$$

$$v_{c_0} = 0 \text{ [m/s]} \quad (2.32)$$

$$\dot{v}_{c_0} = 0 \text{ [m/s}^2\text{]} \quad (2.33)$$

$$v_{w_0} = 0 \text{ [m/s]} \quad (2.34)$$

$$\dot{v}_{w_0} = 0 \text{ [m/s}^2\text{]} \quad (2.35)$$

where ω_{s_0} is the angular velocity of the sheave at the equilibrium point [rad/s], v_{c_0} is the velocity of the car at equilibrium [m/s] and v_{w_0} is the velocity of the counterweight at equilibrium [m/s].

Substituting the above values into Equation 2.19, Equation 2.23, Equation 2.27, Equation 2.28 and Equation 2.29 results in:

$$\begin{aligned}\dot{\omega}_{s_0} = & \frac{c_c r}{J_p} v_{c_0} - \frac{c_w r}{J_p} v_{w_0} - \frac{(c_c + c_w) r^2}{J_p} \omega_{s_0} - \frac{k_c r}{J_p} x_{c_0} \\ & + \frac{k_w r}{J_p} x_{w_0} + \frac{n}{J_p} T_{m_0} - \text{sign}(\omega_s) \frac{(0.2224 |\omega_{s_0}|^{\frac{2}{3}} + 11.3104)}{J_p}\end{aligned}$$

$$\dot{v}_{c_0} = \frac{k_c}{m_c + p_c} x_{c_0} + \frac{c_c r}{m_c + p_c} \omega_{s_0} - \frac{c_c}{m_c + p_c} v_{c_0} - g$$

$$\dot{v}_{w_0} = \frac{k_w}{m_w + p_w} x_{w_0} - \frac{c_w r}{m_w + p_w} \omega_{s_0} - \frac{c_w}{m_w + p_w} v_{w_0} - g$$

$$\dot{x}_{c_0} = \omega_{s_0} r - v_{c_0}$$

$$\dot{x}_{w_0} = -\omega_{s_0} r - v_{w_0}$$

which simplifies to:

$$0 = -\frac{k_c r}{J_p} x_{c_0} + \frac{k_w r}{J_p} x_{w_0} + \frac{n}{J_p} T_{m_0} - \text{sign}(\omega_s) \frac{c_{b_l}}{J_p} \quad (2.36)$$

$$0 = \frac{k_c}{m_c + p_c} x_{c_0} - g \quad (2.37)$$

$$0 = \frac{k_w}{m_w + p_w} x_{w_0} - g \quad (2.38)$$

$$\dot{x}_{c_0} = 0 \quad (2.39)$$

$$\dot{x}_{w_0} = 0 \quad (2.40)$$

where x_{c_0} is the extension of the cabin-side cable at equilibrium [m] and x_{w_0} is the extension of the counterweight-side cable at equilibrium [m].

From Equations 2.37 and 2.38 the following relationships are obtained:

$$x_{c_0} = \frac{(m_c + p_c)g}{k_c} \quad (2.41)$$

$$x_{w_0} = \frac{(m_w + p_w)g}{k_w} \quad (2.42)$$

Substituting the above relationships into [Equation 2.36](#), the motor torque required to hold the elevator car in place (T_{m_0}) can be calculated as:

$$\begin{aligned} T_{m_0} &= \left(\frac{k_c r (m_c + p_c) g}{J_p k_c} - \frac{k_w r (m_w + p_w) g}{J_p k_w} + \text{sign}(\omega_s) \frac{c_{bl}}{J_p} \right) \frac{J_p}{n} \\ &= \left(\frac{(m_c + p_c) g r}{J_p} - \frac{(m_w + p_w) g r}{J_p} + \text{sign}(\omega_s) \frac{c_{bl}}{J_p} \right) \frac{J_p}{n} \end{aligned} \quad (2.43)$$

For perturbation of the system from equilibrium, the variables of the system are defined as:

$$\omega_s = \omega_{s0} + \omega'_s \quad (2.44)$$

$$\dot{\omega}_s = \dot{\omega}_{s0} + \dot{\omega}'_s \quad (2.45)$$

$$v_c = v_{c0} + v'_c \quad (2.46)$$

$$\dot{v}_c = \dot{v}_{c0} + \dot{v}'_c \quad (2.47)$$

$$v_w = v_{w0} + v'_w \quad (2.48)$$

$$\dot{v}_w = \dot{v}_{w0} + \dot{v}'_w \quad (2.49)$$

$$x_c = x_{c0} + x'_c \quad (2.50)$$

$$\dot{x}_c = \dot{x}_{c0} + \dot{x}'_c \quad (2.51)$$

$$x_w = x_{w0} + x'_w \quad (2.52)$$

$$\dot{x}_w = \dot{x}_{w0} + \dot{x}'_w \quad (2.53)$$

$$T_m = T_{m_0} + T'_m \quad (2.54)$$

where ω'_s is the perturbation of the angular velocity of the sheave from the angular velocity at equilibrium [rad/s], v'_c is the perturbation of the cabin velocity from the velocity at equilibrium [m/s], v'_w is the perturbation of the counterweight velocity from the velocity at equilibrium [m/s], x'_c is the perturbation of the cabin-side cable extension from the equilibrium extension [m], x'_w is the perturbation of the counterweight-side cable extension from the extension at the equilibrium point [m] and T'_m is the perturbation of motor torque from that required to hold the cabin in place [N.m].

Using Equations 2.30, 2.31, 2.32, 2.33, 2.34, 2.35, 2.39, 2.40, 2.41, 2.42 and 2.43, Equations 2.44 – 2.54 can be defined as:

$$\omega_s = \omega'_s \quad (2.55)$$

$$\dot{\omega}_s = \dot{\omega}'_s \quad (2.56)$$

$$v_c = v'_c \quad (2.57)$$

$$\dot{v}_c = \dot{v}'_c \quad (2.58)$$

$$v_w = v'_w \quad (2.59)$$

$$\dot{v}_w = \dot{v}'_w \quad (2.60)$$

$$x_c = \frac{(m_c + p_c)g}{k_c} + x'_c \quad (2.61)$$

$$\dot{x}_c = \dot{x}'_c \quad (2.62)$$

$$x_w = \frac{(m_w + p_w)g}{k_w} + x'_w \quad (2.63)$$

$$\dot{x}_w = \dot{x}'_w \quad (2.64)$$

$$T_m = \left(\frac{(m_c + p_c)gr}{J_p} - \frac{(m_w + p_w)gr}{J_p} + \text{sign}(\omega_s) \frac{c_{bl}}{J_p} \right) \frac{J_p}{n} + T'_m \quad (2.65)$$

Substituting the relationships in Equations 2.55 – 2.65 into the governing equations for the system allows for the perturbation equations of motion to be developed:

$$\begin{aligned} \dot{\omega}'_s &= \frac{c_c r}{J_p} v'_c - \frac{c_w r}{J_p} v'_w - \frac{(c_c + c_w) r^2}{J_p} \omega'_s - \frac{k_c r}{J_p} \left(\frac{(m_c + p_c)g}{k_c} + x'_c \right) + \frac{k_w r}{J_p} \left(\frac{(m_w + p_w)g}{k_w} + x'_w \right) \\ &\quad + \frac{n}{J_p} \left(\left(\frac{(m_c + p_c)gr}{J_p} - \frac{(m_w + p_w)gr}{J_p} + \text{sign}(\omega'_s) \frac{c_{bl}}{J_p} \right) \frac{J_p}{n} + T'_m \right) - \text{sign}(\omega'_s) \frac{(c_{bs} |\omega'_s|^{\frac{2}{3}})}{J_p} \\ &= \frac{c_c r}{J_p} v'_c - \frac{c_w r}{J_p} v'_w - \frac{(c_c + c_w) r^2}{J_p} \omega'_s - \frac{(m_c + p_c)gr}{J_p} - \frac{k_c r}{J_p} x'_c + \frac{(m_w + p_w)gr}{J_p} + \frac{k_w r}{J_p} x'_w \\ &\quad + \text{sign}(\omega'_s) \frac{c_{bl}}{J_p} + \frac{(m_c + p_c)gr}{J_p} - \frac{(m_w + p_w)gr}{J_p} + \frac{n}{J_p} T'_m - \text{sign}(\omega'_s) \frac{c_{bs} |\omega'_s|^{\frac{2}{3}}}{J_p} - \text{sign}(\omega'_s) \frac{c_{bl}}{J_p} \end{aligned}$$

$$= \frac{c_c r}{J_p} v'_c - \frac{c_w r}{J_p} v'_w - \frac{(c_c + c_w) r^2}{J_p} \omega'_s - \frac{k_c r}{J_p} x'_c + \frac{k_w r}{J_p} x'_w + \frac{n}{J_p} T'_m - \text{sign}(\omega'_s) \frac{(c_{b_s} |\omega'_s|^{\frac{2}{3}})}{J_p} \quad (2.66)$$

$$\begin{aligned} \dot{v}'_c &= \frac{k_c}{m_c + p_c} \left(\frac{(m_c + p_c)g}{k_c} + x'_c \right) + \frac{c_c r}{m_c + p_c} \omega'_s - \frac{c_c}{m_c + p_c} v'_c - g \\ &= g + \frac{k_c}{m_c + p_c} x'_c + \frac{c_c r}{m_c + p_c} \omega'_s - \frac{c_c}{m_c + p_c} v'_c - g \\ &= \frac{k_c}{m_c + p_c} x'_c + \frac{c_c r}{m_c + p_c} \omega'_s - \frac{c_c}{m_c + p_c} v'_c \end{aligned} \quad (2.67)$$

$$\begin{aligned} \dot{v}'_w &= \frac{k_w}{m_w + p_w} \left(\frac{(m_w + p_w)g}{k_w} + x'_w \right) - \frac{c_w r}{m_w + p_w} \omega'_s - \frac{c_w}{m_w + p_w} v'_w - g \\ &= g + \frac{k_w}{m_w + p_w} x'_w - \frac{c_w r}{m_w + p_w} \omega'_s - \frac{c_w}{m_w + p_w} v'_w - g \\ &= \frac{k_w}{m_w + p_w} x'_w - \frac{c_w r}{m_w + p_w} \omega'_s - \frac{c_w}{m_w + p_w} v'_w \end{aligned} \quad (2.68)$$

$$\dot{x}'_c = \omega'_s r - v'_c \quad (2.69)$$

$$\dot{x}'_w = -\omega'_s r - v'_w \quad (2.70)$$

2.3.6 Actuator

The actuator selected for the baseline elevator model is an armature-controlled DC motor that will be used in conjunction with the gear system of the traction machine to drive the elevator cabin. The circuit diagram for this motor is shown in [Figure 2.7 \[73\]](#).

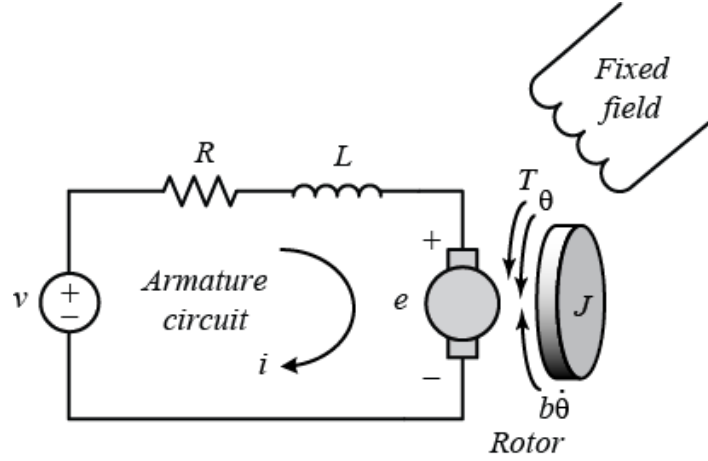


Figure 2.7: Circuit diagram of an armature-controlled DC motor [73]

From Figure 2.7, the governing differential equation of the motor can be derived as [73]:

$$U_m = Ri_m + L \frac{d}{dt} i_m + K_e \omega_m \quad (2.71)$$

where U_m is the voltage through the motor [V], R is the circuit resistance [Ω], i_m is the current flowing through the armature circuit [A], L is the inductance of the circuit [H], K_e is the proportional constant between the back electromotive force (EMF) and the rotational velocity of the motor [V.s/rad].

From Equation 2.17, ω_m can be defined by the following relationship:

$$\omega_m = n\omega_s \quad (2.72)$$

As such, Equation 2.71 can be written as:

$$U_m = Ri_m + L \frac{d}{dt} i_m + nK_e \omega_s \quad (2.73)$$

At equilibrium, Equation 2.73 reduces to:

$$\begin{aligned} U_{m_0} &= Ri_{m_0} + L \frac{d}{dt} i_{m_0} + nK_e \omega_{s_0} \\ &= Ri_{m_0} + L \frac{d}{dt} i_{m_0} \end{aligned} \quad (2.74)$$

where U_{m_0} is the circuit voltage at the equilibrium point [V] and i_{m_0} is the current through the circuit at the equilibrium point [A].

At equilibrium, the current through the circuit (i_m) is time-invariant. As such:

$$\frac{d}{dt} i_{m_0} = 0 \quad (2.75)$$

Hence, Equation 2.74 can be further reduced to:

$$U_{m_0} = Ri_{m_0} \quad (2.76)$$

The state variables associated with the motor can be defined as:

$$U_m = U_{m_0} + U'_m \quad (2.77)$$

$$i_m = i_{m_0} + i'_m \quad (2.78)$$

$$\omega_s = \omega_{s_0} + \omega'_s \quad (2.79)$$

where U'_m is the perturbation of the voltage from the equilibrium voltage [V] and i'_m is the perturbation of the current away from the equilibrium current [A].

Equation 2.71 can be expressed in terms of the equilibrium and perturbation variables as:

$$\begin{aligned} U_{m_0} + U'_m &= R(i_{m_0} + i'_m) + L\left(\frac{d}{dt}i_{m_0} + \frac{d}{dt}i'_m\right) + nK_e(\omega_{s_0} + \omega'_s) \\ Ri_{m_0} + U'_m &= Ri_{m_0} + Ri'_m + L\frac{d}{dt}i'_m + nK_e\omega'_s \\ U'_m &= Ri'_m + L\frac{d}{dt}i'_m + nK_e\omega'_s \end{aligned} \quad (2.80)$$

Rearranging Equation 2.80 to make the rate of change of current the subject of the formula gives the following motor circuit perturbation equation:

$$\frac{d}{dt}i'_m = \frac{U'_m}{L} - \frac{nK_e}{L}\omega'_s - \frac{R}{L}i'_m \quad (2.81)$$

The total power consumption of the motor can subsequently be defined as:

$$P_{m_{tot}} = (U_{m_0} + U'_m)(i_{m_0} + i'_m) \quad (2.82)$$

Equation 2.81 can be added to the perturbation equations of the system given in Equations 2.66 – 2.70 by defining the motor torque using the following equation:

$$T'_m = K_T i'_m \quad (2.83)$$

where K_T is the proportional constant between the armature current and the motor torque [Nm/A].

Counter-current braking can be applied by reversing the polarity of the motor voltage, thereby switching the direction of the flow of current and, according to Equation 2.83, applying a braking torque to the system.

By substituting Equation 2.83 into Equation 2.66 and introducing two new terms to account for motor disturbances and additional damping to the sheave caused by the motor – the equation becomes:

$$\begin{aligned} \dot{\omega}'_s = & \frac{c_c r}{J_p} v'_c - \frac{c_w r}{J_p} v'_w - \frac{(c_c + c_w) r^2}{J_p} \omega'_s - \frac{k_c r}{J_p} x'_c + \frac{k_w r}{J_p} x'_w + \frac{n K_T}{J_p} i'_m + \frac{n}{J_p} T'_d \\ & - \text{sign}(\omega'_s) \frac{\left(c_{b_d} |\omega'_s|^{\frac{2}{3}} + c_m |\omega'_s| \right)}{J_p} \end{aligned} \quad (2.84)$$

where T'_d is the motor torque disturbance, assumed to have a maximum amplitude of approximately 1% of the rated motor torque [17] [N.m], c_{b_d} replaces c_{b_s} and is now referred to as the sheave bearing damping constant [N.m.s/rad], and c_m is the viscous friction damping of the motor as experienced on the sheave, assumed to have a linear relationship to the angular velocity of the drive system [N.m.s/rad].

2.3.7 Sensors

Tachometers can be used as analogue sensors to measure the velocity of an elevator car in conjunction with an overspeed governor. A schematic diagram of an elevator system with an overspeed governor is illustrated in Figure 2.8 [74].

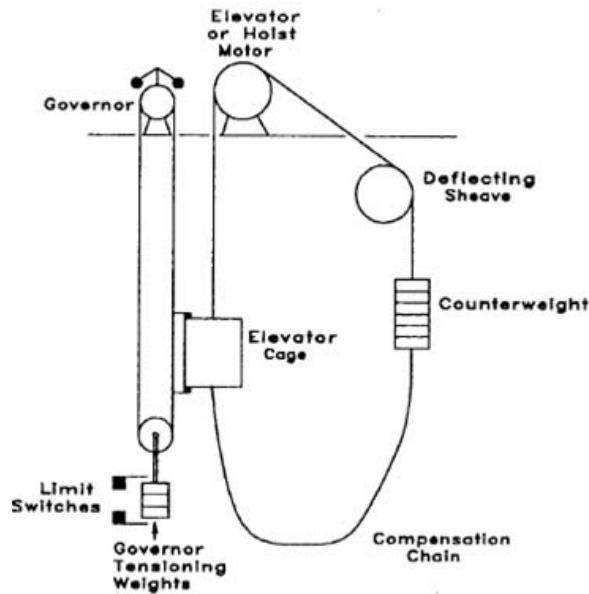


Figure 2.8: Elevator system with an overspeed governor [74]

From Figure 2.8, it can be seen that the overspeed governor is situated in the machine room, although the placement of the governor on the roof of the elevator car is becoming increasingly prevalent. The system consists of two flyweights, two sheaves and a connecting cable. The governor cable has

a high stiffness and plays no part in supporting the weight of the elevator, until such time as the cabin requires emergency braking. The cable translates the translational velocity of the elevator to the angular velocity of the flyweights, which are free to move radially outward from their rotational axis [75]. This outward motion of the flyweights is dependent on the angular velocity of the shaft, with centrifugal force triggering the flyweights to move past a set horizontal threshold, indicating that the elevator car is travelling over the acceptable speed. In such a scenario, power to the motor is cut out and the elevator is brought to an abrupt stop [76].

Feedback for control of the elevator can be achieved by utilising the overspeed governor system. A tachometer can be fixed to the governor shaft and, provided a stiff enough cable is used, the velocity of the cabin can be measured directly with high accuracy. The conversion from angular velocity to a voltage signal is achieved using the following equation:

$$U_{tach} = k_{tach}\omega_{gov} \quad (2.85)$$

where U_{tach} is the voltage signal out of the tachometer [V], k_{tach} is the proportional gain between the angular velocity and the tachometer output voltage [V.s], ω_{gov} is the angular velocity of the governor sheave attached to the shaft [rad/s].

Equation 2.85 can be simplified to:

$$U_{tach} = k_{tach}\frac{v_c}{r_{gov}} \quad (2.86)$$

where r_{gov} is the radius of the governor wheel [m].

The selected tachometer for the system has the following specifications [77]:

Table 2.2: Tachometer specifications [78]

Parameter	Value
Sensor Gain [V/1000RPM]	100
Tachometer Wheel Radius [m]	0.15
Max RMS Ripple [%]	0.35

Substituting the relevant data into Equation 2.86, the tachometer output can be calculated as:

$$\begin{aligned}
 U_{tach} &= \frac{100}{1000 \times \frac{2\pi}{60} \times 0.15} \times v_c \\
 &= 6.3662v_c \quad (2.87)
 \end{aligned}$$

In order to account for sensor noise, the maximum RMS ripple of the tachometer listed in Table 2.2 was considered. A sampled Gaussian noise signal having a maximum amplitude = 1 was generated

using the signal builder block within Simulink. This signal was multiplied by the RMS gain of the tachometer, through which the tachometer output voltage passes. The resulting sensor noise signal was added to the original tachometer output voltage to determine the full feedback signal (U_s).

2.4 Development of Elevator A – A 500 m Tall Elevator Without Compensation Ropes, Having Fluctuating Lifting Cable Stiffness, Constant Lifting Cable Damping and an Override Height of 10 m

2.4.1 Cabin-side cable dynamics of Elevator A

Equation 2.21, which defines the mass of cables on the cabin-side, is repeated below:

$$p_c = l_{cT} q$$

It is important to note that, should the compensation ropes be removed, the mass of the cabling (q) must be doubled in order to maintain industry-standard moving masses for a relevant investigation.

For the case of an elevator system having no compensation ropes, l_{cT} is simply defined as:

$$l_{cT} = l_{ch} \quad (2.88)$$

The length of the hoisting cable (l_{ch}) is computed as follows:

$$l_{ch} = l_{chi} - d_c \quad (2.89)$$

where d_c is the displacement of the elevator car [m].

l_{chi} is calculated using:

$$l_{chi} = l_{top} + l_{override} \quad (2.90)$$

where l_{top} is the distance from the starting floor of the elevator cabin to the top floor of the building [m] and $l_{override}$ is the override height of the system [m]. Elevator override height is defined as the space between the roof of the elevator cabin and the driving pulley when the car has stopped at the highest floor [79]. This distance defines the minimum free rope length of the cables on both sides of the sheave (under normal operation) and is equal to 10 m for the current model.

The cabin displacement (d_c) is calculated as follows:

$$d_c = \int v_c dt \quad (2.91)$$

The fluctuating stiffness of the main cabin-hoisting cable at any point of travel is defined using Equation 2.1, which is repeated:

$$k_c = \frac{EA}{l_{ch}}$$

The damping of the cabin-side lifting cable (c_c) is to be set at a constant value of 10000 N.s/m, as Elevator A will be used to analyse the effects of fluctuating cable stiffness and mass on either side of the sheave for a system having relatively low damping. This value was not chosen at random, as the system should have realistic damping to account for the high stiffness of the cable as the cabin nears the summit of the elevator shaft; however it should not be so high that vibrations are unnaturally dissipated. In order to determine an appropriate damping coefficient, it must first be understood how the cable damping would fluctuate under normal circumstances. This fluctuation is defined by Equation 2.92:

$$c_c = 2\zeta \sqrt{k_c(m_c + p_c)} \quad (2.92)$$

where ζ is the damping ratio of the lifting cables.

By making use of Equations 2.21 and 2.4.1 and assuming $\zeta = 0.2$, $E = 60 \text{ GPa}$, $A = 0.00015 \text{ m}^2$, $m_c = 3200 \text{ kg}$, $q = 14 \text{ kg/m}$ and $l_{ch} = 510 \text{ m}$ [28] [68] [80] [81], the progression of c_c can be plotted for an elevator travelling from the ground floor to a height of 500 m:

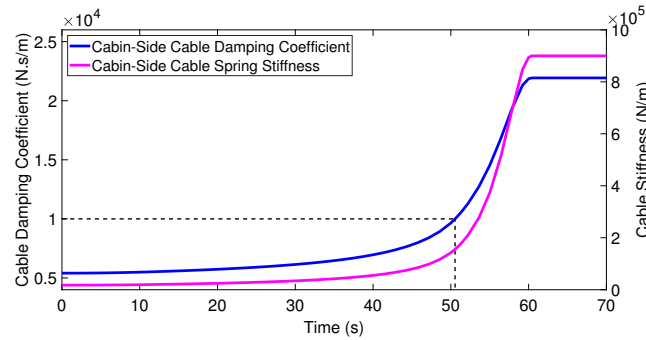


Figure 2.9: Fluctuation in c_c and k_c for an elevator without compensation ropes travelling to a height of 500 m

As can be seen in Figure 2.9, the significant increase in the cable stiffness towards the end of travel induces a similar rise in the value of c_c . $c_c = 10000 \text{ N.s/m}$ is highlighted in the figure, with this value corresponding to a cabin displacement of roughly 450 m (approximately 90% of the journey). This is a suitable choice for a constant c_c value, being low enough to introduce a realistic control challenge, but high enough to avoid inducing overly unnatural vibrations towards the end of travel.

2.4.2 Counterweight-side cable dynamics of Elevator A

Equation 2.25, which defines the total mass of counterweight-side cables, is rewritten as:

$$p_w = l_{wT} q$$

where l_{wT} is given as:

$$l_{wT} = l_{wh} \quad (2.93)$$

where l_{wh} is the length of the counterweight-lifting cable at any given point of travel [m] and is computed in Equation 2.94:

$$l_{wh} = l_{wh_i} - d_w \quad (2.94)$$

where l_{wh_i} is the initial length of the counterweight-hoisting cable before operation of the elevator [m] and d_w is the displacement of the elevator counterweight [m].

l_{wh_i} is defined as:

$$l_{wh_i} = l_{ground} + l_{override} \quad (2.95)$$

where l_{ground} is the distance from the starting floor of the elevator cabin to the lowest floor served by the elevator (assumed to be the ground floor for the current system) [m]

d_w , being the integral with respect to time of the velocity of the counterweight, is defined by:

$$d_w = \int v_w dt \quad (2.96)$$

The stiffness of the counterweight-side lifting cable (k_w) is calculated as follows:

$$k_w = \frac{EA}{l_{wh}} \quad (2.97)$$

The counterweight-side cable damping coefficient (c_w) is set at a constant value of 10000 N.s/m, equal to that of the cabin-side cable damping coefficient (c_c) selected in Section 2.4.1.

2.5 Development of Elevator B – A 1000 m Tall Elevator With Compensation Ropes, Having Fluctuating Lifting Cable Stiffness, Fluctuating Lifting Cable Damping and an Override Height of 10 m

2.5.1 Cabin-side cable dynamics of Elevator B

The equation defining the mass of cabling on the cabin-side of the sheave (Equation 2.21) is provided:

$$p_c = l_{cT} q$$

For the case of an elevator system with compensation ropes being present, l_{cT} will remain constant throughout operation and can be calculated as follows:

$$l_{cT} = l_{ch} + l_{cc} \quad (2.98)$$

where l_{cc} is the length of a single cabin-side compensation rope [m] and is defined by:

$$l_{cc} = l_{cc_i} + d_c \quad (2.99)$$

where l_{cc_i} is the initial length of a single cabin-side compensation rope before operation of the elevator [m].

After substituting Equations 2.89 and 2.99, Equation 2.98 becomes:

$$l_{cT} = l_{ch_i} + l_{cc_i} \quad (2.100)$$

which is always equal to the total lifting height of the system plus the override height.

As is the case in Elevator A, the stiffness of the cabin-side lifting cable is dependent on the length of the hoist cable at any given moment. Equation 2.4.1 is repeated here:

$$k_c = \frac{EA}{l_{ch}}$$

The damping coefficient of the cabin-side hoisting cable at any given moment is defined by Equation 2.92, which is repeated below:

$$c_c = 2\zeta \sqrt{k_c(m_c + p_c)}$$

2.5.2 Counterweight-side cable dynamics of Elevator B

Equation 2.25 is provided again:

$$p_w = l_{wT}q$$

l_{wT} is calculated as follows:

$$l_{wT} = l_{wh} + l_{wc} \quad (2.101)$$

where l_{wc} is the length of an individual counterweight-side compensation rope [m] and is defined by:

$$l_{wc} = l_{wc_i} + d_w \quad (2.102)$$

where l_{wc_i} is the initial length of a single counterweight-side compensation rope before operation of the elevator [m].

By introducing Equations 2.94 and 2.102 into Equation 2.101, it can be reduced to:

$$l_{wT} = l_{wh_i} + l_{wc_i} \quad (2.103)$$

which is a constant value, equal to the total lifting height plus the override height of the elevator.

Equation 2.97, which defines the stiffness of the counterweight-side lifting cable, is rewritten as:

$$k_w = \frac{EA}{l_{wh}}$$

The equation describing the fluctuating damping coefficient of the counterweight hoisting cable is given:

$$c_w = 2\zeta \sqrt{k_w(m_w + p_w)} \quad (2.104)$$

2.6 Development of Elevator C – A 1000 m Tall Elevator With Compensation Ropes, Having Fluctuating Lifting Cable Stiffness, Fluctuating Lifting Cable Damping and an Override Height of 2 m

2.6.1 Cabin-side cable dynamics of Elevator C

For the development of Elevator C, the override height ($l_{override}$) is reduced from 10 m to 2 m. For clarity, a schematic of an elevator system illustrating override height is provided in Figure 2.10 [79], while a visual comparison of the override heights for all three elevator models is shown in Figure 2.11.

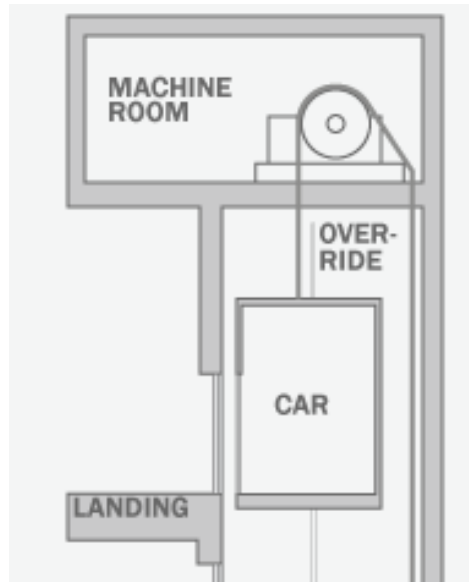


Figure 2.10: Example of elevator override height [79]

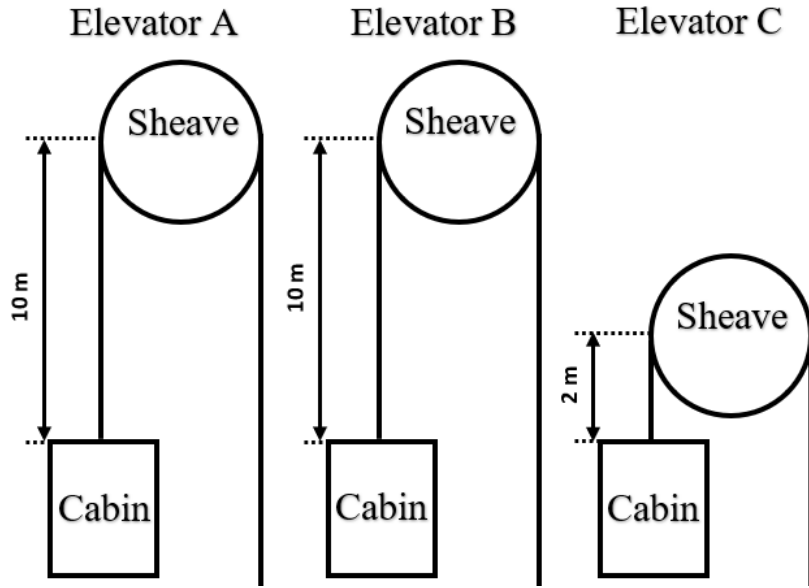


Figure 2.11: Comparison between the override heights of Elevator A, B and C (cabins stopped at the top floor of the building)

The cable dynamics on the cabin-side of Elevator C can be defined by the same equations as in Section 2.5.1. The main effect of lowering the override height ($l_{override}$) is the subsequent reduction in the minimum free rope length of the cabin-side hoisting cable (l_{ch}). This reduction will have a significant effect on the change of cabin-side cable stiffness (k_c) as the cabin travels to/from the top floor of the building. As per Equation 2.2, for a 1000 m tall elevator travelling upwards from the ground to top floor, an override height of 10 m would see k_c increase by 10000%. Following the reduction in override height to 2 m, k_c would increase by 50000% while making the same journey. Following the marginal reduction in the total length of cabling for the system, the cable mass per meter (q) must be slightly increased in order to maintain the industry standard moving masses defined in Table 1.1.

2.6.2 Counterweight-side cable dynamics of Elevator C

As is the case with the cabin-side lifting cable, the reduction in override height will greatly affect the progression of the counterweight-side cable stiffness (k_w). These dynamics can be determined using the same equations as in Section 2.5.2.

2.7 Summary of the Model Parameters of Elevators A, B and C

The parameters of the plant models of each elevator system are given in Table 2.3, while the actuator specifications are provided in Table 2.4:

Table 2.3: Plant specifications of Elevators A, B and C [68] [80] [81]

Parameter	Elevator A	Elevator B	Elevator C
Maximum Lifting Height [m]	500	1000	1000
Standard Cabin Mass (m_c) [kg]	3200	3200	3200
Counterweight Mass (m_w) [kg]	2400	2400	2400
Traction Machine Inertia (J_p) [kg.m ²]	5000	1000	1000
Combined Cable Mass per Meter (q) [kg/m]	14	4.406	4.411
Cable Elastic Modulus (E) [GPa]	60	60	60
Lifting Cable Cross-Sectional Area (A) [m ²]	0.00015	0.00015	0.00015
Cabin-Side Cable Damping Coefficient (c_c) [N.s/m]	10000	FLUCTUATING	FLUCTUATING
Counterweight-Side Cable Damping Coefficient (c_w) [N.s/m]	10000	FLUCTUATING	FLUCTUATING
Cable Damping Ratio (ζ)	-	0.2	0.2
Override Height ($l_{override}$) [m]	10	10	2
Transmission Gear Ratio (n)	12	12	12
Main Sheave Radius (r) [m]	1	0.5	0.5

Table 2.4: Motor specifications of Elevators A, B and C [17] [73] [82] [83]

Parameter	Elevator A	Elevator B	Elevator C
Motor Rated Voltage [V]	810	440	440
Motor Rated Torque [N.m]	8100	1307	2245
Motor Rated Current [A]	900	796	1367
Motor Rated Power Consumption [kW]	729	351	601
Motor Resistance (R) [Ω]	0.9	0.5525	0.3218
Motor Inductance (L) [mH]	0.49	0.1	0.1
Motor Torque Constant (K_T) [N.m/A]	9	1.642	1.642
Sheave Bearing Damping Constant (c_{b_d}) [N.m.s/rad]	0.2224	0.2224	0.2224
Motor Damping Constant (c_m) [N.m.s/rad]	0.1	0.1	0.1
Motor Back EMF Constant (K_e) [V.s/rad]	0.01	0.01	0.01
Maximum Motor Disturbance Torque (T_d) [N.m]	± 81	± 13.07	± 22.45

2.8 Model Analysis and Verification of Elevator A

2.8.1 Governing equations for Elevator A

The full set of system governing equations for Elevator A can be defined by rewriting Equations 2.66 – 2.70, replacing Equation 2.66 with Equation 2.84, introducing Equation 2.81 as the final governing equation and repeating Equations 2.21, 2.4.1, 2.25 and 2.97. The perturbation equations of motion for Elevator A, which will henceforth simply be referred to as the equations of motion for Elevator A, can finally be given as:

$$\begin{aligned} \dot{\omega}_s = & \frac{c_c r}{J_p} v_c - \frac{c_w r}{J_p} v_w - \frac{(c_c + c_w) r^2}{J_p} \omega_s - \frac{k_c r}{J_p} x_c + \frac{k_w r}{J_p} x_w \\ & + \frac{n K_T}{J_p} i_m - \text{sign}(\omega_s) \frac{(c_{b_d} |\omega_s|^{\frac{2}{3}} + c_m |\omega_s|)}{J_p} \end{aligned} \quad (2.105)$$

$$\dot{v}_c = \frac{k_c}{m_c + p_c} x_c + \frac{c_c r}{m_c + p_c} \omega_s - \frac{c_c}{m_c + p_c} v_c \quad (2.106)$$

$$\dot{v}_w = \frac{k_w}{m_w + p_w} x_w - \frac{c_w r}{m_w + p_w} \omega_s - \frac{c_w}{m_w + p_w} v_w \quad (2.107)$$

$$\dot{x}_c = \omega_s r - v_c \quad (2.108)$$

$$\dot{x}_w = -\omega_s r - v_w \quad (2.109)$$

$$\frac{d}{dt} i_m = \frac{U_m}{L} - \frac{n K_e}{L} \omega_s - \frac{R}{L} i_m \quad (2.110)$$

with the equations describing the cable dynamics defined as:

$$k_c = \frac{EA}{l_{ch}} \quad (2.111)$$

$$k_w = \frac{EA}{l_{wh}} \quad (2.112)$$

$$p_c = l_{cT} q \quad (2.113)$$

$$p_w = l_{wT} q \quad (2.114)$$

2.8.2 Model verification for Elevator A

In order to verify the model in an uncontrolled state, an impulse voltage input of 240 V was applied to the system. The subsequent responses are provided in Figures 2.12 – 2.15.

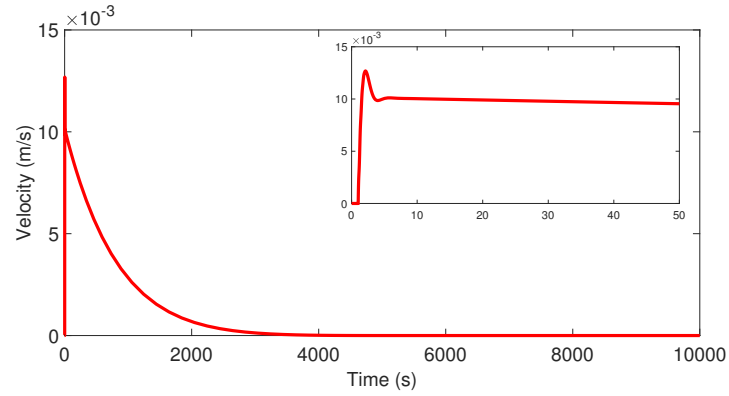


Figure 2.12: Uncontrolled Elevator A plant velocity response to a 240 V impulse input at $t = 1$ s (featuring an inset zoomed into the period between $t = 0$ s and $t = 50$ s)

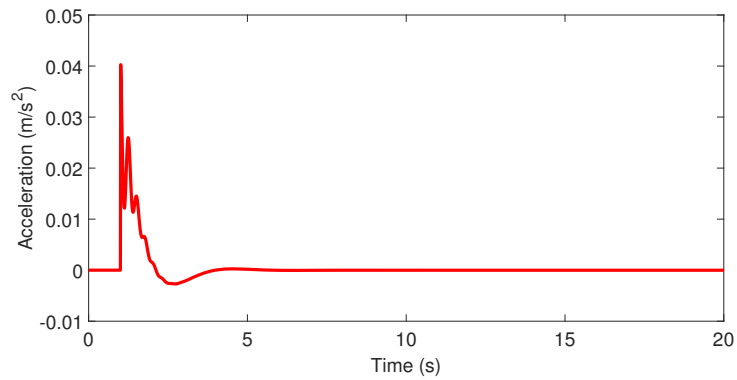


Figure 2.13: Uncontrolled Elevator A plant acceleration response to a 240 V impulse input at $t = 1$ s

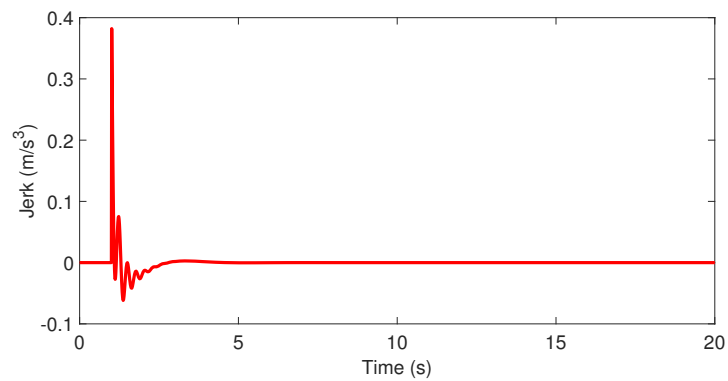


Figure 2.14: Uncontrolled Elevator A plant jerk response to a 240 V impulse input at $t = 1$ s

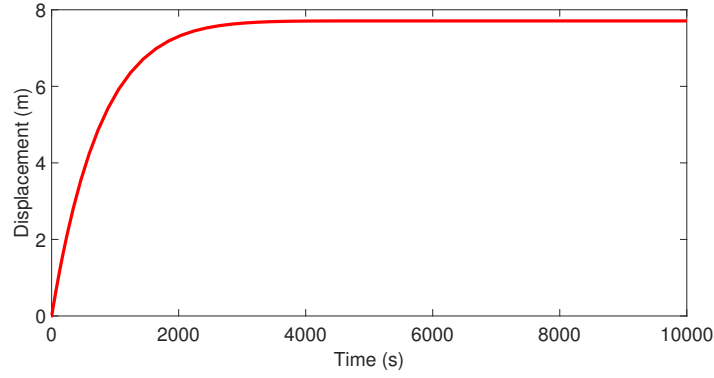


Figure 2.15: Uncontrolled Elevator A plant displacement response to a 240 V impulse input at $t = 1$ s

As can be seen in [Figure 2.12](#), the elevator system gradually returns to rest after being excited by the perturbation impulse, with a closer look at the oscillations provided in the embedded figure. The excessive time taken for the elevator to return to rest is not a cause for concern, as one of the assumptions made for the development of the model is that friction effects on the elevator cabin and counterweight are negligible. Hence the elevator conforms to Newton's first law, slowed only by relatively small forces such as the motor and sheave damping. As the impulse input is a perturbation voltage input, with the equilibrium voltage (U_{m0}) remaining constant even after the impulse has been applied, the elevator would continue indefinitely if not decelerated by these forces.

2.9 Model Analysis and Verification of Elevator B

2.9.1 Governing equations for Elevator B

The majority of the governing equations for Elevator B are the same as those for Elevator A (Equations [2.105](#) – [2.114](#)). The cabin and counterweight-side cable damping values are computed using Equations [2.92](#) and [2.104](#). The model can be shown to be a third-order system by using input-output linearisation to determine the relative degree of the system. This is done by differentiating the output equation ([Equation 2.106](#)) until the input (U_m) appears explicitly. Equations [2.106](#), [2.105](#), [2.108](#) and [2.110](#) can be written as:

$$\dot{v}_c = A_f k_c x_c + B_f c_c \omega_s - C_f c_c v_c \quad (2.115)$$

$$\begin{aligned} \dot{\omega}_s = & D_f c_c v_c - E_f c_w v_w - F_f c_c \omega_s - F_f c_w \omega_s - G_f k_c x_c + H_f k_w x_w + I_f i_m + J_f T_d \\ & - \text{sign}(\omega_s) \left(K_f |\omega_s|^{\frac{2}{3}} + L_f |\omega_s| \right) \end{aligned} \quad (2.116)$$

$$\dot{x}_c = M_f \omega_s - v_c \quad (2.117)$$

$$\frac{d}{dt} i_m = N_f U_m - O_f \omega_s - P_f i_m \quad (2.118)$$

where $A_f = \frac{1}{m_c + p_c}$, $B_f = \frac{r}{m_c + p_c}$, $C_f = \frac{1}{m_c + p_c}$, $D_f = \frac{r}{J_p}$, $E_f = \frac{r}{J_p}$, $F_f = \frac{r^2}{J_p}$,
 $G_f = \frac{r}{J_p}$, $H_f = \frac{r}{J_p}$, $I_f = \frac{nK_T}{J_p}$, $J_f = \frac{n}{J_p}$, $K_f = \frac{c_{b_d}}{J_p}$, $L_f = \frac{c_m}{J_p}$,
 $M_f = r$, $N_f = \frac{1}{L}$, $O_f = \frac{nK_e}{L}$, $P_f = \frac{R}{L}$.

Differentiating Equation 2.115 with respect to time and rearranging gives:

$$\ddot{v}_c = A_f \dot{k}_c x_c + A_f k_c \dot{x}_c + B_f \dot{c}_c \omega_s + B_f c_c \dot{\omega}_s - C_f \dot{c}_c v_c - C_f c_c \dot{v}_c \quad (2.119)$$

Substituting Equations 2.117, 2.116 and 2.115 into Equation 2.119 and multiplying through results in the following equation:

$$\begin{aligned} \ddot{v}_c = & A_f \dot{k}_c x_c + A_f M_f k_c \omega_s - A_f k_c v_c + B_f \dot{c}_c \omega_s + B_f D_f c_c^2 v_c - B_f E_f c_c c_w v_w \\ & - B_f F_f c_c^2 \omega_s - B_f F_f c_c c_w \omega_s - B_f G_f c_c k_c x_c + B_f H_f c_c k_w x_w \\ & - \text{sign}(\omega_s) \left(B_f K_f c_c |\omega_s|^{\frac{2}{3}} + B_f L_f c_c |\omega_s| \right) - C_f \dot{c}_c v_c - A_f C_f c_c k_c x_c - B_f C_f c_c^2 \omega_s \\ & + C_f^2 c_c^2 v_c + B_f I_f c_c i_m + B_f J_f c_c T_d \end{aligned} \quad (2.120)$$

This equation can then be differentiated once more and multiplied through to develop the following third-order equation:

$$\begin{aligned} \ddot{\ddot{v}}_c = & A_f \ddot{k}_c x_c + A_f \dot{k}_c \dot{x}_c + A_f M_f \dot{k}_c \omega_s + A_f D_f M_f c_c k_c v_c - A_f E_f M_f c_w k_c v_w \\ & - A_f F_f M_f c_c k_c \omega_s - A_f F_f M_f c_w k_c \omega_s - A_f G_f M_f k_c^2 x_c + A_f H_f M_f k_c k_w x_w \\ & + A_f I_f M_f k_c i_m + A_f J_f M_f k_c T_d - \text{sign}(\omega_s) \left(A_f K_f M_f k_c |\omega_s|^{\frac{2}{3}} + A_f L_f M_f k_c |\omega_s| \right) \\ & - A_f \dot{k}_c v_c - A_f k_c \dot{v}_c + B_f \ddot{c}_c \omega_s + B_f D_f \dot{c}_c c_c v_c - B_f E_f \dot{c}_c c_w v_w - B_f F_f \dot{c}_c c_c \omega_s \\ & - B_f F_f \dot{c}_c c_w \omega_s - B_f G_f \dot{c}_c k_c x_c + B_f H_f \dot{c}_c k_w x_w + B_f I_f \dot{c}_c i_m + B_f J_f \dot{c}_c T_d \\ & - \text{sign}(\omega_s) \left(B_f K_f \dot{c}_c |\omega_s|^{\frac{2}{3}} + B_f L_f \dot{c}_c |\omega_s| \right) + 2B_f D_f \dot{c}_c c_c v_c + B_f D_f c_c^2 \dot{v}_c \\ & - B_f E_f \dot{c}_c c_w v_w - B_f E_f c_c \dot{c}_w v_w - B_f E_f c_c c_w \dot{v}_w - 2B_f F_f \dot{c}_c c_c \omega_s - B_f D_f F_f c_c^3 v_c \\ & + B_f E_f F_f c_c^2 c_w v_w + B_f F_f^2 c_c^3 + B_f F_f^2 c_c^2 c_w \omega_s + B_f F_f G_f c_c^2 k_c x_c \\ & - B_f F_f H_f c_c^2 k_w x_w - B_f F_f I_f c_c^2 i_m - B_f F_f J_f c_c^2 T_d \\ & + \text{sign}(\omega_s) \left(B_f F_f K_f c_c^2 |\omega_s|^{\frac{2}{3}} + B_f F_f L_f c_c^2 |\omega_s| \right) - B_f F_f \dot{c}_c c_w \omega_s - B_f F_f c_c \dot{c}_w \omega_s \\ & - B_f D_f F_f c_c^2 c_w v_c + B_f E_f F_f c_c c_w^2 v_w + B_f F_f^2 c_c^2 c_w \omega_s + B_f F_f^2 c_c c_w^2 \omega_s \\ & + B_f F_f G_f c_c c_w k_c x_c - B_f F_f H_f c_c c_w k_w x_w - B_f F_f I_f c_c c_w i_m - B_f F_f J_f c_c c_w T_d \\ & + \text{sign}(\omega_s) \left(B_f F_f K_f c_c c_w |\omega_s|^{\frac{2}{3}} + B_f F_f L_f c_c c_w |\omega_s| \right) - B_f G_f \dot{c}_c k_c x_c - B_f G_f c_c \dot{k}_c x_c \end{aligned} \quad (2.121)$$

$$\begin{aligned}
& -B_f G_f c_c k_c \dot{x}_c + B_f H_F \dot{c}_c k_w x_w + B_f H_F c_c \dot{k}_w x_w + B_f H_F c_c k_w \dot{x}_w \\
& - \text{sign}(\omega_s) \left[\left(B_f K_f \dot{c}_c |\omega_s|^{\frac{2}{3}} + B_f L_f \dot{c}_c |\omega_s| + \frac{2B_f D_f K_f}{3} c_c^2 \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} v_c \right. \right. \\
& - \frac{2B_f E_f K_f}{3} c_c c_w \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} v_w - \frac{2B_f F_f K_f}{3} c_c^2 \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} \omega_s - \frac{2B_f F_f K_f}{3} c_c c_w \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} \omega_s \\
& - \frac{2B_f G_f K_f}{3} c_c k_c \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} x_c + \frac{2B_f H_f K_f}{3} c_c k_w \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} x_w + \frac{2B_f I_f K_f}{3} c_c \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} i_m \\
& + \frac{2B_f J_f K_f}{3} c_c \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} T_d - \text{sign}(\omega_s) \left(\frac{2B_f K_f^2}{3} c_c \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} |\omega_s|^{\frac{2}{3}} + \frac{2B_f K_f L_f}{3} c_c \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} |\omega_s| \right) \\
& + B_f D_f L_f c_c^2 \frac{\omega_s}{|\omega_s|} v_c - B_f E_f L_f c_c c_w \frac{\omega_s}{|\omega_s|} v_w - B_f F_f L_f c_c^2 \frac{\omega_s}{|\omega_s|} \omega_s \\
& - B_f F_f L_f c_c c_w \frac{\omega_s}{|\omega_s|} \omega_s - B_f G_f L_f c_c k_c \frac{\omega_s}{|\omega_s|} x_c + B_f H_f L_f c_c k_w \frac{\omega_s}{|\omega_s|} x_w + B_f I_f L_f c_c \frac{\omega_s}{|\omega_s|} i_m \\
& + B_f J_f L_f c_c \frac{\omega_s}{|\omega_s|} T_d - \text{sign}(\omega_s) \left(B_f K_f L_f c_c \frac{\omega_s}{|\omega_s|} |\omega_s|^{\frac{2}{3}} + B_f L_f^2 c_c \frac{\omega_s}{|\omega_s|} |\omega_s| \right) \Big] - C_f \ddot{c}_c v_c \\
& - C_f \dot{c}_c \dot{v}_c - A_f C_f \dot{c}_c k_c x_c - A_f C_f c_c \dot{k}_c x_c - A_f C_f c_c k_c \dot{x}_c - 2B_f C_f \dot{c}_c c_c \omega_s - B_f C_f D_f c_c^2 v_c \\
& + B_f C_f E_f c_c c_w v_w + B_f C_f F_f c_c^2 \omega_s + B_f C_f F_f c_c c_w \omega_s + B_f C_f G_f c_c k_c x_c \\
& - B_f C_f H_f c_c k_w x_w - B_f C_f I_f c_c i_m - B_f C_f J_f c_c T_d \\
& + \text{sign}(\omega_s) \left(B_f C_f K_f c_c |\omega_s|^{\frac{2}{3}} + B_f C_f L_f c_c |\omega_s| \right) + 2C_f^2 \dot{c}_c c_c v_c + C_f^2 c_c^2 \dot{v}_c + B_f I_f \dot{c}_c i_m \\
& + B_f I_f N_f c_c U_m - B_f I_f O_f c_c \omega_s - B_f I_f P_f c_c i_m + B_f J_f \dot{c}_c T_d + B_f J_f c_c \dot{T}_d
\end{aligned}$$

Rearranging Equation 2.121 for clarity allows the equation to be written as:

$$\begin{aligned}
\ddot{v}_c = & - \left(A_f k_c + C_f \dot{c}_c - (B_f D_f + C_f^2) c_c^2 \right) \dot{v}_c - \left(A_f \dot{k}_c - C_f \ddot{c}_c - (3B_f D_f + 2C_f^2) \dot{c}_c c_c \right. \\
& - A_f D_f M_f c_c k_c + (B_f D_f F_f c_c + B_f C_f D_f) c_c^2 + B_f D_f F_f c_c^2 c_w \Big) v_c \\
& - B_f E_f c_c c_w \dot{v}_w - \left(2B_f E_f \dot{c}_c c_w + B_f E_f c_c \dot{c}_w \right. \\
& + A_f E_f M_f c_w k_c - (B_f E_f F_f c_c + B_f C_f E_f) c_c c_w - B_f E_f F_f c_c c_w^2 \Big) v_w \\
& + \left(A_f \dot{k}_c - (B_f G_f + A_f C_f) c_c k_c \right) \dot{x}_c + \left(A_f \ddot{k}_c - (2B_f G_f + A_f C_f) \dot{c}_c k_c \right. \\
& - (B_f G_f + A_f C_f) c_c \dot{k}_c \\
& - A_f G_f M_f k_c^2 + (B_f F_f G_f c_c + B_f C_f G_f) c_c k_c + B_f F_f G_f c_c c_w k_c \Big) x_c \\
& + B_f H_F c_c k_w \dot{x}_w + \left(B_f H_F c_c \dot{k}_w + 2B_f H_f \dot{c}_c + A_f H_f M_f k_c k_w \right.
\end{aligned} \tag{2.122}$$

$$\begin{aligned}
& - \left(B_f F_f H_f c_c + B_f C_f H_f \right) c_c k_w - B_f F_f H_f c_c c_w k_w \Big) x_w \\
& + \left(2B_f I_f \dot{c}_c + A_f I_f M_f k_c - \left(B_f F_f I_f c_c + B_f C_f I_f + B_f I_f P_f \right) c_c - B_f F_f I_f c_c c_w \right) \dot{c}_m \\
& + \left(A_f M_f \dot{k}_c + B_f \ddot{c}_c - \left(3B_f F_f + 2B_f C_f \right) \dot{c}_c c_c - 2B_f F_f \dot{c}_c c_w - B_f F_f c_c \dot{c}_w - B_f I_f O_f c_c \right. \\
& - A_f F_f M_f c_c k_c + \left(B_f F_f^2 c_c + B_f C_f F_f \right) c_c^2 + B_f F_f^2 c_c^2 c_w \\
& - A_f F_f M_f c_w k_c + \left(B_f F_f^2 c_c + B_f C_f F_f \right) c_c c_w + B_f F_f^2 c_c c_w^2 \Big) \omega_s \\
& - \text{sign}(\omega_s) \left[\left(\left(A_f K_f M_f k_c + 2B_f K_f \dot{c}_c - \left(B_f F_f K_f c_c + B_f C_f K_f \right) c_c - B_f F_f K_f c_c c_w \right) |\omega_s|^{\frac{2}{3}} \right. \right. \\
& + \left(A_f L_f M_f k_c + 2B_f L_f \dot{c}_c - \left(B_f F_f L_f c_c + B_f C_f L_f \right) c_c - B_f F_f L_f c_c c_w \right) |\omega_s| \\
& + \left(\frac{2B_f D_f K_f}{3} c_c^2 \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_f D_f L_f c_c^2 \frac{\omega_s}{|\omega_s|} \right) v_c \\
& - \left(\frac{2B_f E_f K_f}{3} c_c c_w \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_f E_f L_f c_c c_w \frac{\omega_s}{|\omega_s|} \right) v_w \\
& - \left(\frac{2B_f G_f K_f}{3} c_c k_c \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_f G_f L_f c_c k_c \frac{\omega_s}{|\omega_s|} \right) x_c \\
& + \left(\frac{2B_f H_f K_f}{3} c_c k_w \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_f H_f L_f c_c k_w \frac{\omega_s}{|\omega_s|} \right) x_w \\
& + \left(\frac{2B_f I_f K_f}{3} c_c \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_f I_f L_f c_c \frac{\omega_s}{|\omega_s|} \right) \dot{c}_m \\
& - \left(\frac{2B_f F_f K_f}{3} c_c^2 \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_f F_f L_f c_c^2 \frac{\omega_s}{|\omega_s|} + \frac{2B_f F_f K_f}{3} c_c c_w \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_f F_f L_f c_c c_w \frac{\omega_s}{|\omega_s|} \right) \omega_s \\
& - \text{sign}(\omega_s) \left(\frac{2B_f K_f^2}{3} c_c \frac{\omega_s}{|\omega_s|^{\frac{2}{3}}} + \left(\frac{2B_f K_f L_f}{3} + B_f K_f L_f \right) c_c \frac{\omega_s}{|\omega_s|^{\frac{1}{3}}} + B_f L_f^2 c_c \omega_s \right) \Big] \\
& + B_f I_f N_f c_c U_m + B_f J_f c_c \dot{T}_d + \left(A_f J_f M_f k_c + 2B_f J_f \dot{c}_c - \left(B_f F_f J_f c_c + B_f C_f J_f \right) c_c \right. \\
& - B_f F_f J_f c_c c_w \Big) T_d - \text{sign}(\omega_s) \left(\left(\frac{2B_f J_f K_f}{3} c_c \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_f J_f L_f c_c \frac{\omega_s}{|\omega_s|} \right) T_d \right)
\end{aligned}$$

The relevant higher derivatives of the cable parameters are defined as follows:

$$\dot{k}_c = \frac{EA v_c}{(l_{chi} - d_c)^2} \quad (2.123)$$

$$\ddot{k}_c = \frac{EA \left((l_{chi} - d_c)^2 \dot{v}_c + 2(l_{chi} - d_c) v_c^2 \right)}{(l_{chi} - d_c)^4} \quad (2.124)$$

$$\dot{c}_c = \zeta \sqrt{m_c + p_c} \frac{\dot{k}_c}{\sqrt{k_c}} \quad (2.125)$$

$$\ddot{c}_c = \zeta \sqrt{m_c + p_c} \left(\sqrt{k_c} \ddot{k}_c - \frac{1}{2} \frac{\dot{k}_c}{\sqrt{k_c}} \right) \frac{1}{k_c} \quad (2.126)$$

$$\dot{k}_w = \frac{EA v_w}{(l_{whi} - d_w)^2} \quad (2.127)$$

$$\dot{c}_w = \zeta \sqrt{m_w + p_w} \frac{\dot{k}_w}{\sqrt{k_w}} \quad (2.128)$$

As seen in Equation 2.122, U_m appears explicitly in the third-order equation, verifying that the model is a third-order system.

2.9.2 Model verification for Elevator B

The same 240 V impulse input applied to Elevator A is used to actuate the system. As can be seen in Figures 2.16 – 2.19, the system gradually returns to rest; with the time taken to decelerate being caused by a combination of the ever-present equilibrium voltage (U_{m0}) and relatively low friction effects.

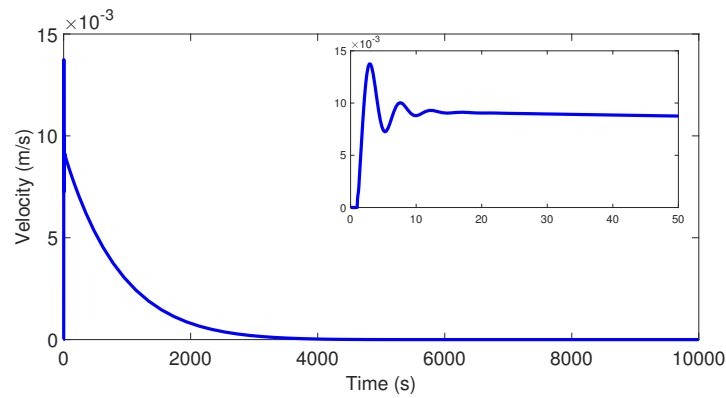


Figure 2.16: Uncontrolled Elevator B plant velocity response to a 240 V impulse input at $t = 1$ s (featuring an inset zoomed into the period between $t = 0$ s and $t = 50$ s)

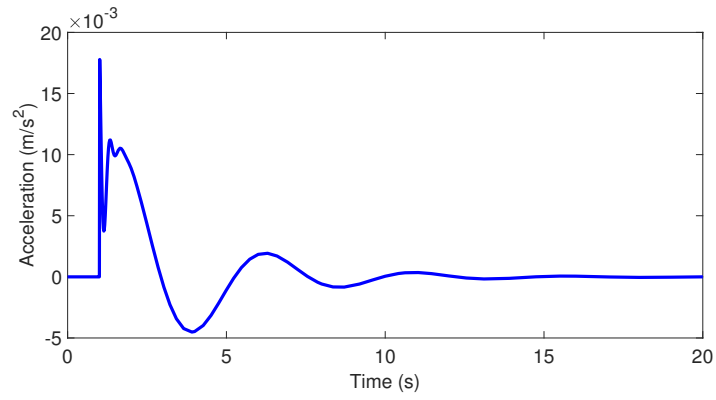


Figure 2.17: Uncontrolled Elevator B plant acceleration response to a 240 V impulse input at $t = 1$ s

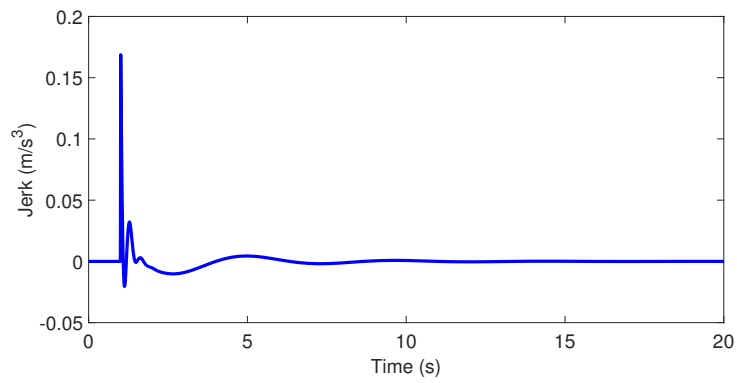


Figure 2.18: Uncontrolled Elevator B plant jerk response to a 240 V impulse input at $t = 1$ s

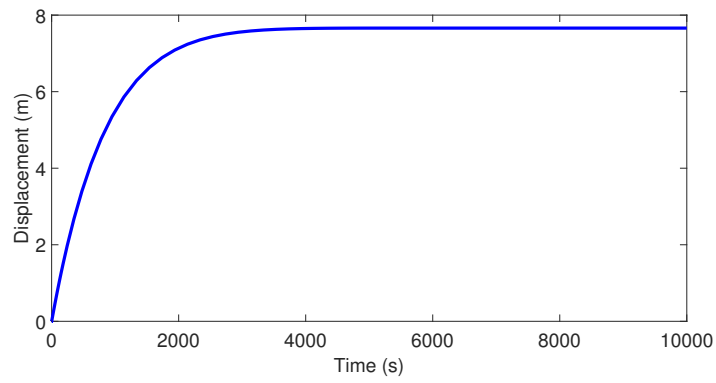


Figure 2.19: Uncontrolled Elevator B plant displacement response to a 240 V impulse input at $t = 1$ s

2.10 Model Analysis and Verification of Elevator C

2.10.1 Governing equations for Elevator C

The governing equations for Elevator C are identical to those of Elevator B (refer to Section 2.9.1).

2.10.2 Model verification for Elevator C

The responses of Elevator C to a 240 V impulse input are shown in Figures 2.20 – 2.23.

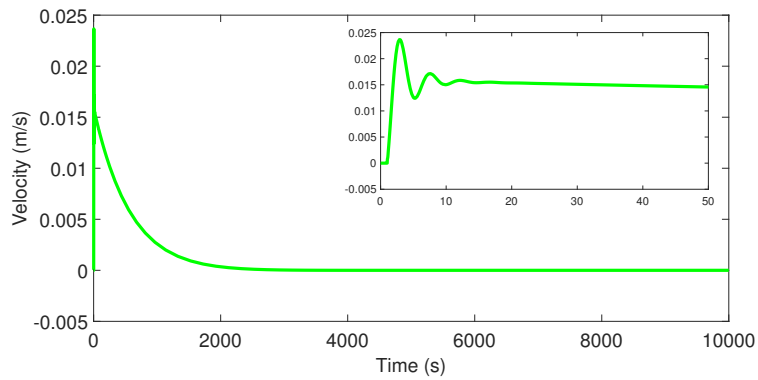


Figure 2.20: Uncontrolled Elevator C plant velocity response to a 240 V impulse input at $t = 1$ s (featuring an inset zoomed into the period between $t = 0$ s and $t = 50$ s)

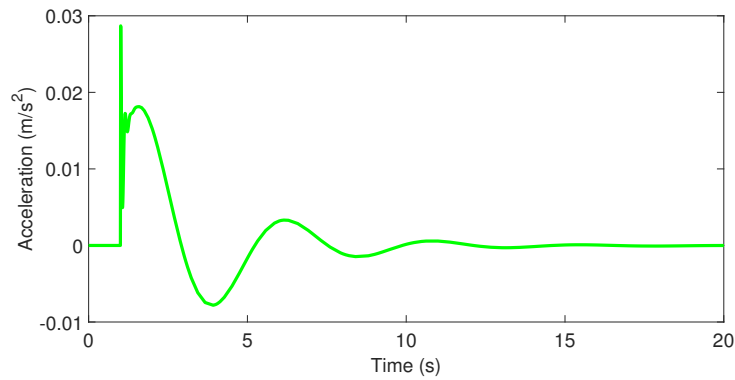


Figure 2.21: Uncontrolled Elevator C plant acceleration response to a 240 V impulse input at $t = 1$ s

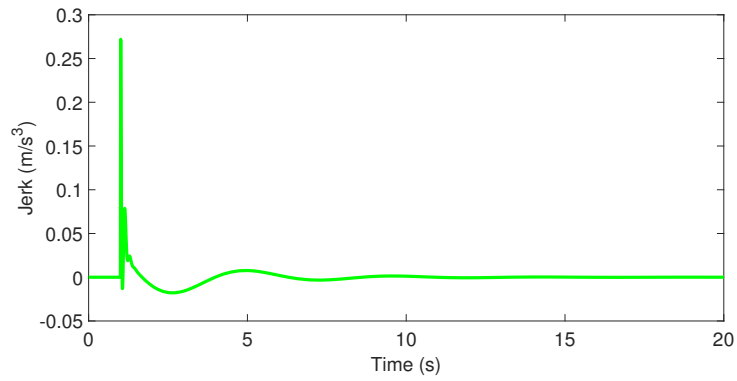


Figure 2.22: Uncontrolled Elevator C plant jerk response to a 240 V impulse input at $t = 1$ s

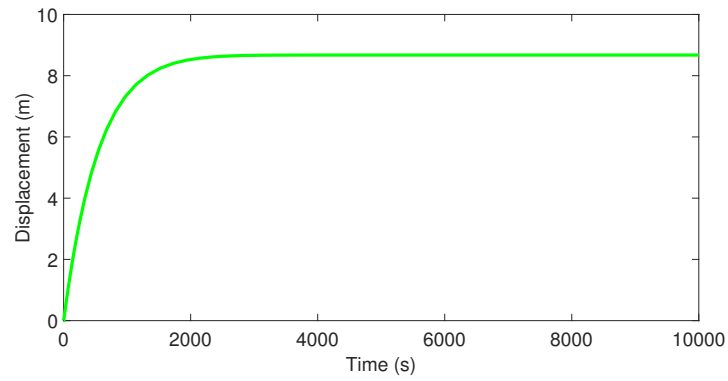


Figure 2.23: Uncontrolled Elevator C plant displacement response to a 240 V impulse input at $t = 1$ s

2.11 Setpoint Signals

2.11.1 Velocity setpoint signal for Elevator A

The desired velocity profile (v_d) consists of three modes of operation – acceleration, steady-state travel and deceleration. An example of a generic velocity profile is illustrated in [Figure 2.24](#).

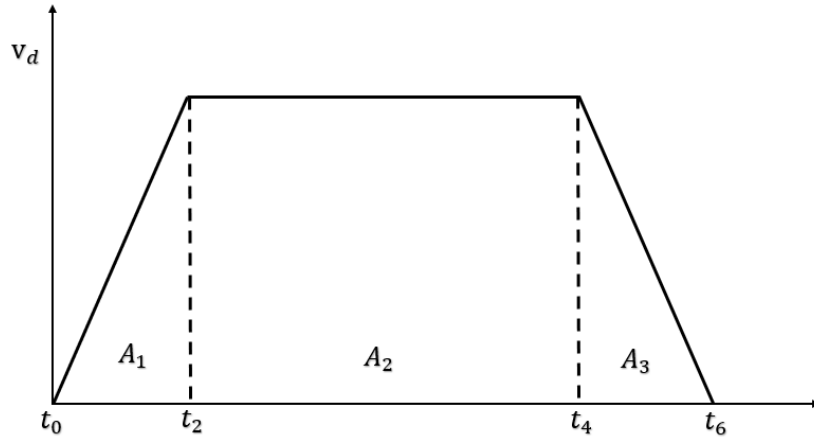


Figure 2.24: Generic desired velocity profile

For an elevator car designed to accelerate at 1 m/s^2 to a velocity of 10 m/s before decelerating at -1 m/s^2 back to a stationary position, the acceleration/deceleration time can be calculated as:

$$a = \frac{v_{t_2} - v_{t_0}}{t_2 - t_0} = -\frac{v_{t_6} - v_{t_4}}{t_6 - t_4} \quad (2.129)$$

$$1 = \frac{10 - 0}{t_2 - t_0} = -\frac{0 - 10}{t_6 - t_4}$$

$$t_2 - t_0 = t_6 - t_4 = 10 \text{ s}$$

The time over which the elevator must travel at a velocity of 10 m/s can now be calculated using the desired displacement, with the area under the velocity profile being equal to the cabin displacement. As shown in Figure 2.24, the area under the velocity profile is divided into three sections. Hence, for an elevator car set to travel a distance of 500 m :

$$d_d = A_1 + A_2 + A_3 = \frac{1}{2}(t_2 - t_0)(v_{t_2}) + (t_4 - t_2)(v_{t_4}) + \frac{1}{2}(t_6 - t_4)(v_{t_4}) \quad (2.130)$$

$$500 = \frac{1}{2}(10)(10) + (t_4 - t_2)(10) + \frac{1}{2}(10)(10)$$

$$t_4 - t_2 = 40 \text{ s}$$

The subsequent velocity signal is defined as:

$$v_d(t) = \begin{cases} t, & 0 \text{ s} \leq t < 10 \text{ s} \\ 10, & 10 \text{ s} \leq t < 50 \text{ s} \\ -t + 110, & 50 \text{ s} \leq t < 60 \text{ s} \\ 0, & \text{otherwise} \end{cases} \quad (2.131)$$

with the displacement profile calculated as follows:

$$d_d(t) = \int v_d(t) dt \quad (2.132)$$

The desired velocity signal is converted to a voltage signal by utilising the same constant used to convert the actual cabin velocity to a voltage signal in [Equation 2.87](#):

$$U_d = 6.3362v_d \quad (2.133)$$

2.11.2 Velocity setpoint signal for Elevators B and C

For the control of Elevator B using CPID, CPDF, NPID and NPDF control, each controller will have two variants for an initial analysis. The first variant will utilise the setpoint signal defined in this section, henceforth referred to as the simple velocity setpoint due to the simplicity of derivation. The second variant will have the velocity signal derived from the acceleration signal detailed in [Section 2.11.3](#), henceforth referred to as the exact velocity setpoint, due to the fact that it represents the exact profile that the elevator cabin should follow. For control of Elevator C, each controller will utilise a single setpoint signal based on the results of the preliminary simulations of Elevator B.

As with Elevator A, Elevators B and C will accelerate at 1 m/s^2 for a period of 10 seconds. For a travel distance of 1000 m, the generic velocity profile in [Figure 2.24](#) can be used to calculate the time that the cars will need to travel at a velocity of 10 m/s:

$$d_d = A_1 + A_2 + A_3 = \frac{1}{2}(t_2 - t_0)(v_{t_2}) + (t_4 - t_2)(v_{t_4}) + \frac{1}{2}(t_6 - t_4)(v_{t_4}) \quad (2.134)$$

$$1000 = \frac{1}{2}(10)(10) + (t_4 - t_2)(10) + \frac{1}{2}(10)(10)$$

$$t_4 - t_2 = 90 \text{ s}$$

The simple velocity setpoint can then be defined as:

$$v_d(t) = \begin{cases} t, & 0 \text{ s} \leq t < 10 \text{ s} \\ 10, & 10 \text{ s} \leq t < 100 \text{ s} \\ -t + 110, & 100 \text{ s} \leq t < 110 \text{ s} \\ 0, & \text{otherwise} \end{cases} \quad (2.135)$$

with the displacement profile calculated by taking the intergral with respect to time of $v_d(t)$, as shown in [Equation 2.132](#) which is repeated here:

$$d_d(t) = \int v_d(t) dt$$

2.11.3 Acceleration setpoint signal for Elevators B and C

It is important to note that the velocity profile given in Figure 2.24 does not account for jerk, with instantaneous transitions occurring from a state of rest to acceleration to steady-state travel. While it is possible for controllers to be tuned in such a way that this profile is tracked as effectively as possible without exceeding the jerk constraints [32] [33], it can be preferable to input the exact setpoint to be tracked. The simplest way to achieve this is to generate the ideal acceleration signal, before integrating the signal to obtain a velocity profile that accounts for jerk. An example of a generic acceleration profile is illustrated in Figure 2.25.

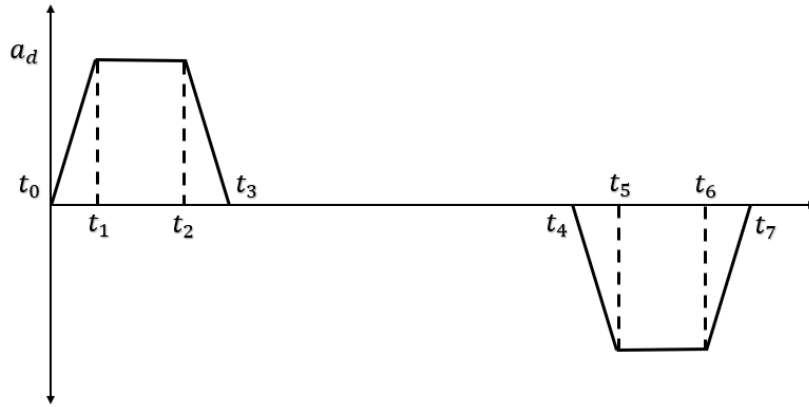


Figure 2.25: Generic desired acceleration profile

For a jerk of 1.6 m/s^3 , the time of transition both to and from the target acceleration can be calculated:

$$j = \frac{a_{t_1} - a_{t_0}}{t_1 - t_0} = -\frac{a_{t_3} - a_{t_2}}{t_3 - t_2} = -\frac{a_{t_5} - a_{t_4}}{t_5 - t_4} = \frac{a_{t_7} - a_{t_6}}{t_7 - t_6} \quad (2.136)$$

$$1.6 = \frac{1 - 0}{t_1 - t_0} = -\frac{0 - 1}{t_3 - t_2} = -\frac{-1 - 0}{t_5 - t_4} = \frac{0 + 1}{t_7 - t_6}$$

$$t_1 - t_0 = t_3 - t_2 = t_5 - t_4 = t_7 - t_6 = 0.625 \text{ s} \quad (2.137)$$

Noting that the values of t_0 , t_2 , t_4 and t_6 match with those of the simple velocity setpoint signal in Equation 2.135, the equation defining the acceleration profile is as follows:

$$a_d(t) = \begin{cases} 1.6t, & 0 \text{ s} \leq t < 0.625 \text{ s} \\ 1, & 0.625 \text{ s} \leq t < 10 \text{ s} \\ -1.6t + 17, & 10 \text{ s} \leq t < 10.625 \text{ s} \\ -1.6t + 160, & 100 \text{ s} \leq t < 100.625 \text{ s} \\ -1, & 100.625 \text{ s} \leq t < 110 \text{ s} \\ 1.6t - 177, & 110 \text{ s} \leq t < 110.625 \text{ s} \\ 0, & \text{otherwise} \end{cases} \quad (2.138)$$

The exact velocity setpoint signal can then be calculated as:

$$v_d(t) = \int a_d(t) dt \quad (2.139)$$

with the displacement profile once again being the integral with respect to time of $v_d(t)$, as shown in Equation 2.132.

2.11.4 Jerk setpoint signal for Elevators B and C

As shown in Equations 1.10 and 1.11, sliding mode control of an elevator system having a relative degree of 4 would require the tracking of a jerk setpoint. A generic jerk profile is illustrated in Figure 2.26.

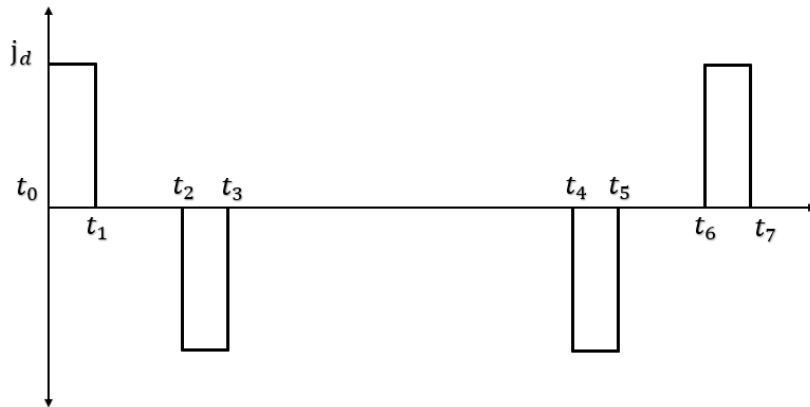


Figure 2.26: Generic desired jerk profile

Noting that t_0 through t_7 match with the times illustrated in [Figure 2.25](#) and described in [Equation 2.138](#); the jerk setpoint equation can be given as:

$$j_d(t) = \begin{cases} 1.6, & 0 \text{ s} \leq t < 0.625 \text{ s} \\ -1.6, & 10 \text{ s} \leq t < 10.625 \text{ s} \\ -1.6, & 100 \text{ s} \leq t < 100.625 \text{ s} \\ 1.6, & 110 \text{ s} \leq t < 110.625 \text{ s} \\ 0, & \text{otherwise} \end{cases} \quad (2.140)$$

The snap setpoint ($s_d(t)$) can be calculated by taking the time-derivative of $j_d(t)$:

$$s_d(t) = \frac{d}{dt} j_d(t) \quad (2.141)$$

while $a_d(t)$ is calculated by:

$$a_d(t) = \int j_d(t) dt \quad (2.142)$$

2.11.5 Adaptive re-levelling for Elevator C

Elevator re-levelling is defined as an operation to adjust the final position of an elevator car after it has come to rest, achieved by successive movements if necessary [84]. For the purposes of this dissertation, re-levelling is defined as an operation that occurs after the elevator has arrived; while arrival is defined as the moment that the elevator cabin is within 0.1 m of the arrival floor (and does not necessarily mean that the cabin is stationary). Re-levelling may be applied to a slow-moving cabin, assuming it has arrived by the above definition. "Door-open" is specified as the instant that the elevator cabin is within 3 mm of the target destination, if and only if the cabin does not subsequently fluctuate in excess of ± 3 mm of the arrival floor. This is the point where the doors may be safely opened, allowing for passengers to enter or exit the cabin.

A factor that must be considered is that arrival and peak jerk are likely to occur concurrently, as the control systems attempt to bring the cabin to rest. Attempting to actuate the system too abruptly at this point is likely to result in a violation of the jerk constraint. As such, the re-levelling operation must be split into two sub-operations – a gentle re-levelling procedure around the time of arrival to edge the cabin towards the desired position, followed by the full actuation of the system a few seconds later. The h^{th} re-levelling procedure is defined in [Equation 2.143](#), with the specific sub-operation undertaken being dependent on the value of h :

$$v_{r-h}(t) = \begin{cases} v_{r-h-1}(t) = \begin{cases} 4(d_d - d_c)t - 4(d_d - d_c)(t_{arrival} + 0.25h - 0.25), & t_{arrival} + 0.25h - 0.25 \leq t < t_{arrival} + 0.25h - 0.125 \\ -4(d_d - d_c)t + 4(d_d - d_c)(t_{arrival} + 0.25h), & t_{arrival} + 0.25h - 0.125 \leq t < t_{arrival} + 0.25h \end{cases}, & 1 \leq h < 9 \\ v_{r-h-2}(t) = \begin{cases} 4(d_d - d_c)t - 4(d_d - d_c)(t_{arrival} + h - 7), & t_{arrival} + h - 7 \leq t < t_{arrival} + h - 6.5 \\ -4(d_d - d_c)t + 4(d_d - d_c)(t_{arrival} + h - 6), & t_{arrival} + h - 6.5 \leq t < t_{arrival} + h - 6 \end{cases}, & 9 \leq h < \infty \\ 0, & \text{otherwise} \end{cases} \quad (2.143)$$

where $t_{arrival}$ is the actual arrival time of the cabin [s], $v_{r-h-1}(t)$ is the first re-levelling sub-operation, $v_{r-h-2}(t)$ is the second sub-operation and $h = [1, 2, 3, \dots, \infty]$.

Hence, the complete adaptive re-levelling signal for h number of operations is defined by:

$$v_{d-r}(t) = v_{r-1}(t) + v_{r-2}(t) + \dots + v_{r-h}(t) \quad (2.144)$$

For the case of control using the exact velocity setpoint derived from the acceleration signal, as well as control using SMC (which makes use of displacement, acceleration, jerk and snap setpoint signals); $v_{d-r}(t)$ can be differentiated/integrated as required and applied to the relevant signals as follows:

$$d_{d-r}(t) = d_d(t) + \left(\int v_{d-r}(t) dt \right) \quad (2.145)$$

$$a_{d-r}(t) = a_d(t) + \dot{v}_{d-r}(t) \quad (2.146)$$

$$j_{d-r}(t) = j_d(t) + \ddot{v}_{d-r}(t) \quad (2.147)$$

$$s_{d-r}(t) = s_d(t) + \ddot{\ddot{v}}_{d-r}(t) \quad (2.148)$$

In order to limit the experienced acceleration and/or jerk, an appropriate filter should be used for derivation of the re-levelling signals during simulation.

3 Controller Implementation

3.1 Chapter Outline

An overview of the structures of the controllers is provided in this chapter, in addition to the performance requirements that the control systems must achieve. Finally, an explanation of the GA-code is given for optimisation of the controllers for Elevator A, following which a number of alterations are made for tuning of the controllers for Elevators B and C.

3.2 Control System Architectures

3.2.1 CPID controller for Elevators A and B

CPID control is the most common method of feedback control in industry, having found widespread use since its development by Nicolas Minorsky in 1922 for automatic ship steering [85]. The robust and relatively simple nature of the CPID algorithm ensures that it is capable of effectively dealing with the varied dynamic characteristics of a typical mechatronics system. The CPID algorithm consists of a proportional, integral and derivative mode; making use of both phase-lead and phase-lag compensation. An example of a GA-tuned CPID controller block diagram is illustrated in [Figure 3.1](#), with the mathematical s-domain representation (as it is modelled in Simulink) being provided in [Equation 3.1](#):

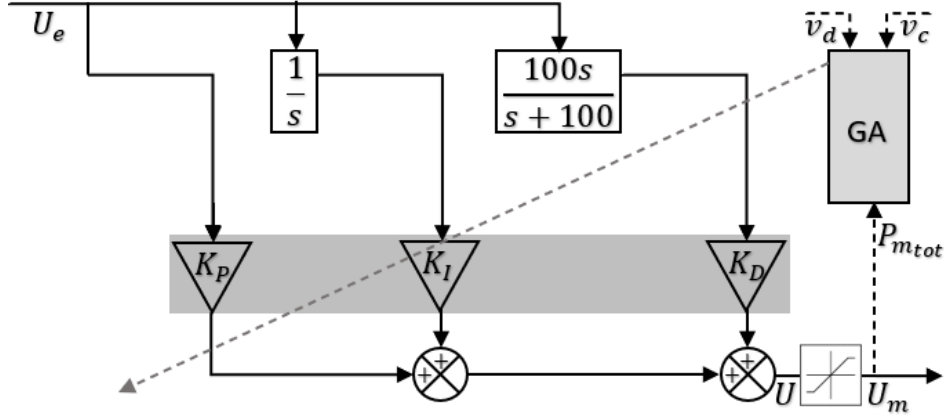


Figure 3.1: GA-tuned CPID controller architecture

$$U(s) = K_P U_e(s) + \frac{K_I}{s} U_e(s) + K_D \frac{100s}{s+100} U_e(s) \quad (3.1)$$

where U is the control output signal that is subsequently passed through a saturator to obtain U_m without exceeding the maximum allowable motor voltage, K_P is the proportional gain, K_I is the integral gain, K_D is the derivative gain and U_e is the control error signal, which is calculated as follows:

$$U_e = U_d - U_s \quad (3.2)$$

The proportional mode of the controller adjusts the output signal in direct proportion to the error signal. The proportional gain can therefore reduce the error, but cannot eliminate it entirely. To account for this, the integral mode is implemented and acts as a means of eliminating the steady-state errors. Essentially, the integral mode automatically corrects for any offsets that can occur between the desired value and the output of the process [86].

Although, the integral mode improves the steady-state error, it also degrades the transient performance of the system. This problem can be solved by means of the derivative mode. This mode is primarily used to damp out oscillations within the response, as the derivative gain is dependent on the error rate. This reduction in oscillations leads to a better transient response [86]. The derivative action is sometimes referred to as pre-action, as it essentially predicts the future behaviour of the response by analysing the derivative of the controlled variable. While derivative action should always improve the control in theory, this is not the case when there is a large amount of noise within the system. For this reason, a filter can be applied to the derivative mode in order to attenuate any high-frequency noises that may occur. Such a filter is applied in Equation 3.1, with the filter for the current model having a coefficient of 100.

Despite CPID control being successfully implemented in a wide array of applications (including elevator control) there are a number of disadvantages associated with the architecture. As mentioned

in Section 1.3.3.4, Alipour et al., [47] found that for control of a ropeless elevator system using a CPID controller, the system performance was heavily influenced by external disturbances. In addition to this, the control scheme is incapable of responding simultaneously to conflicting signals and is susceptible to the negative effects of numerator dynamics due to its structure. Numerator dynamics in a CPID-controlled system can be better understood by referring to the following CPID-controlled servomechanism block diagram (Figure 3.2) and subsequent transfer function at the output (Equation 3.4). The existence of zeros in the numerator of Equation 3.4 were reported to be the cause of degraded system performance [87].

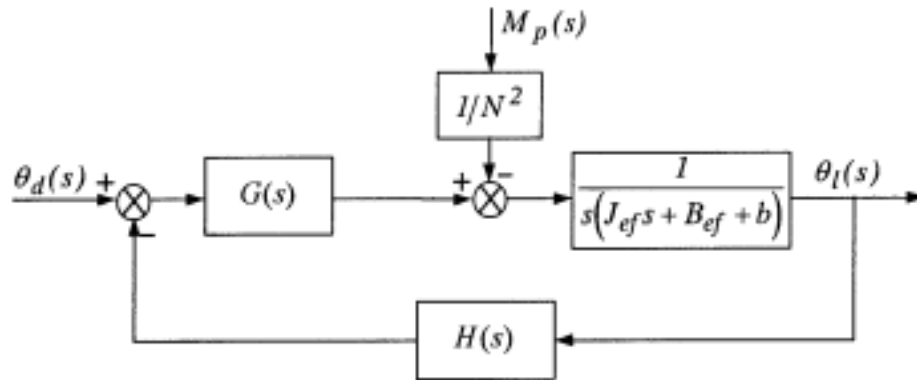


Figure 3.2: CPID-controlled servomechanism block diagram [87]

$$G[s] = K_p + \frac{K_I}{s} + K_D s \quad (3.3)$$

$$\frac{\theta_l[s]}{\theta_d[s]} = \frac{K_D s^2 + K_P s + K_I}{J_{ef} s^3 + (B_{ef} + b + K_D) s^2 + K_P s + K_I} \quad (3.4)$$

3.2.2 CPDF controller for Elevators A and B

The disadvantages associated with CPID control can be avoided by adapting the algorithm to have the proportional and derivative modes implemented in the feedback path. This is known as CPDF (or I-PD) control and operates using the "Principle of One Master," with only the integral mode existing in the forward path [88]. As such, a CPDF controller can benefit from the advantages associated with including a derivative mode whilst simultaneously avoiding the problem of numerator dynamics. A schematic of a GA-tuned CPDF controller is provided in Figure 3.3, with the s-domain equation defined in Equation 3.5:

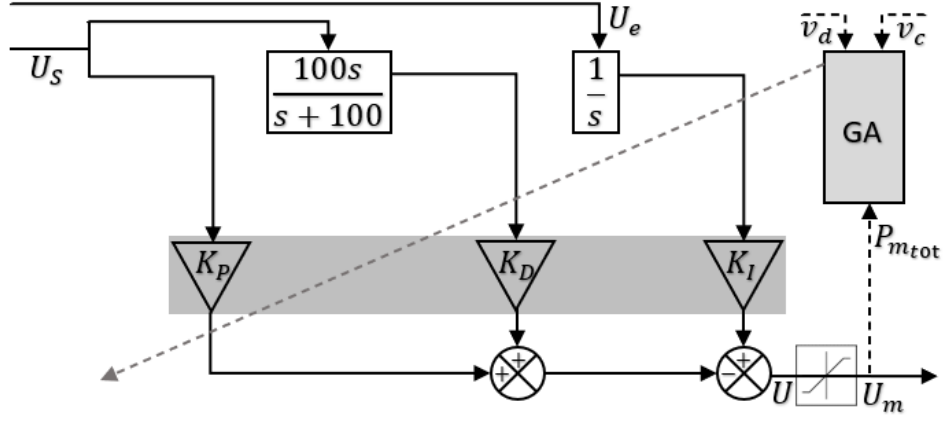


Figure 3.3: GA-tuned CPDF controller architecture

$$U(s) = \frac{K_I}{s} U_e(s) - K_P U_s(s) - K_D \frac{100s}{s+100} U_s(s) \quad (3.5)$$

Referring to the CPID-controlled servomechanism in Figure 3.2, applying CPDF control to the same system results in the following block diagram and transfer function:

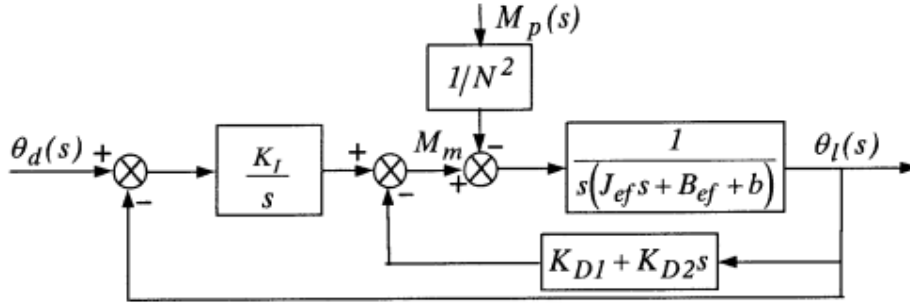


Figure 3.4: CPDF-controlled servomechanism block diagram [87]

$$\frac{\theta_l[s]}{\theta_d[s]} = \frac{K_I}{J_{ef}s^3 + (B_{ef} + b + K_{D2})s^2 + K_{D1}s + K_I} \quad (3.6)$$

As can be seen in Equation 3.6, numerator dynamics were eliminated following the adaptation of the control system; resulting in improved control performance being achieved.

3.2.3 NPID controller for Elevators A, B and C

The block diagram of a GA-tuned NPID controller and mathematical expression are provided:

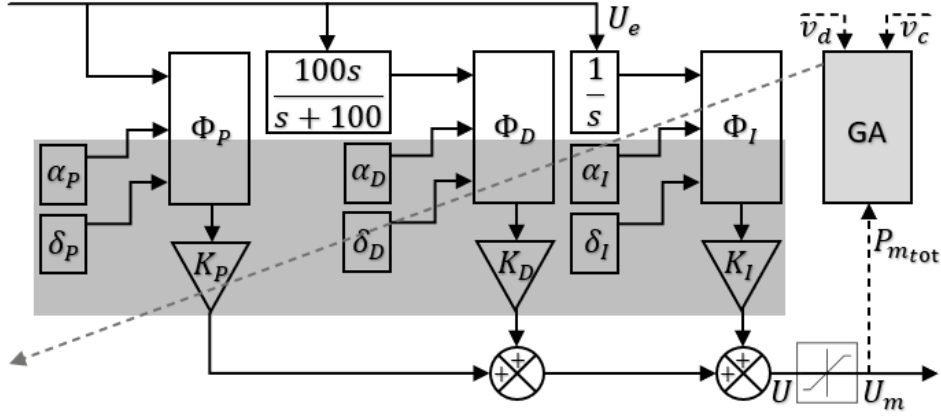


Figure 3.5: GA-tuned NPID controller architecture

$$U(s) = K_P \Phi_P(U_e(s), \alpha_P, \delta_P) + K_I \Phi_I\left(\frac{U_e(s)}{s}, \alpha_I, \delta_I\right) + K_D \Phi_D\left(\frac{100s}{s+100} U_e(s), \alpha_D, \delta_D\right) \quad (3.7)$$

As described in Section 1.3.3.2, the nonlinear functions of each mode can be defined using Equation 1.8:

$$\Phi(x, \alpha, \delta) = \begin{cases} |x|^\alpha \cdot \text{sign}(x), & |x| > \delta \\ \delta^{\alpha-1} \cdot x, & \text{otherwise} \end{cases}$$

3.2.4 NPDP controller for Elevators A, B and C

The NPDP controller structure is illustrated in Figure 3.6. As with NPID control, the error signal (U_e) is adapted by the integral nonlinear function (Φ_{I-NPDP}) before the output passes through the integral gain. The feedback sensor signal (U_s) is sent through Φ_{P-NPDP} and Φ_{D-NPDP} , with the adapted sensor signals then being multiplied by the respective controller gains. The s-domain equation of a GA-tuned NPDP controller may be found in Equation 3.8:

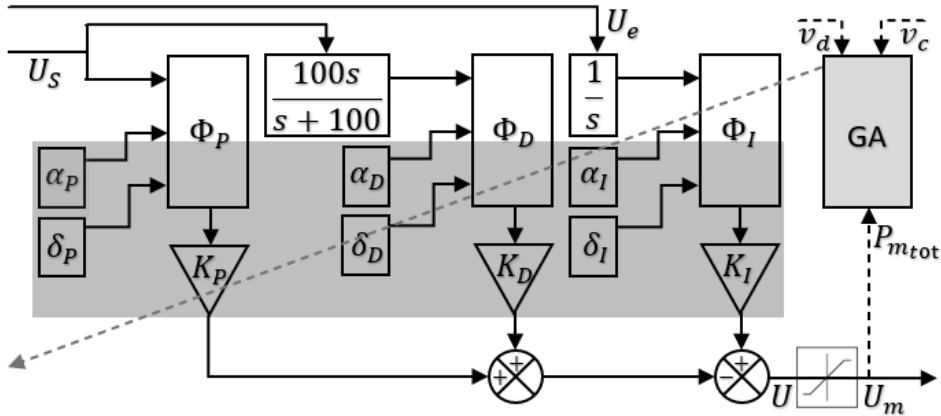


Figure 3.6: GA-tuned NPDP controller architecture

$$U(s) = K_I \Phi_I \left(\frac{U_e(s)}{s}, \alpha_I, \delta_I \right) - K_P \Phi_P (U_s(s), \alpha_P, \delta_P) - K_D \Phi_D \left(\frac{100s}{s+100} U_s(s), \alpha_D, \delta_D \right) \quad (3.8)$$

The three nonlinear functions (Φ_{P-NPDF} , Φ_{I-NPDF} and Φ_{D-NPDF}) are defined by Equation 1.8.

3.2.5 FSMC for Elevators B and C

The architecture of the GA-tuned FSMC is illustrated in Figure 3.7, with the equations defining the structure of the controller derived from Equation 3.9 onwards.

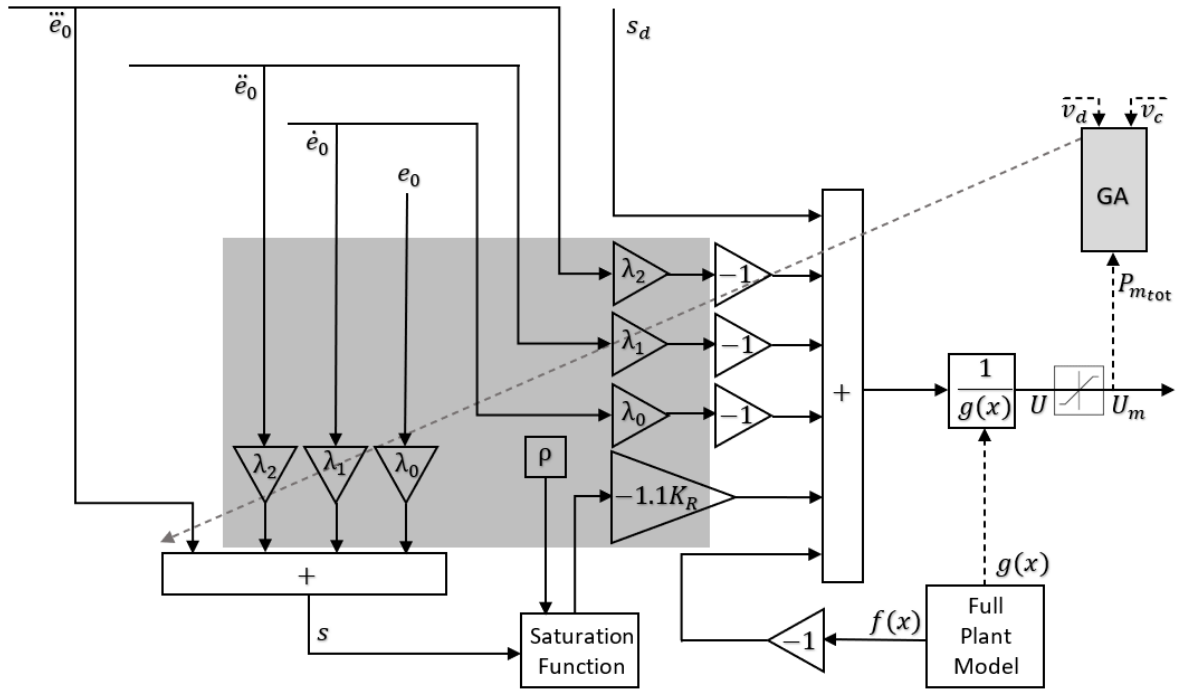


Figure 3.7: GA-tuned full sliding mode controller architecture

The third-order equation derived in Equation 2.122 is written in the form of Equation 1.9:

$$\begin{aligned}
x_1 &= h(x) = d_c \\
\dot{x}_1 &= x_2 = v_c \\
\dot{x}_2 &= x_3 = \dot{v}_c \\
\dot{x}_3 &= x_4 = \ddot{v}_c \\
\dot{x}_4 &= \ddot{\ddot{v}}_c = f(x) + g(x)U + \Delta b(x) \\
&= -\left(A_f k_c + C_f \dot{c}_c - (B_f D_f + C_f^2) c_c^2\right) \dot{v}_c - \left(A_f \dot{k}_c - C_f \ddot{c}_c - (3B_f D_f + 2C_f^2) \dot{c}_c c_c\right. \\
&\quad \left.- A_f D_f M_f c_c k_c + (B_f D_f F_f c_c + B_f C_f D_f) c_c^2 + B_f D_f F_f c_c^2 c_w\right) v_c \\
&\quad - B_f E_f c_c c_w \dot{v}_w - \left(2B_f E_f \dot{c}_c c_w + B_f E_f c_c \dot{c}_w\right. \\
&\quad \left.+ A_f E_f M_f c_w k_c - (B_f E_f F_f c_c + B_f C_f E_f) c_c c_w - B_f E_f F_f c_c c_w^2\right) v_w \\
&\quad + \left(A_f \dot{k}_c - (B_f G_f + A_f C_f) c_c k_c\right) \dot{x}_c + \left(A_f \ddot{k}_c - (2B_f G_f + A_f C_f) \dot{c}_c k_c\right. \\
&\quad \left.- (B_f G_f + A_f C_f) c_c \dot{k}_c\right. \\
&\quad \left.- A_f G_f M_f k_c^2 + (B_f F_f G_f c_c + B_f C_f G_f) c_c k_c + B_f F_f G_f c_c c_w k_c\right) x_c \\
&\quad + B_f H_F c_c k_w \dot{x}_w + \left(B_f H_F c_c \dot{k}_w + 2B_f H_f \dot{c}_c\right. \\
&\quad \left.+ A_f H_f M_f k_c k_w - (B_f F_f H_f c_c + B_f C_f H_f) c_c k_w - B_f F_f H_f c_c c_w k_w\right) x_w \\
&\quad + \left(2B_f I_f \dot{c}_c + A_f I_f M_f k_c - (B_f F_f I_f c_c + B_f C_f I_f + B_f I_f P_f) c_c - B_f F_f I_f c_c c_w\right) i_m \\
&\quad + \left(A_f M_f \dot{k}_c + B_f \ddot{c}_c - (3B_f F_f + 2B_f C_f) \dot{c}_c c_c - 2B_f F_f \dot{c}_c c_w - B_f F_f c_c \dot{c}_w - B_f I_f O_f c_c\right. \\
&\quad \left.- A_f F_f M_f c_c k_c + (B_f F_f^2 c_c + B_f C_f F_f) c_c^2 + B_f F_f^2 c_c^2 c_w\right. \\
&\quad \left.- A_f F_f M_f c_w k_c + (B_f F_f^2 c_c + B_f C_f F_f) c_c c_w + B_f F_f^2 c_c c_w^2\right) \omega_s \\
&\quad - \text{sign}(\omega_s) \left[\left(\left(A_f K_f M_f k_c + 2B_f K_f \dot{c}_c - (B_f F_f K_f c_c + B_f C_f K_f) c_c - B_f F_f K_f c_c c_w \right) |\omega_s|^{\frac{2}{3}} \right. \right. \\
&\quad \left. \left. + \left(A_f L_f M_f k_c + 2B_f L_f \dot{c}_c - (B_f F_f L_f c_c + B_f C_f L_f) c_c - B_f F_f L_f c_c c_w \right) |\omega_s| \right. \right. \\
&\quad \left. \left. + \left(\frac{2B_f D_f K_f}{3} c_c^2 \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_f D_f L_f c_c^2 \frac{\omega_s}{|\omega_s|} \right) v_c \right]
\end{aligned} \tag{3.9}$$

$$\begin{aligned}
& - \left(\frac{2B_f E_f K_f}{3} c_c c_w \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_f E_f L_f c_c c_w \frac{\omega_s}{|\omega_s|} \right) v_w \\
& - \left(\frac{2B_f G_f K_f}{3} c_c k_c \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_f G_f L_f c_c k_c \frac{\omega_s}{|\omega_s|} \right) x_c \\
& + \left(\frac{2B_f H_f K_f}{3} c_c k_w \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_f H_f L_f c_c k_w \frac{\omega_s}{|\omega_s|} \right) x_w \\
& + \left(\frac{2B_f I_f K_f}{3} c_c \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_f I_f L_f c_c \frac{\omega_s}{|\omega_s|} \right) i_m \\
& - \left(\frac{2B_f F_f K_f}{3} c_c^2 \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_f F_f L_f c_c^2 \frac{\omega_s}{|\omega_s|} + \frac{2B_f F_f K_f}{3} c_c c_w \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_f F_f L_f c_c c_w \frac{\omega_s}{|\omega_s|} \right) \omega_s \\
& - \text{sign}(\omega_s) \left(\frac{2B_f K_f^2}{3} c_c \frac{\omega_s}{|\omega_s|^{\frac{2}{3}}} + \left(\frac{2B_f K_f L_f}{3} + B_f K_f L_f \right) c_c \frac{\omega_s}{|\omega_s|^{\frac{1}{3}}} + B_f L_f^2 c_c \omega_s \right) \Bigg] \\
& + B_f I_f N_f c_c U_m + B_f J_f c_c \dot{T}_d + \left(A_f J_f M_f k_c + 2B_f J_f \dot{c}_c - (B_f F_f J_f c_c + B_f C_f J_f) c_c \right. \\
& \left. - B_f F_f J_f c_c c_w \right) T_d - \text{sign}(\omega_s) \left(\left(\frac{2B_f J_f K_f}{3} c_c \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_f J_f L_f c_c \frac{\omega_s}{|\omega_s|} \right) T_d \right)
\end{aligned}$$

As can be seen in [Equation 3.9](#), the system has a relative degree of $r = 4$. Therefore, the sliding mode function takes the form [\[43\]](#):

$$s = \ddot{e}_0 + \lambda_2 \dot{e}_0 + \lambda_1 e_0 + \lambda_0 e_0 \quad (3.10)$$

where λ_2, λ_1 and $\lambda_0 > 0$ in order to satisfy the Hurwitz condition.

The tracking error and its derivatives are calculated:

$$e_0 = d_c - d_d \quad (3.11)$$

$$\dot{e}_0 = v_c - v_d \quad (3.12)$$

$$\ddot{e}_0 = \dot{v}_c - a_d \quad (3.13)$$

$$\ddot{\dot{e}}_0 = \ddot{v}_c - \dot{a}_d \quad (3.14)$$

The sliding mode control law, as defined in [Equation 1.11](#), can now be designed as follows:

$$U = \frac{1}{\mathcal{L}_g \mathcal{L}_f^3 h(x)} \left(s_d - \mathcal{L}_f^4 h(x) - \lambda_2 \ddot{e}_0 - \lambda_1 \dot{e}_0 - \lambda_0 e_0 - 1.1 K_R \text{sat}(s) \right) \quad (3.15)$$

The Lie derivatives of $h(x)$ along the vector $f(x)$ are taken:

$$\begin{aligned}
\mathcal{L}_f(x_1) &= \left(\frac{\partial x_1}{\partial x_1}, \frac{\partial x_1}{\partial x_2}, \frac{\partial x_1}{\partial x_3}, \frac{\partial x_1}{\partial x_4} \right) \cdot (x_2, x_3, x_4, f(x)) = (1, 0, 0, 0) \cdot (x_2, x_3, x_4, f(x)) = x_2 \\
\mathcal{L}_f^2(x_1) &= \left(\frac{\partial x_2}{\partial x_1}, \frac{\partial x_2}{\partial x_2}, \frac{\partial x_2}{\partial x_3}, \frac{\partial x_2}{\partial x_4} \right) \cdot (x_2, x_3, x_4, f(x)) = (0, 1, 0, 0) \cdot (x_2, x_3, x_4, f(x)) = x_3 \\
\mathcal{L}_f^3(x_1) &= \left(\frac{\partial x_3}{\partial x_1}, \frac{\partial x_3}{\partial x_2}, \frac{\partial x_3}{\partial x_3}, \frac{\partial x_3}{\partial x_4} \right) \cdot (x_2, x_3, x_4, f(x)) = (0, 0, 1, 0) \cdot (x_2, x_3, x_4, f(x)) = x_4 \\
\mathcal{L}_f^4(x_1) &= \left(\frac{\partial x_4}{\partial x_1}, \frac{\partial x_4}{\partial x_2}, \frac{\partial x_4}{\partial x_3}, \frac{\partial x_4}{\partial x_4} \right) \cdot (x_2, x_3, x_4, f(x)) = (0, 0, 0, 1) \cdot (x_2, x_3, x_4, f(x)) = f(x)
\end{aligned} \tag{3.16}$$

The Lie derivative of $\mathcal{L}_f^3 h(x)$ along $g(x)$ is calculated:

$$\mathcal{L}_g \mathcal{L}_f^3(x_1) = \left(\frac{\partial x_4}{\partial x_1}, \frac{\partial x_4}{\partial x_2}, \frac{\partial x_4}{\partial x_3}, \frac{\partial x_4}{\partial x_4} \right) \cdot (x_2, x_3, x_4, g(x)) = g(x) \tag{3.17}$$

Hence, Equation 3.15 can be written as:

$$U = \frac{1}{g(x)} \left(s_d - f(x) - \lambda_2 \ddot{e}_0 - \lambda_1 \dot{e}_0 - \lambda_0 e_0 - 1.1 K_R \text{sat}(s, \rho) \right) \tag{3.18}$$

Comparing Equation 3.18 with Equation 1.11, the sign function has been replaced with a saturation function. This was done in order to reduce chattering, which could possibly cause the jerk constraint to be exceeded. Additionally, the saturation function parameter ρ is to be tuned during the optimisation process, leaving open the possibility of the algorithm determining that a value of $\rho = 0$ offers the best solution. In this case, the saturation function will replicate the operation of a sign function. An illustration of a typical saturation function may be found in Figure 1.10, with the equation defining the saturation function provided in Equation 1.20 and repeated here:

$$\text{sat}(s, \rho) = \begin{cases} 1, & s > \rho \\ s, & -\rho \leq s \leq \rho \\ -1, & s < -\rho \end{cases}$$

where $\rho > 0$ and has a small value.

The reaching law gain (K_R) must ensure that $\Delta b(x)$ is overcome, however it should not be so large that chattering is induced. The optimisation process must ensure that the rule defined in Equation 1.13, which is repeated below, is maintained:

$$K_R \geq |\Delta b(x)|$$

The Lyapunov function is defined as in Equation 1.18:

$$V = \frac{1}{2} s^2$$

with the time derivative taking the form of Equation 1.19:

$$\dot{V} = s\dot{s}$$

and $\dot{s}$, first described in Equation 1.15, being repeated:

$$\dot{s} = -1.1K_R \text{sign}(s) + \mathcal{L}_{\Delta f}^{(z-1)} h(x)$$

By taking the Lie derivative of $h(x)$ along $\Delta b(x)$ and replacing the sign function with a saturation function, $\dot{s}$ can be defined as:

$$\dot{s} = -1.1K_R \text{sat}(s, \rho) + \Delta b(x) \quad (3.19)$$

The reaching law must guarantee that $\dot{V} < 0$, thereby ensuring that $s \rightarrow 0$ as $t \rightarrow \infty$.

3.2.6 SSMC for Elevators B and C

The configuration of the GA-tuned SSMC is displayed in Figure 3.8, following which the design of the controller is described.

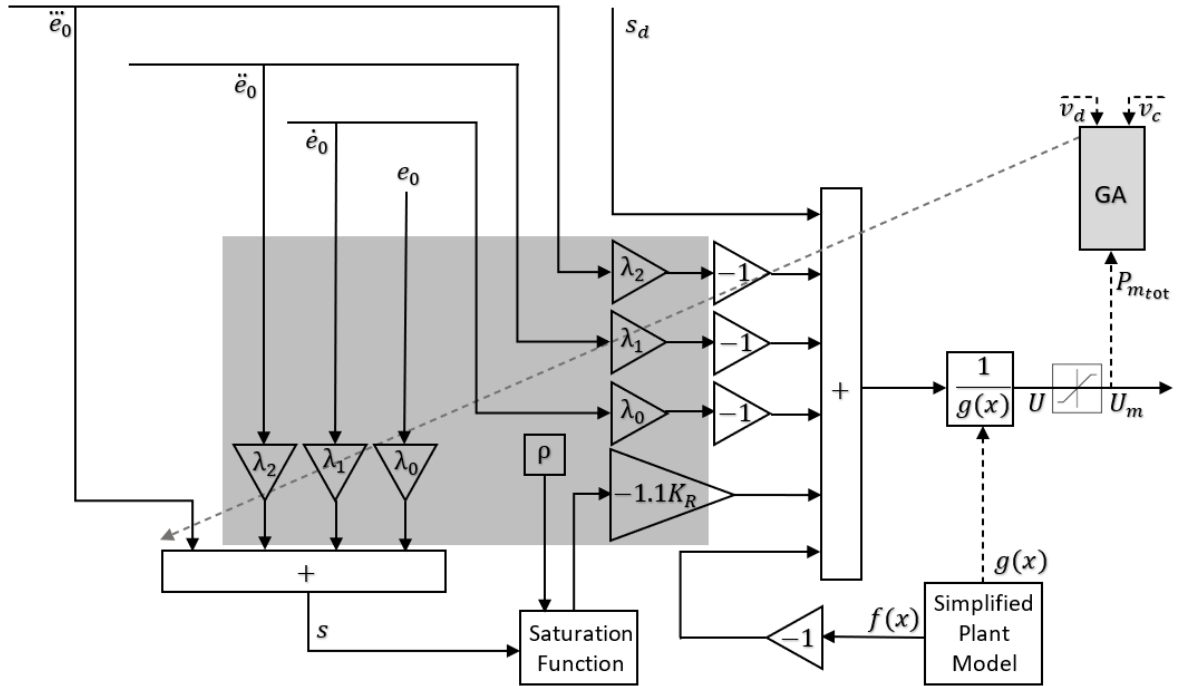


Figure 3.8: GA-tuned simplified sliding mode controller architecture

First and foremost, it is important to clarify the differences between the SSMC and the FSMC. Both control architectures are essentially identical, differing only in the derivations of $f(x)$, $g(x)$ and $\Delta b(x)$. Both controllers control the exact same elevator model, with $f(x)$, $g(x)$ and $\Delta b(x)$ being derived from said model in the FSMC equations; while these terms are taken from a simplified version of the elevator model for the development of the SSMC.

Equations 2.106, 2.105, 2.108 and 2.110 are rewritten, however the values of k_c , k_w , c_c and c_w are assumed to be constant, hence the simplification:

$$\dot{v}_c = A_s x_c + B_s \omega_s - C_s v_c \quad (3.20)$$

$$\begin{aligned} \dot{\omega}_s = & D_s v_c - E_s v_w - F_s \omega_s - G_s x_c + H_s x_w + I_s i_m + J_s T_d \\ & - \text{sign}(\omega_s) \left(K_s |\omega_s|^{\frac{2}{3}} + L_s |\omega_s| \right) \end{aligned} \quad (3.21)$$

$$\dot{x}_c = M_s \omega_s - v_c \quad (3.22)$$

$$\frac{d}{dt} i_m = N_s U_m - O_s \omega_s - P_s i_m \quad (3.23)$$

where $A_s = \frac{k_c}{m_c + p_c}$, $B_s = \frac{c_c r}{m_c + p_c}$, $C_s = \frac{c_c}{m_c + p_c}$, $D_s = \frac{c_c r}{J_p}$, $E_s = \frac{c_w r}{J_p}$,
 $F_s = \frac{(c_c + c_w) r^2}{J_p}$, $G_s = \frac{k_c r}{J_p}$, $H_s = \frac{k_w r}{J_p}$, $I_s = \frac{n K_T}{J_p}$, $J_s = \frac{n}{J_p}$,
 $K_s = \frac{c_{bd}}{J_p}$, $L_s = \frac{c_m}{J_p}$, $M_s = r$, $N_s = \frac{1}{L}$, $O_s = \frac{n K_e}{L}$,
 $P_s = \frac{R}{L}$.

Differentiating Equation 3.20, substituting in Equations 3.21 and 3.22, multiplying through, rearranging and factorising results in the following second-order equation:

$$\begin{aligned} \ddot{v}_c = & - \left(A_s - B_s D_s - C_s^2 \right) v_c - B_s E_s v_w - \left(A_s C_s + B_s G_s \right) x_c + B_s H_s x_w \\ & + \left(A_s M_s - B_s F_s - B_s C_s \right) \omega_s - \text{sign}(\omega_s) \left(B_s K_s |\omega_s|^{\frac{2}{3}} + B_s L_s |\omega_s| \right) + B_s I_s i_m + B_s J_s T_d \end{aligned} \quad (3.24)$$

Equation 3.24 can then be differentiated, before Equations 3.21 and 3.23 are substituted in to obtain the following equation:

$$\begin{aligned} \ddot{\ddot{v}}_c = & - \left(A_s - B_s D_s - C_s^2 \right) \dot{v}_c - B_s E_s \dot{v}_w - \left(A_s C_s + B_s G_s \right) \dot{x}_c + B_s H_s \dot{x}_w \\ & + \left(A_s M_s - B_s F_s - B_s C_s \right) \left(D_s v_c - E_s v_w - F_s \omega_s - G_s x_c + H_s x_w + I_s i_m + J_s T_d \right. \\ & \left. - \text{sign}(\omega_s) \left(K_s |\omega_s|^{\frac{2}{3}} + L_s |\omega_s| \right) \right) - \text{sign}(\omega_s) \left(\left(\frac{2 B_s D_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s D_s L_s \frac{\omega_s}{|\omega_s|} \right) v_c \right. \\ & \left. - \left(\frac{2 B_s E_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s E_s L_s \frac{\omega_s}{|\omega_s|} \right) v_w - \left(\frac{2 B_s F_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s F_s L_s \frac{\omega_s}{|\omega_s|} \right) \omega_s \right) \end{aligned} \quad (3.25)$$

$$\begin{aligned}
& - \left(\frac{2B_s G_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s G_s L_s \frac{\omega_s}{|\omega_s|} \right) x_c + \left(\frac{2B_s H_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s H_s L_s \frac{\omega_s}{|\omega_s|} \right) x_w \\
& + \left(\frac{2B_s I_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s I_s L_s \frac{\omega_s}{|\omega_s|} \right) i_m + \left(\frac{2B_s J_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s J_s L_s \frac{\omega_s}{|\omega_s|} \right) T_d \\
& - \text{sign}(\omega_s) \left(\frac{2B_s K_s^2}{3} \frac{\omega_s}{|\omega_s|^{\frac{2}{3}}} + \left(\frac{2B_s K_s L_s}{3} + B_s K_s L_s \right) \frac{\omega_s}{|\omega_s|^{\frac{1}{3}}} + B_s L_s^2 \omega_s \right) \\
& + B_s I_s N_s U_m - B_s I_s O_s \omega_s - B_s I_s P_s i_m + B_s J_s \dot{T}_d
\end{aligned}$$

Equation 3.25 can then be rearranged and factorised in order to obtain the final form of the third-order equation:

$$\begin{aligned}
\ddot{v}_c = & - \left(A_s - B_s D_s - C_s^2 \right) \dot{v}_c + \left(A_s D_s M_s - B_s D_s F_s - B_s C_s D_s \right) v_c - B_s E_s \dot{v}_w \\
& - \left(A_s E_s M_s - B_s E_s F_s - B_s C_s E_s \right) v_w - \left(A_s C_s + B_s G_s \right) \dot{x}_c \\
& - \left(A_s G_s M_s - B_s F_s G_s - B_s C_s G_s \right) x_c + B_s H_s \dot{x}_w + \left(A_s H_s M_s - B_s F_s H_s - B_s C_s H_s \right) x_w \\
& + \left(A_s I_s M_s - B_s F_s I_s - B_s C_s I_s - B_s I_s P_s \right) i_m - \left(A_s F_s M_s - B_s F_s^2 - B_s C_s F_s + B_s I_s O_s \right) \omega_s \\
& - \text{sign}(\omega_s) \left(\left(A_s K_s M_s - B_s F_s K_s - B_s C_s K_s \right) |\omega_s|^{\frac{2}{3}} + \left(A_s L_s M_s - B_s F_s L_s - B_s C_s L_s \right) |\omega_s| \right. \\
& + \left. \left(\frac{2B_s D_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s D_s L_s \frac{\omega_s}{|\omega_s|} \right) v_c - \left(\frac{2B_s E_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s E_s L_s \frac{\omega_s}{|\omega_s|} \right) v_w \right. \\
& - \left. \left(\frac{2B_s G_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s G_s L_s \frac{\omega_s}{|\omega_s|} \right) x_c + \left(\frac{2B_s H_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s H_s L_s \frac{\omega_s}{|\omega_s|} \right) x_w \right. \\
& + \left. \left(\frac{2B_s I_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s I_s L_s \frac{\omega_s}{|\omega_s|} \right) i_m - \left(\frac{2B_s F_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s F_s L_s \frac{\omega_s}{|\omega_s|} \right) \omega_s \right. \\
& - \left. \text{sign}(\omega_s) \left(\frac{2B_s K_s^2}{3} \frac{\omega_s}{|\omega_s|^{\frac{2}{3}}} + \left(\frac{2B_s K_s L_s}{3} + B_s K_s L_s \right) \frac{\omega_s}{|\omega_s|^{\frac{1}{3}}} + B_s L_s^2 \omega_s \right) \right) \\
& + B_s I_s N_s U_m + B_s J_s \dot{T}_d + \left(A_s J_s M_s - B_s F_s J_s - B_s C_s J_s \right) T_d \\
& - \text{sign}(\omega_s) \left(\left(\frac{2B_s J_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s J_s L_s \frac{\omega_s}{|\omega_s|} \right) T_d \right)
\end{aligned} \tag{3.26}$$

Hence, the model can be defined in standard state-space form as:

$$\begin{aligned}
x_1 &= h(x) = d_c \\
\dot{x}_1 &= x_2 = v_c \\
\dot{x}_2 &= x_3 = \dot{v}_c \\
\dot{x}_3 &= x_4 = \ddot{v}_c \\
\dot{x}_4 &= \ddot{v}_c = f(x) + g(x)U + \Delta b(x) \\
&= -\left(A_s - B_s D_s - C_s^2\right) \dot{v}_c + \left(A_s D_s M_s - B_s D_s F_s - B_s C_s D_s\right) v_c - B_s E_s \dot{v}_w \\
&\quad - \left(A_s E_s M_s - B_s E_s F_s - B_s C_s E_s\right) v_w - \left(A_s C_s + B_s G_s\right) \dot{x}_c \\
&\quad - \left(A_s G_s M_s - B_s F_s G_s - B_s C_s G_s\right) x_c + B_s H_s \dot{x}_w + \left(A_s H_s M_s - B_s F_s H_s - B_s C_s H_s\right) x_w \\
&\quad + \left(A_s I_s M_s - B_s F_s I_s - B_s C_s I_s - B_s I_s P_s\right) i_m - \left(A_s F_s M_s - B_s F_s^2 - B_s C_s F_s + B_s I_s O_s\right) \omega_s \\
&\quad - \text{sign}(\omega_s) \left(\left(A_s K_s M_s - B_s F_s K_s - B_s C_s K_s \right) |\omega_s|^{\frac{2}{3}} + \left(A_s L_s M_s - B_s F_s L_s - B_s C_s L_s \right) |\omega_s| \right. \\
&\quad \left. + \left(\frac{2B_s D_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s D_s L_s \frac{\omega_s}{|\omega_s|} \right) v_c - \left(\frac{2B_s E_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s E_s L_s \frac{\omega_s}{|\omega_s|} \right) v_w \right. \\
&\quad \left. - \left(\frac{2B_s G_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s G_s L_s \frac{\omega_s}{|\omega_s|} \right) x_c + \left(\frac{2B_s H_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s H_s L_s \frac{\omega_s}{|\omega_s|} \right) x_w \right. \\
&\quad \left. + \left(\frac{2B_s I_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s I_s L_s \frac{\omega_s}{|\omega_s|} \right) i_m - \left(\frac{2B_s F_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s F_s L_s \frac{\omega_s}{|\omega_s|} \right) \omega_s \right. \\
&\quad \left. - \text{sign}(\omega_s) \left(\frac{2B_s K_s^2}{3} \frac{\omega_s}{|\omega_s|^{\frac{2}{3}}} + \left(\frac{2B_s K_s L_s}{3} + B_s K_s L_s \right) \frac{\omega_s}{|\omega_s|^{\frac{1}{3}}} + B_s L_s^2 \omega_s \right) \right) \\
&\quad + B_s I_s N_s U_m + B_s J_s \dot{T}_d + \left(A_s J_s M_s - B_s F_s J_s - B_s C_s J_s \right) T_d \\
&\quad - \text{sign}(\omega_s) \left(\left(\frac{2B_s J_s K_s}{3} \frac{\omega_s}{|\omega_s|^{\frac{4}{3}}} + B_s J_s L_s \frac{\omega_s}{|\omega_s|} \right) T_d \right)
\end{aligned} \tag{3.27}$$

The remaining equations defining the SSMC are derived in the same way as the FSMC detailed in Section 3.2.5 and are given below:

$$\begin{aligned}
s &= \ddot{e}_0 + \lambda_2 \ddot{e}_0 + \lambda_1 \dot{e}_0 + \lambda_0 e_0 \\
K_R &\geq |\Delta b(x)| \\
U &= \frac{1}{g(x)} \left(s_d - f(x) - \lambda_2 \ddot{e}_0 - \lambda_1 \dot{e}_0 - \lambda_0 e_0 - 1.1 K_R \text{sat}(s, \rho) \right)
\end{aligned}$$

$$\begin{aligned}
sat(s, \rho) &= \begin{cases} 1, & s > \rho \\ s, & -\rho \leq s \leq \rho \\ -1, & s < -\rho \end{cases} \\
V &= \frac{1}{2}s^2 \\
\dot{V} &= s\dot{s} \\
\dot{s} &= -1.1K_R sat(s, \rho) + \Delta b(x)
\end{aligned}$$

Noting the relatively minimal effect that the sheave damping terms have on the system response, Equation 3.27 can be further simplified by removing the corresponding terms. As such, the dynamic model can be defined as:

$$\begin{aligned}
x_1 &= h(x) = d_c \\
\dot{x}_1 &= x_2 = v_c \\
\dot{x}_2 &= x_3 = \dot{v}_c \\
\dot{x}_3 &= x_4 = \ddot{v}_c \\
\dot{x}_4 &= \ddot{v}_c = f(x) + g(x)U + \Delta b(x) \\
&= -\left(A_s - B_s D_s - C_s^2\right)\dot{v}_c + \left(A_s D_s M_s - B_s D_s F_s - B_s C_s D_s\right)v_c - B_s E_s \dot{v}_w \\
&\quad -\left(A_s E_s M_s - B_s E_s F_s - B_s C_s E_s\right)v_w - \left(A_s C_s + B_s G_s\right)\dot{x}_c \\
&\quad -\left(A_s G_s M_s - B_s F_s G_s - B_s C_s G_s\right)x_c + B_s H_s \dot{x}_w + \left(A_s H_s M_s - B_s F_s H_s - B_s C_s H_s\right)x_w \\
&\quad + \left(A_s I_s M_s - B_s F_s I_s - B_s C_s I_s - B_s I_s P_s\right)i_m - \left(A_s F_s M_s - B_s F_s^2 - B_s C_s F_s + B_s I_s O_s\right)\omega_s \\
&\quad + B_s I_s N_s U_m + B_s J_s \dot{T}_d + \left(A_s J_s M_s - B_s F_s J_s - B_s C_s J_s\right)T_d
\end{aligned} \tag{3.28}$$

These removals can be validated by developing two SSMCs, one defined by the original equation given in Equation 3.27, with the control law of the other derived from the further simplified equation described in Equation 3.28. Both SSMCs will be compared to a FSMC, with all three systems having identical, randomly selected control parameters ($\rho = 0.01$, $K_R = 100$, $\lambda_0 = 100$, $\lambda_1 = 100$ and $\lambda_2 = 100$). The subsequent plots of $f(x)$, $g(x)$ and $\Delta b(x)$ are displayed in Figures 3.9, 3.10 and 3.11, respectively:

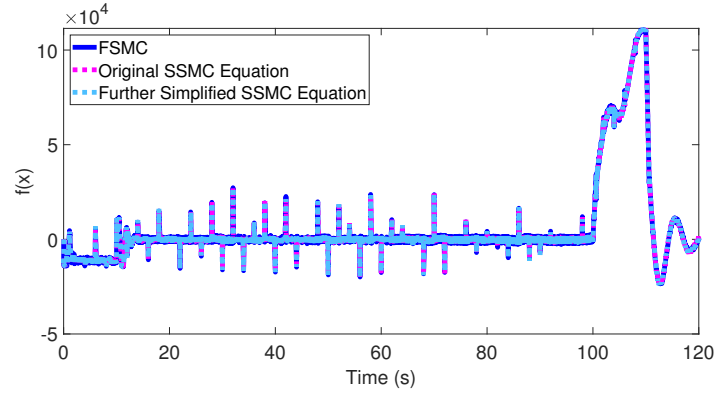


Figure 3.9: Evolution of $f(x)$ during simulation

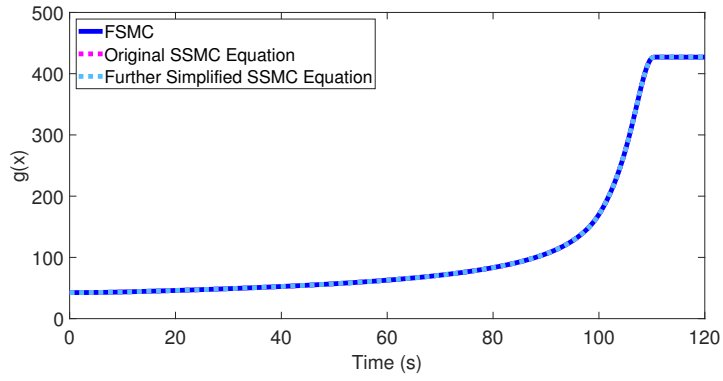


Figure 3.10: Evolution of $g(x)$ during simulation

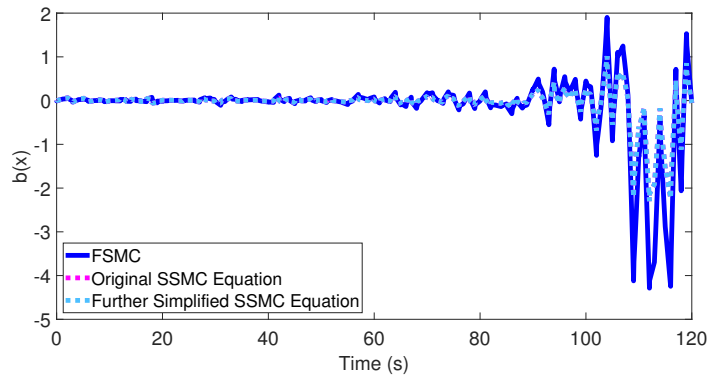


Figure 3.11: Evolution of $\Delta b(x)$ during simulation

In terms of comparing the two SSMCs, it can be seen in Figures 3.9 – 3.11 that both equations result in almost identical responses, with $f(x)$ and $\Delta b(x)$ in the original control law of the SSMC peaking at marginally greater values than the further simplified SSMC. As such, Equation 3.28 is selected as the equation to define the SSMC, with the removal of the sheave damping terms potentially further reducing simulation run time without significantly affecting the system response. It should be noted

that, while this is unlikely to have a significant effect on the run time of an individual simulation, any benefits will accumulate during an optimisation procedure where the model will likely be simulated tens of thousands of times.

With regards to the FSMC, it can be seen in Figure 3.9 that $f(x)$ peaks at marginally higher values than the corresponding SSMCs. $g(x)$ is completely identical for all SMCs, due to the fact that the terms defining the function maintain the following relationship throughout:

$$B_f I_f N_f c_c = B_s I_s N_s \quad (3.29)$$

The main deviation between the full and simplified versions of the controller can be seen in Figure 3.11, with $\Delta b(x)$ of the FSMC being notably larger from $t = 100$ s onwards. $t = 100$ s is the moment that the system begins braking, with the proximity to the top floor causing c_c and k_c to begin rapidly approaching their maximum values. The discrepancy between the responses is not necessarily an issue, as a reaching law gain of $K_R \geq 5$ would be suitable to maintain $K_R \geq |\Delta b(x)|$ for both variants of the controller. Additionally, a factor of safety can be applied to K_R in order to make certain that disturbances are overcome and $s \rightarrow 0$ as $t \rightarrow \infty$.

3.2.7 RBFNN-SMC for Elevator C

The composition of the RBFNN-SMC is shown in Figure 3.12, with the structure of the RBFNN illustrated in Figure 3.13.

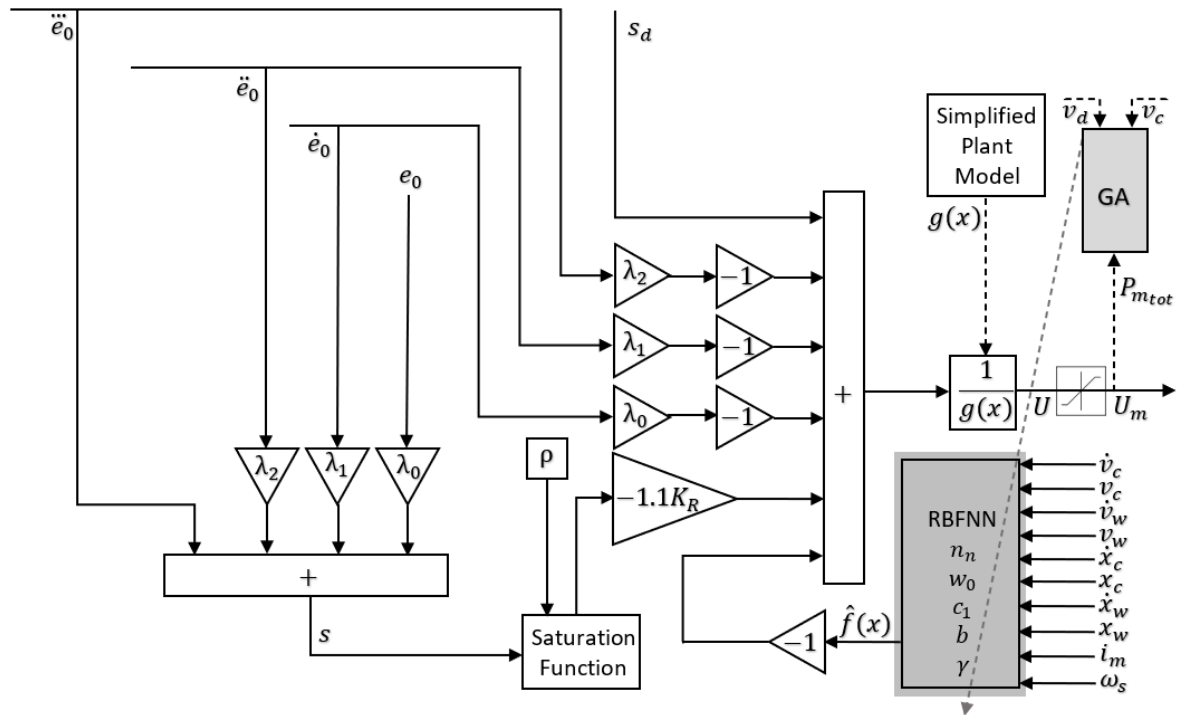


Figure 3.12: GA-tuned RBFNN-SMC architecture

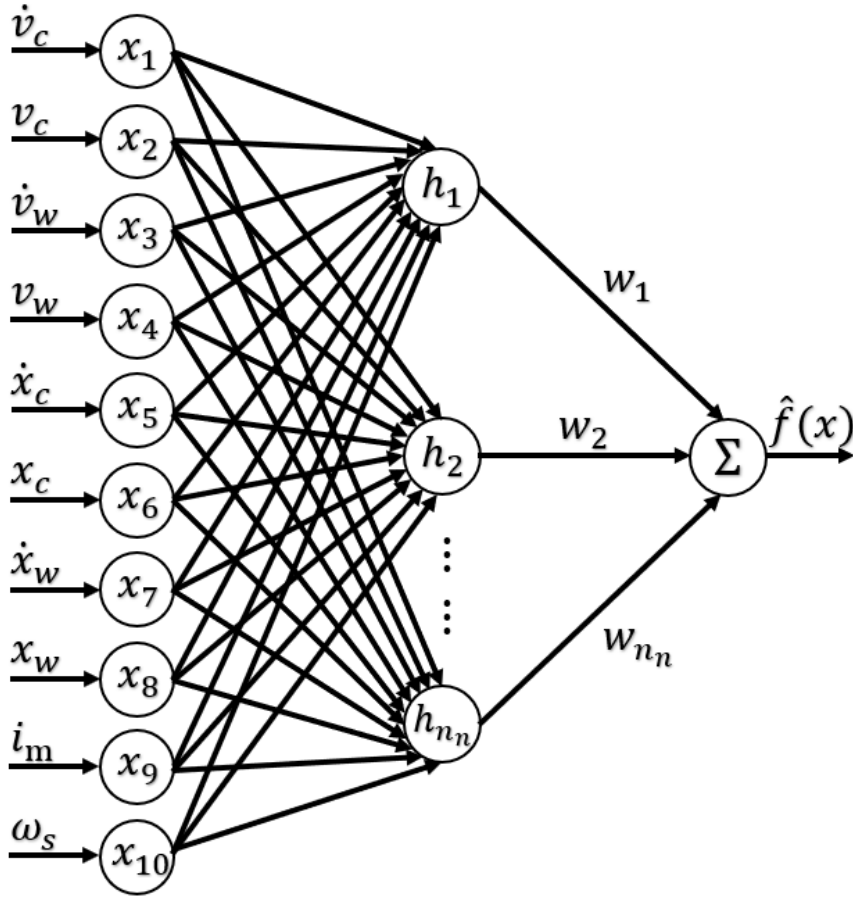


Figure 3.13: Structure of the RBFNN for the RBFNN-SMC

As can be seen in Figure 3.12, the genetic algorithm is used to optimise the initial connection weights of the RBFNN (w_0), as well as the constant parameters of the network such as the number of hidden layer neurons (n_n), the radial centre of the first hidden layer node (c_1), the spread of the radial centres (b) and the adaptive law parameter (γ). Once the number of neurons and first radial centre are defined, the distance between radial centres ($d_{centres}$) can be calculated as:

$$d_{centres} = \frac{2|c_1|}{n_n - 1} \quad (3.30)$$

Hence, the value of the j^{th} radial centre is found as follows:

$$c_j = c_1 + (j - 1)d_{centres} \quad j = 1, 2, \dots, n_n \quad (3.31)$$

Although the connection weight parameters are to be adjusted online according to the adaptive law (to be defined later in this section), the selection of initial weight values could have a noticeable impact on the tracking performance of the controller. Each of the connection weights from w_1 through to w_{n_n} will have their initial value set to w_0 , which must be carefully optimised by the GA.

The SMC parameters (ρ , K_R , λ_0 , λ_1 and λ_2) are obtained from a GA-optimised standard SSMC, with the parameters to be manually adjusted if required. The SSMC is used as the basis for the RBFNN

design, utilising the dynamic model of the controller defined in Equation 3.28. Hence, the inputs to the network are the states $\mathbf{x} = [\dot{v}_c \ v_c \ \dot{v}_w \ v_w \ \dot{x}_c \ x_c \ \dot{x}_w \ x_w \ i_m \ \omega_s]^T$.

The system is written in standard state-space form:

$$\begin{aligned}
 x_1 &= h(x) = d_c \\
 \dot{x}_1 &= x_2 = v_c \\
 \dot{x}_2 &= x_3 = \dot{v}_c \\
 \dot{x}_3 &= x_4 = \ddot{v}_c \\
 \dot{x}_4 &= \ddot{\ddot{v}}_c = f(x) + g(x)U + \Delta b(x) \\
 &= f(x) + B_s I_s N_s U_m + B_s J_s \dot{T}_d + \left(A_s J_s M_s - B_s F_s J_s - B_s C_s J_s \right) T_d
 \end{aligned} \tag{3.32}$$

where $f(x)$ is an unknown nonlinear function to be approximated by the RBFNN and is defined by Equation 1.23, which is repeated here:

$$f(x) = \mathbf{W}^{*T} \mathbf{h}(x) + \epsilon$$

The output of the network displayed in Figure 3.13 takes the form of Equation 1.24:

$$\hat{f}(x) = \hat{\mathbf{W}}^T \mathbf{h}(x)$$

with the j^{th} Gaussian radial activation function (h_j), first described in Equation 1.22, defined by:

$$h_j = \exp\left(-\frac{\|\mathbf{x} - \mathbf{c}_j\|^2}{2b^2}\right)$$

The control law of the RBFNN-SMC is designed:

$$U = \frac{1}{g(x)} \left(s_d - \hat{f}(x) - \lambda_2 \ddot{e}_0 - \lambda_1 \dot{e}_0 - \lambda_0 e_0 - 1.1 K_R \text{sat}(s, \rho) \right) \tag{3.33}$$

The equation defining the sliding mode function takes the same form as Equation 3.10:

$$s = \ddot{e}_0 + \lambda_2 \dot{e}_0 + \lambda_1 e_0 + \lambda_0 e_0$$

while its time derivative, defined in Equation 1.26, can be rewritten as:

$$\dot{s} = -1.1 K_R \text{sat}(\rho, s) + \epsilon + \Delta b(x) - \tilde{\mathbf{W}}^T \mathbf{h}(x) \tag{3.34}$$

where $\tilde{\mathbf{W}} = \hat{\mathbf{W}} - \mathbf{W}^*$.

According to Equation 1.28, the Lyapunov function is defined as:

$$V = \frac{1}{2} s^2 + \frac{1}{2\gamma} \tilde{\mathbf{W}}^T \tilde{\mathbf{W}}$$

hence, $\dot{V}$ takes the form:

$$\dot{V} = -1.1K_R \text{sat}(\rho, s)s + (\epsilon + \Delta b(x))s + \tilde{\mathbf{W}}^T \left(\frac{1}{\gamma} \dot{\tilde{\mathbf{W}}} - s\mathbf{h}(x) \right) \quad (3.35)$$

Finally, the adaptive law is designed as:

$$\dot{\tilde{\mathbf{W}}} = \gamma s \mathbf{h}(x) \quad (3.36)$$

From Equation 3.35, it can be seen that a reaching law gain value of $K_R \geq |\epsilon_{max}| + |\Delta b(x)|$ is required in order to ensure the limitation of the Lyapunov function.

3.3 Controller Performance Specifications

3.3.1 Controller performance specifications for Elevator A

All of the controllers for Elevator A must meet the following performance requirements and constraints [81] [89] [90]:

- The elevator car must reach a steady-state speed of 10 (± 0.05) m/s.
- The elevator car may not accelerate faster than the maximum allowable acceleration ($\dot{v}_{c_{max-A}}$) of 1.1 m/s² at any point during operation.
- The cabin occupants may not experience a jerk in excess of the maximum allowable jerk ($\ddot{v}_{c_{max-A}}$) of 1.7 m/s³ at any point of travel
- The elevator cabin must stop within 0.1 m of the target destination.
- The elevator cabin must arrive within 65 s.
- The total motor voltage may not exceed 810 V at any point during operation of the 3200 kg cabin. The total motor voltage may not exceed 891 V (+10% of the rated motor voltage [91]) for an overloaded cabin.
- The 5% – 95% rise time to steady-state velocity may not exceed 9 s.
- The settling time to steady-state velocity may not exceed 12 s.
- The velocity overshoot in transitioning from acceleration to steady-state velocity may not exceed 1%.

In addition to these quantitative performance specifications, the effectiveness of the control systems will be evaluated qualitatively using the following cost function (J_A):

$$J_A = \frac{\xi_{J-A}}{t_{sim}} \int_0^{t_{sim}} \left[\beta_{J-A} (v_d - v_c)^2 + \gamma_{J-A} (d_d - d_c)^2 + \epsilon_{J-A} \left(\frac{\dot{v}_c}{\dot{v}_{cL-A}} \right)^2 + \eta_{J-A} \left(\frac{\ddot{v}_c}{\ddot{v}_{cL-A}} \right)^2 + \kappa_{J-A} \left(\frac{P_{m_{tot}}}{P_{R-A}} \right)^2 \right] dt \quad (3.37)$$

where t_{sim} is the simulation run time [s], $\dot{v}_{cL-A}$ is the ideal maximum Elevator A cabin acceleration [1 m/s²], $\ddot{v}_{cL-A}$ is the ideal maximum Elevator A cabin jerk [1.6 m/s³], $P_{m_{tot}}$ is the total power consumption of the motor [kW] and P_{R-A} is the rated power consumption of the motor of Elevator A [729 kW].

The terms in the integrand of J_A relate to tracking of the velocity setpoint, tracking of the car displacement, minimisation of the experienced acceleration, jerk and power consumption, respectively. As GA-optimisation mimics natural selection, the cost function is converted into a fitness function for the optimisation procedure to represent "survival of the fittest":

$$F_A = J_A^{-1} \quad (3.38)$$

A number of weighting factors are present in Equation 3.37 and can be customised depending on whether performance, ride comfort, power consumption or a combination of any of the above are prioritised. β_{J-A} is the velocity tracking weighting factor for Elevator A, γ_{J-A} is the displacement tracking weighting factor for Elevator A, ϵ_{J-A} is the acceleration minimisation weighting factor for Elevator A, η_{J-A} is the jerk minimisation weighting factor for Elevator A and κ_{J-A} is the power consumption minimisation weighting factor for Elevator A. The term ξ_{J-A} is not a weighting factor, but rather an arbitrary constant used to ensure that the fitness is output at a manageable value. For example, it is easier to visually compare fitness values of $F = 534.428$ and $F = 50.601$ than it is to compare values of $F = 0.0000534428$ and $F = 0.0000050601$. As such, a suitable ξ_{J-A} value is selected to ensure this conversion, with the specific value being directly dependent on the selection of the chosen weighting factors. Should the solution fail to meet any of the performance requirements or constraints, ξ_{J-A} will be divided by a value of 1×10^{10} , ensuring that the solution is unequivocally recorded as being unfit.

For control of Elevator A, performance is prioritised. Hence, the corresponding cost function parameters are defined in Table 3.1.

Table 3.1: Cost function parameters for evaluation of the controllers for Elevator A

Parameter	Value
β_{J-A}	10000
γ_{J-A}	10000
ϵ_{J-A}	1
η_{J-A}	1
κ_{J-A}	1
ξ_{J-A}	1e-07

Additionally, it must be noted that $\dot{v}_{c_{L-A}}$ and $\ddot{v}_{c_{L-A}}$, respectively defined as the **ideal** maximum acceleration and jerk values, are not the same as the **absolute** maximum acceleration ($\dot{v}_{c_{max-A}}$) and jerk ($\ddot{v}_{c_{max-A}}$) values. As seen in Equation 3.37, should the **ideal** maximum values be exceeded during simulation, this would result in a reduction of the fitness value. While such an occurrence would be undesirable, it would not be grounds for failure of the solution. On the other hand, should the **absolute** maximum jerk and/or acceleration limits be exceeded at any point, the solution will immediately be deemed to have failed.

3.3.2 Controller performance specifications for Elevators B and C

All of the developed controllers for Elevators B and C must meet the following performance requirements and constraints. [81] [89] [90]:

- The elevator car must reach a steady-state speed of 10 (± 0.05) m/s.
- The elevator car may not accelerate faster than the absolute maximum acceleration ($\dot{v}_{c_{max-B}}/\dot{v}_{c_{max-C}}$) of 1.5 m/s² at any point during operation.
- The cabin occupants may not experience a jerk in excess of the absolute maximum jerk ($\ddot{v}_{c_{max-B}}/\ddot{v}_{c_{max-C}}$) of 1.7 m/s³ at any point of travel.
- The elevator cabin must settle within 0.1 m of the target destination (without the need for re-levelling).
- The elevator cabin may not travel further than 0.1 m beyond the target destination at any point, even if the car subsequently returns to within 0.1 m of its destination.
- The actual arrival time of the cabin ($t_{arrival}$) should not be later than 5 seconds after the scheduled arrival (t_{sched}). Actual arrival time is defined as the moment that the actual cabin is within 0.1 m of the destination, while the scheduled arrival time is defined as the moment that the

setpoint cabin would arrive to 100% accuracy. The scheduled arrival time is dependent on the travel distance of the elevator, with the times for every possible travel scenario provided in [Table 3.2](#).

Table 3.2: Scheduled elevator arrival times (t_{sched})

Travel Distance [m]	Scheduled Arrival Time (t_{sched}) [s]
100	20
200	30
300	40
400	50
500	60
600	70
700	80
800	90
900	100
1000	110

- The time to door-open should not be later than 7 seconds after t_{sched} . Door-open is defined as the moment that the cabin both reaches and subsequently settles within 3 mm of the arrival floor following the re-levelling procedure. It is important to note that this requirement applies only to Elevator C, as re-levelling will not be applied to Elevator B.
- Starting 5 seconds after the scheduled arrival, the cabin occupants must not experience a jerk in excess of 0.17 m/s^3 (10% of $\ddot{v}_{c_{max-B}}$ and $\ddot{v}_{c_{max-C}}$). The jerk response after this time is defined as end jerk (EJ).
- The total motor voltage may not exceed the rated motor voltage of 440 V for a cabin mass lower than or equal to the standard mass of 3200 kg. For an overloaded cabin less than or equal to 25% over the rated occupancy (i.e., a total cabin mass of 3600 kg), a maximum total motor voltage of 484 V (+10% of the rated voltage) is acceptable. For a cabin mass beyond 3600 kg, the maximum total motor voltage should not exceed 20% of the rated voltage. While the subsequent current through the motor at a voltage of 528 V would likely damage the motor over a prolonged period of time; such a scenario would generally only occur in the infrequent event of an evacuation procedure. For clarity, the cabin mass-dependent motor voltage specifications are detailed in [Table 3.3](#).

Table 3.3: Maximum allowable motor voltage

Cabin Mass [kg]	Maximum Motor Voltage [V]
$1600 \leq m_c \leq 3200$	440
$3200 < m_c \leq 3600$	484
$3600 < m_c$	528

- The 5% – 95% rise time to steady-state velocity may not exceed 11 s.
- The settling time to steady-state velocity may not exceed 15 s.
- The maximum allowable velocity overshoot in transitioning to steady-state velocity is 1%.

The cost function for GA-optimisation of the controllers for Elevator B is defined:

$$J_B = \frac{\xi_{J-B}}{t_{sim}} \int_0^{t_{sim}} \left[\beta_{J-B} (v_d - v_c)^2 + \gamma_{J-B} (d_d - d_c)^2 + \epsilon_{J-B} \left(\frac{\dot{v}_c}{\dot{v}_{cL-B}} \right)^2 + \eta_{J-B} \left(\frac{\ddot{v}_c}{\ddot{v}_{cL-B}} \right)^2 + \kappa_{J-B} \left(\frac{P_{m_{tot}}}{P_{R-B}} \right)^2 \right] dt \quad (3.39)$$

where $\dot{v}_{cL-B}$ is the ideal maximum Elevator B cabin acceleration [1.1 m/s²], $\ddot{v}_{cL-B}$ is the ideal maximum Elevator B cabin jerk [1.6 m/s³] and P_{R-B} is the rated power consumption of the motor of Elevator B [351 kW].

The cost function can then be converted into a fitness function (F_B) as follows:

$$F_B = J_B^{-1} \quad (3.40)$$

Due to the implementation of a more powerful motor compared to Elevator B, the cost function (J_C) for optimisation of the controllers for Elevator C takes the form:

$$J_C = \frac{\xi_{J-C}}{t_{sim}} \int_0^{t_{sim}} \left[\beta_{J-C} (v_d - v_c)^2 + \gamma_{J-C} (d_d - d_c)^2 + \epsilon_{J-C} \left(\frac{\dot{v}_c}{\dot{v}_{cL-C}} \right)^2 + \eta_{J-C} \left(\frac{\ddot{v}_c}{\ddot{v}_{cL-C}} \right)^2 + \kappa_{J-C} \left(\frac{P_{m_{tot}}}{P_{R-C}} \right)^2 \right] dt \quad (3.41)$$

where P_{R-C} is the rated power consumption of the motor of Elevator C [601 kW].

The fitness function (F_C) is then computed using:

$$F_C = J_C^{-1} \quad (3.42)$$

Noting that the controllers for Elevator C will be evaluated using a performance-oriented fitness function, the cost function parameters are defined as follows:

Table 3.4: Cost function parameters for evaluation of the controllers for Elevator C

Parameter	Value
β_{J-C}	10000
γ_{J-C}	10000
ϵ_{J-C}	1
η_{J-C}	1
κ_{J-C}	1
ξ_{J-C}	1e-04

As mentioned in Section 2.11.2, each of the CPID, CPDF, NPID and NPDF controllers will have two variants for an initial comparison; one utilising the simple velocity setpoint signal defined in Equation 2.135, with the other controlling the system to track the exact velocity setpoint signal given in Equation 2.139. In order to properly compare these eight controllers, in addition to the two versions of the SMCs, v_d and d_d in J_B and J_C will always be calculated from the exact velocity setpoint signal (Equation 2.139), regardless of the setpoint used for control.

An important aspect to note with regards to the displacement term in the cost functions (J_B and J_C) is that it is evaluated only from the point that the cabin is deemed to have arrived (i.e., the cabin is within 0.1 m of the target destination). This is due to the fact that the displacement tracking of the cabin throughout the majority of the journey is essentially meaningless; with the important factors being how quickly it reaches the destination and the accuracy of the arrival. Until the elevator has arrived, the term is set as $|d_d - d_c| = 0.1$ m, with the actual value only being calculated once $|d_d - d_c| < 0.1$ m. This ensures that the term will prioritise solutions that arrive earlier and closer to the target destination.

3.3.2.1 Controller robustness specifications for Elevators B and C

In order to evaluate the sensitivity of the controllers to parameter variations, numerous robustness assessment simulations will be performed; wherein travel distance, travel direction and cabin mass are to be varied. Despite the elevators being express elevators that stop at only 11 floors, there are still 110 possible trips that each elevator can make. Ten of these trips have been selected for the robustness analysis, encompassing a wide range of travel distances and starting heights. This information is summarised in Table 3.5 and illustrated in Figure 3.14.

Table 3.5: Elevator travel distance information for robustness analysis

Travel Distance [m]	Starting Height (Above Ground) [m]	Arrival Height (Above Ground) [m]
200	400	600
400	300	700
600	200	800
800	100	900
1000	0	1000
-1000	1000	0
-800	900	100
-600	800	200
-400	700	300
-200	600	400

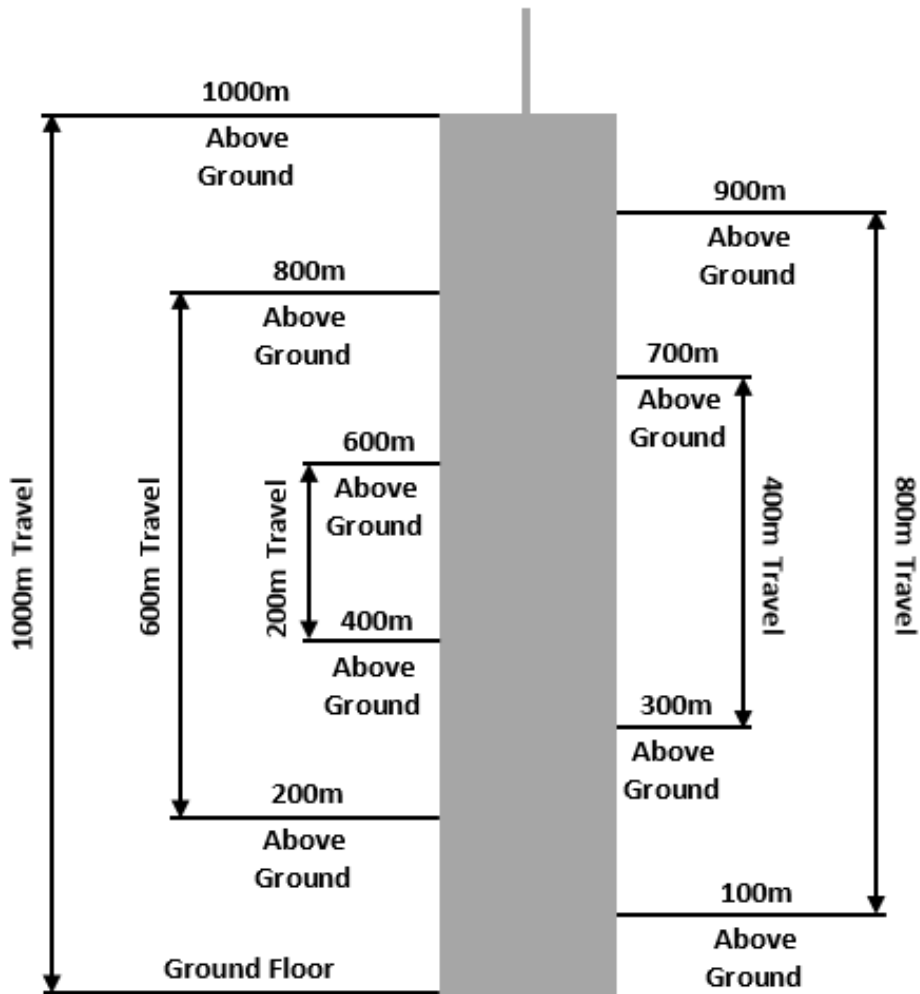


Figure 3.14: Illustration of elevator travel for robustness analysis

In addition to the analyses of multiple travel procedures, each of the controllers will be assessed on their ability to account for fluctuations in the cabin mass. Five cabin masses will be considered, the details of which are provided in [Table 3.6](#).

Table 3.6: Cabin occupancy information for robustness analysis

Cabin Occupancy [%]	Approximate Number of Occupants	Mass of Occupants [kg]	Total Cabin Mass [kg]
0	0	0	1600
50	11	800	2400
100	21	1600	3200
125	26	2000	3600
150	32	2400	4000

This is a suitable array of potential cabin masses; ranging from an empty cabin to the theoretical scenario of a cabin that is 50% over the maximum rated load. This is likely the physical occupancy limit for the elevator cabin, considering the area taken up by the average adult human [92].

The controllers will be evaluated on their ability to meet the performance requirements and constraints for every combination of travel distance, direction and cabin mass given in [Tables 3.5](#) and [3.6](#). A colour-coded robustness performance matrix will be generated for each controller, with each cell in the matrix taking the following form:

Table 3.7: Generic example of a robustness performance matrix cell

Cabin Mass	
Travel Distance and Direction	Fitness Function
	Summary of Result

The first line of the cell will display the fitness of the solution, as calculated using either [Equation 3.40](#) or [Equation 3.42](#). The second line will provide a summary of the result; either indicating that the solution met all of the requirements and constraints by displaying 'Pass' as the summary of result, or specifying the most severe failure of the controller. The cell is to be colour-coded to provide a visual summary of the controller performance, with an explanation of the meaning of each colour detailed in [Table 3.8](#). Information relating to the summary of results and quantitative criteria defining the meanings in [Table 3.8](#) may be found in [Table 3.9](#). This includes the corresponding severity rating, which dictates what information is to be displayed in the performance matrix.

Table 3.8: Robustness analysis colour chart

Colour	Meaning	Description
Green	Good Performance	All performance requirements and constraints met.
Yellow	Acceptable Performance	Failures can be easily rectified. Minimal passenger inconvenience. No danger to occupants.
Orange	Poor Performance	Failures can be rectified, but not as easily. Noticeable passenger inconvenience. No danger to occupants.
Red	Unacceptable Performance	Failures cannot be easily rectified. Major passenger inconvenience. Possible safety issue.

Table 3.9: Robustness analysis criteria in the case of failure to meet any of the performance requirements or constraints

Performance Requirement or Constraint Failed	Summary of Result	Acceptable Performance	Severity Rating	Poor Performance	Severity Rating	Unacceptable Performance	Severity Rating
Cabin Jerk [m/s^3]	$J (\max(\ddot{v}_c) - 1.7)$	N/A	N/A	N/A	N/A	$1.7 < \max(\ddot{v}_c)$	6
Cabin Acceleration [m/s^2]	$A (\max(\dot{v}_c) - 1.5)$	N/A	N/A	N/A	N/A	$1.5 < \max(\dot{v}_c)$	6
Cabin Velocity [m/s]	$V (\max(v_c) - 10.05)$	$10.05 < \max(v_c) \leq 10.1$	3	$10.1 < \max(v_c) \leq 10.5$	4	$10.5 < \max(v_c)$	5
Cabin Displacement [m]	$D (\max(d_c) - \max(d_d))$	$0.1 < \max(d_c) - \max(d_d) \leq 0.3$	2	$0.3 < \max(d_c) - \max(d_d) \leq 0.5$	3	$0.5 < \max(d_c) - \max(d_d)$	4
Cabin Arrival Time [s]	$L (t_{arrival} - t_{sched})$	$2 < t_{arrival} - t_{sched} \leq 4$	1	$4 < t_{arrival} - t_{sched} \leq 7$	2	$7 < t_{arrival} - t_{sched}$	3
Cabin End Jerk [m/s^3]	$EJ (\max(EJ) - 0.17)$	$0.17 < \max(EJ) \leq 0.5$	1	$0.5 < \max(EJ) \leq 1$	3	$1 < \max(EJ)$	4

As stipulated in Table 3.9, any failure to meet the jerk and/or acceleration constraints will be deemed as unacceptable control performance. For the case of a solution wherein multiple requirements and/or constraints have not been met, only the failed parameter with the highest severity rating will be indicated. Should any of the parameters have equivalent severity ratings (e.g., a failure to limit both the jerk and acceleration constraints), the matrix will display the parameter that exhibited the worst performance. For example, for the hypothetical case of an elevator (having a cabin mass of 1600 kg, travelling upwards for a distance of 200 m) that experiences a maximum jerk of 10 m/s^3 , a maximum acceleration of 2 m/s^2 and overshoots the target floor by 0.4 m; the corresponding cell of the robustness performance matrix would be expressed as follows:

Table 3.10: Specific example of a robustness performance matrix cell

	1600 kg
200 m	2.34e-09 J (+8.3m/s ³)

3.4 GA-Optimisation

GA is a numerical optimisation algorithm that operates by imitating the process of natural selection. This is achieved by defining the parameters to be optimised as strings that are akin to biological structures. With each iteration, a new set of strings are generated, with each string comprising of parts taken from two strings of the previous generation [93]. Generally, GAs utilise three operations for the production of new generations; namely selection, crossover and mutation. Following completion of the process, the newly developed generation replaces the old and the cycle repeats [33].

3.4.1 Application of GA-optimisation for Elevator A

The four steps used for development of the GA-code are as follows:

Step 1: Initialise

Define the probability of mutation and crossover occurring and set the generation counter to $k_{GA} = 0$. Incorporate the fitness function (F_A) into the GA-code, applying a boolean operator to penalise the solution if any performance requirements and/or constraints are not met. This is achieved by dividing the fitness function by a factor of 1×10^{10} , thereby ensuring that unfit solutions are clearly defined and recorded as such. Generate M_{GA} uniformly distributed random points from the search interval (ψ) of each gain. Store the gains of each generation and their corresponding fitness values in P_{GA} . Store the fittest member of the first generation in the first row of F_{GA} . If a fitter individual emerges, replace row 2 of S_{GA} with row 1 and write the new fittest solution into the top row. For clarity, examples of the

structures of matrices P_{GA} and F_{GA} for optimisation of the K_P , K_I and K_D gains of a CPID controller are provided:

$$P_{GA} = \begin{bmatrix} K_{P_1} & K_{I_1} & K_{D_1} & F_{A_1} \\ K_{P_2} & K_{I_2} & K_{D_2} & F_{A_2} \\ \vdots & \vdots & \vdots & \vdots \\ K_{P_{M-1}} & K_{I_{M-1}} & K_{D_{M-1}} & F_{A_{M-1}} \\ K_{P_M} & K_{I_M} & K_{D_M} & F_{A_M} \end{bmatrix}$$

$$F_{GA} = \begin{bmatrix} K_{P_{fit1}} & K_{I_{fit1}} & K_{D_{fit1}} & F_{A_{fit1}} \\ K_{P_{fit2}} & K_{I_{fit2}} & K_{D_{fit2}} & F_{A_{fit2}} \end{bmatrix}$$

Step 2: Stopping Conditions

Table 3.11: GA-code stopping condition definitions

Stopping Condition	Definition
GA Stopping Condition 1	If the maximum iteration ($k_{GA_{max}}$) is reached, terminate the code.
GA Stopping Condition 2	If the fittest individual does not change after θ_{GA} number of generations, stop the GA if and only if $k_{GA_{min}}$ has been reached.

Step 3: Offspring Generation

Selection: Choose parent points using a fitness-proportional selection operation known as roulette wheel selection. This biases the process to enforce a higher probability of crossover occurring between the fitter individuals in the population.

Crossover: The probability of crossover taking place between the individuals in a parent pair is P_{GA_c} . Generate a random real number (R_{GA_c}) in the range of $0 \leq R_{GA_c} \leq 1$. Perform single-point crossover if and only if $P_{GA_c} \geq R_{GA_c}$. Single-point crossover involves converting all of the base-10 parent genes into strings, cutting a pair of parent strings at a random locus and swapping the tails of the strings. The resulting individuals obtained through crossover (or the lack of it) are termed offspring.

Mutation: The probability of mutation of an element in the offspring genes is P_{GA_m} . Generate a random real number (R_{GA_m}) in the range $0 \leq R_{GA_m} \leq 1$. Execute mutation if and only if $P_{GA_m} \geq R_{GA_m}$. Store all offspring and their corresponding fitnesses as points in matrix O_{GA} , which has the same structure as the parent matrix (P_{GA}).

Step 4: Update the Parent Matrix

Elitism: If the fittest individual in O_{GA} is less fit than the fittest individual in F_{GA} , replace the least fit individual in O_{GA} with the fittest individual in F_{GA} . This process is known as elitism and allows for a

balance between exploration of the search space and the manipulation of discoveries made within the space. This is done in a manner that improves the algorithm speed, without compromising the ability to converge upon the global optimum solution.

Update F_{GA} : If the fittest individual in O_{GA} is a better solution than the first row of F_{GA} , replace the latter with the former. The now former fittest individual is written into the second row of F_{GA} .

Overwrite P_{GA} : Replace the P_{GA} matrix with the O_{GA} matrix, whether or not elitism has transpired.

3.4.2 Application of GA-optimisation for Elevators B and C

The general structure of the GA-code for optimisation of the controllers for Elevators B and C is identical to that described in Section 3.4.1. Two notable adaptations to Step 2 are to be implemented in an attempt to minimise run time.

Step 2: Stopping Conditions

In order to further improve run time, the following adjustment is made to the GA Stopping Condition 2 from Table 3.11.

Table 3.12: Updated definitions of GA-code stopping conditions

Stopping Condition	Old Definition	New Definition
GA Stopping Condition 2	If the fittest individual does not change after θ_{GA} number of generations, stop the GA if and only if $k_{GA_{min}}$ has been reached.	If the fitness of the fittest individual does not increase by more than 0.005% after θ_{GA} number of generations, stop the GA if and only if $k_{GA_{min}}$ has been reached.

Although a value of 0.005% is a seemingly marginal requirement for an assumption of convergence, this adaptation to the stopping condition will prevent the GA from continuing to run due to completely insignificant changes in the fitness value.

In addition to the stopping conditions for the GA-code, numerous simulation stopping conditions are to be implemented. These will initiate a premature termination of the simulation of an individual if any of the requirements and constraints detailed in Section 3.3.2 are not adhered to. Additionally, the simulation will be stopped if it is determined earlier on in the run that the final solution will not be competitive. These additions will ensure a significant reduction in the total run time of the optimisation process. The simulation stopping conditions are presented in Table 3.13.

Table 3.13: Simulation stopping condition definitions for optimisation of the controllers for Elevators B and C

Stopping Condition	Definition
Simulation Stopping Condition 1	If $ v_c > 10.05$ m/s, stop the simulation.
Simulation Stopping Condition 2	If $ \dot{v}_c > 1.5$ m/s ² , stop the simulation.
Simulation Stopping Condition 3	If $ \ddot{v}_c > 1.7$ m/s ³ , stop the simulation.
Simulation Stopping Condition 4	If $t_{sim} \geq t_{sched} + 5$ s and $ \ddot{v}_c > 0.17$ m/s ³ , stop the simulation.
Simulation Stopping Condition 5	If $ d_d - d_c > 0.1$ m after arrival, stop the simulation.
Simulation Stopping Condition 6	If $t_{sim} = 2$ s and $ v_c < 1$ m/s, stop the simulation.
Simulation Stopping Condition 7	If $t_{sim} = 15$ s and $ v_c < 9.95$ m/s, stop the simulation.

It should be noted that the GA-optimisation procedure detailed in Section 3.4.1 prioritises finding the best possible solution for the specific scenario of a 3200 kg cabin travelling upwards. There is the potential that such a solution, while effective for said case, could be particularly inefficient should any of the parameters be varied. The reality of fluctuating elevator parameters must be accounted for during GA-optimisation; however, it would be infeasible to account for a large number of possible occupancy-travel combinations. It is hypothesised that a solution having a high robustness to parameter variations across the board can be achieved simply by considering the four extreme cases; namely, cabins at 0% and 150% of the rated occupancy travelling for 1000 m in both directions. In order to achieve this, an adaptation to the calculation of the fitness functions F_B and F_C is required. Equations 3.40 and 3.42 are represented simply by F:

$$F = [J_{3200-1000-up}]^{-1} \quad (3.43)$$

Following the adaptation, $F_{combined}$ takes the form:

$$F_{combined} = [J_{combined}]^{-1} \quad (3.44)$$

with $J_{combined}$ being calculated using:

$$J_{combined} = 0.6J_{3200-1000-up} + 0.1J_{4000-1000-up} + 0.1J_{1600-1000-up} \\ + 0.1J_{4000-1000-down} + 0.1J_{1600-1000-down} \quad (3.45)$$

where $J_{4000-1000-up}$ is the cost function for a 4000 kg cabin travelling upwards for a distance of 1000 m, $J_{1600-1000-up}$ is the cost function for a 1600 kg cabin travelling upwards for a distance of 1000 m, $J_{4000-1000-down}$ is the cost function for a 4000 kg cabin travelling downwards for a distance of 1000 m and $J_{1600-1000-down}$ is the cost function for a 1600 kg cabin travelling downwards for a distance of 1000 m.

Each of the above cost functions are calculated in the same way as J_B and J_C , taking the same structure as either Equation 3.39 or Equation 3.41, depending on the elevator being controlled. As can be seen

in Equation 3.45, the cost function is calculated in a manner that continues to prioritise optimisation of an elevator having a cabin mass of 3200 kg travelling upwards to the top floor of the building; however, the optimisation process now also accounts for each of the four extreme cabin mass and travel distance combinations. Naturally, the addition of four additional simulations per generation of the GA will significantly increase run time; however, this can be somewhat offset by carefully designing the simulation procedure. The order in which the simulations take place is summarised in Table 3.14 :

Table 3.14: Order of elevator simulations performed within a generation of the GA

Simulation Order	Elevator Parameters
1st Simulation	3200 kg elevator cabin travelling upwards for a distance of 1000 m
2nd Simulation	4000 kg elevator cabin travelling upwards for a distance of 1000 m
3rd Simulation	1600 kg elevator cabin travelling upwards for a distance of 1000 m
4th Simulation	4000 kg elevator cabin travelling downwards for a distance of 1000 m
5th Simulation	1600 kg elevator cabin travelling downwards for a distance of 1000 m

Run time per generation in the GA can be improved by dictating that the code should only proceed to the next simulation if a suitable cost function was recorded during the preceding simulation. As such, rather than five simulations being performed within each iteration every single time, this will only occur for solutions that meet the necessary criteria during the first four simulations. For the 1st simulation, all performance requirements and constraints must be met to proceed. For all subsequent simulations, the criteria for continuation is that at least acceptable performance (as defined in Table 3.9) must be achieved. A generic cost function having a high value (i.e., low fitness) can then be recorded for simulations that do not occur. This process is summarised in Table 3.15, with the calculated cost functions of successful simulations that took place being highlighted in green, while the calculated cost functions of failed simulations that took place are highlighted in orange. The generic cost functions having high values that are applied to skipped simulations that follow failed simulations are highlighted in red.

Table 3.15: Calculation/generation of cost functions during GA-optimisation

Number of Completed Simulations	Number of Successful Simulations	$J_{3200-1000-up}$	$J_{4000-1000-up}$	$J_{1600-1000-up}$	$J_{4000-1000-down}$	$J_{1600-1000-down}$
1	0	$J_{3200-1000-up} \times 10^{10}$	$J_{3200-1000-up} \times 10^4$	$J_{3200-1000-up} \times 10^4$	$J_{3200-1000-up} \times 10^4$	$J_{3200-1000-up} \times 10^4$
2	1	$J_{3200-1000-up}$	$J_{4000-1000-up} \times 10^{10}$	$J_{3200-1000-up} \times 10^3$	$J_{3200-1000-up} \times 10^3$	$J_{3200-1000-up} \times 10^3$
3	2	$J_{3200-1000-up}$	$J_{4000-1000-up}$	$J_{1600-1000-up} \times 10^{10}$	$J_{3200-1000-up} \times 10^2$	$J_{3200-1000-up} \times 10^2$
4	3	$J_{3200-1000-up}$	$J_{4000-1000-up}$	$J_{1600-1000-up}$	$J_{4000-1000-down} \times 10^{10}$	$J_{3200-1000-up} \times 10$
5	4	$J_{3200-1000-up}$	$J_{4000-1000-up}$	$J_{1600-1000-up}$	$J_{4000-1000-down}$	$J_{1600-1000-down} \times 10^{10}$
5	5	$J_{3200-1000-up}$	$J_{4000-1000-up}$	$J_{1600-1000-up}$	$J_{4000-1000-down}$	$J_{1600-1000-down}$

As can be seen, this process will give precedence to solutions that achieve effective control of the highest number of occupancy-travel combinations. The order of the simulations detailed in [Table 3.14](#) is important, with the first simulation relating to operation of a cabin at the rated occupancy, which is the priority for optimisation. An elevator cabin travelling upwards at 150% of the rated load is the second setup for analysis, as this is the most likely configuration to encounter a failure; thereby allowing the GA-code to proceed to the next iteration, improving the run time of the optimisation exercise. An empty elevator cabin travelling upwards is the third setup to be simulated, as a successful simulation for this configuration would ensure suitable control of each of the cabin masses travelling in this direction. For the elevator cars travelling downwards, the 4000 kg car is simulated first, in the hopes of improving run time should the simulation fail.

4 Numerical Simulations for Control of Elevator A

4.1 Chapter Outline

Control of Elevator A using CPID, CPDF, NPID and NPDF control is examined in this chapter. Firstly, the GA-parameters for optimisation of each of the controllers are provided. The repeatability of the obtained solutions is then analysed by performing ten independent optimisation runs for each controller, following which the means and standard deviations of the results are recorded. The fittest solution for each controller is then selected and the corresponding system responses are compared. A sensitivity analysis is subsequently performed, with cabin mass being varied by $\pm 20\%$.

4.2 GA Parameters for Optimisation of the Controllers for Elevator A

As there are only three parameters to be tuned for the CPID controller, a population size of $M_{GA} = 30$ is deemed to be suitable. Crossover probability (P_{GA_c}) is set to 0.8, while the probability of mutation (P_{GA_m}) is set at a value of 0.1. A mutation probability of 10% is selected under the assumption that it is sufficient to prevent convergence to a local maxima, but is not so high that the GA is transformed into a random search algorithm. The search spaces of the three controller gains were identified through manual tuning of the controller, with gains in excess of the upper bounds being unlikely to achieve acceptable control. A $k_{GA_{min}}$ value of 500 and a θ_{GA} value of 200 are selected to ensure that premature convergence is avoided, at the expense of increased run time. The GA parameters for optimisation of the CPDF controller are almost identical to those of the CPID controller, with the only exceptions being increased search spaces due to an acceptable range of CPDF gains being more difficult to determine.

With the incorporation of six extra parameters to be tuned compared to a CPID controller, the population size (M_{GA}) for optimisation of the NPID controllers is doubled to $M_{GA} = 60$. Additionally, the upper bounds of the K_P , K_I and K_D gains are increased. The search spaces for α_P and α_D are

set to $0 - 2$, as terms in excess of a value of 2 often lead to ineffective control. The lower bound of ψ_{α_I} is set at -2, as a negative value of α_I could possibly achieve a similar effect to variable-structure CPID control. By increasing integral action for smaller errors, while reducing it when the error is large; integral windup can be avoided [94]. The lower and upper bounds for all δ terms are set at 0.01 and 10, respectively, with the magnitudes of these terms defining the sizes of linear areas within the nonlinear functions. The selected GA parameters for optimisation of the NPID controller are similar to those for the NPID controller, with one of the main differences being the increased search spaces for the controller gains. Additionally, the lower and upper bounds of ψ_{α_P} , ψ_{α_I} and ψ_{α_D} have been set at 0.5 and 1.5 respectively; with values outside of this range almost always achieving inadequate control. The full set of GA parameters for the initial optimisation of the controllers are provided in Table 4.1.

Table 4.1: GA parameters for optimisation of the controllers for Elevator A

Parameter	CPID Controller	CPDF Controller	NPID Controller	NPID Controller
Population Size (M_{GA})	30	30	60	60
Probability of Crossover (P_{GA_c})	0.8	0.8	0.8	0.8
Probability of Mutation (P_{GA_m})	0.1	0.1	0.1	0.1
K_P Search Space (ψ_{K_P})	0 – 30	0 – 9999	0 – 50	0 – 9999
K_I Search Space (ψ_{K_I})	0 – 0.1	0 – 9999	0 – 30	0 – 9999
K_D Search Space (ψ_{K_D})	0 – 0.5	0 – 9999	0 – 5	0 – 9999
α_P Search Space (ψ_{α_P})	-	-	0 – 2	0.5 – 1.5
α_I Search Space (ψ_{α_I})	-	-	-2 – 0	0.5 – 1.5
α_D Search Space (ψ_{α_D})	-	-	0 – 2	0.5 – 1.5
δ_P Search Space (ψ_{δ_P})	-	-	0.01 – 10	0.01 – 10
δ_I Search Space (ψ_{δ_I})	-	-	0.01 – 10	0.01 – 10
δ_D Search Space (ψ_{δ_D})	-	-	0.01 – 10	0.01 – 10
GA Stopping Condition 1 ($k_{GA_{max}}$)	1000	1000	1000	1000
GA Stopping Condition 2.1 ($k_{GA_{min}}$)	500	500	500	500
GA Stopping Condition 2.2 (θ_{GA})	200	200	200	200

4.3 Solution Repeatability for Elevator A

Table 4.2: Solution repeatability of controller optimisation for Elevator A

Parameter	CPID		CPDF		NPID		NPDF	
	Controller		Controller		Controller		Controller	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Proportional Gain (K_P)	21.39	0.67	1869.98	298.49	39.28	10.16	1709.19	556.89
Integral Gain (K_I)	0.0085	0.001	5280.57	840.43	20.93	7.73	4233.96	1480.11
Derivative Gain (K_D)	0.2177	0.148	400.44	52.75	1.0330	1.3598	457.96	150.97
Proportional Alpha Term (α_P)	-	-	-	-	0.7586	0.1680	0.9665	0.0273
Integral Alpha Term (α_I)	-	-	-	-	-1.1295	0.2478	0.9938	0.0504
Derivative Alpha Term (α_D)	-	-	-	-	1.0028	0.6053	0.8069	0.0833
Proportional Delta Term (δ_P)	-	-	-	-	5.5312	1.6042	2.0240	1.8534
Integral Delta Term (δ_I)	-	-	-	-	4.3921	1.9662	6.3650	2.4741
Derivative Delta Term (δ_D)	-	-	-	-	4.3915	3.1490	7.0337	2.2590
Fitness Value (F_A)	12.387	0.732	121.426	1.120	16.752	1.117	118.106	12.661
GA Iterations (k_{GA})	724	204	767	249	710	169	720	226
GA Run Time [s]	28010	14430	29061	9434	77589	43650	93432	48950
GA Run Time/10 Individuals [s]	12.39	3.66	12.75	1.85	17.70	6.15	21.12	6.54

4.4 Comparison of Control Results for Elevator A

Table 4.3: Controller performance summary – Elevator A

Parameter	CPID Controller	CPDF Controller	NPID Controller	NPDF Controller
Proportional Gain (K_P)	22	1743.50	45.17	1522.70
Integral Gain (K_I)	0.0080	4948.80	8.60	4306
Derivative Gain (K_D)	0.1562	378.30	0.4257	291.24
Proportional Alpha Term (α_P)	-	-	0.6756	0.9474
Integral Alpha Term (α_I)	-	-	-0.8492	0.9412
Derivative Alpha Term (α_D)	-	-	1.3790	0.9942
Proportional Delta Term (δ_P)	-	-	5.3536	3.1729
Integral Delta Term (δ_I)	-	-	3.8257	9.4064
Derivative Delta Term (δ_D)	-	-	1.5424	4.9108
Fitness Value (F_A)	13.061	122.687	17.977	131.372
GA Iterations (k_{GA})	501	1000	570	893
GA Run Time [s]	15343	34319	75858	106474
GA Run Time/10 Individuals [s]	10.21	11.44	22.18	19.87
Rise Time [s]	9.34	8.95	9.24	8.92
Settling Time [s]	12.58	10.14	11.18	10.13
Velocity Overshoot [%]	0.58	0.59	0.61	0.74

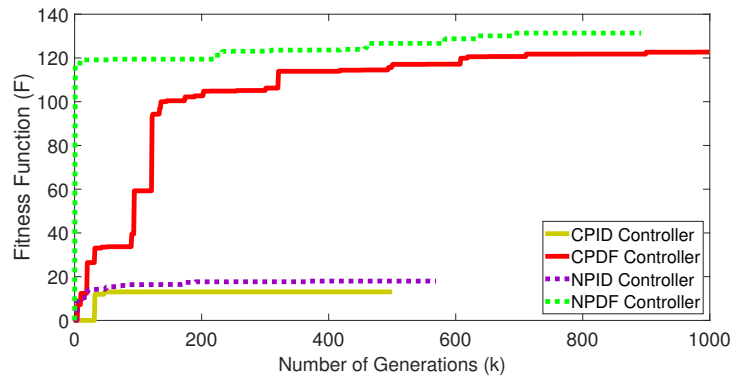


Figure 4.1: Evolution of the fitness function (F_A) vs. the number of population generations in the GA (k_{GA}) – Elevator A

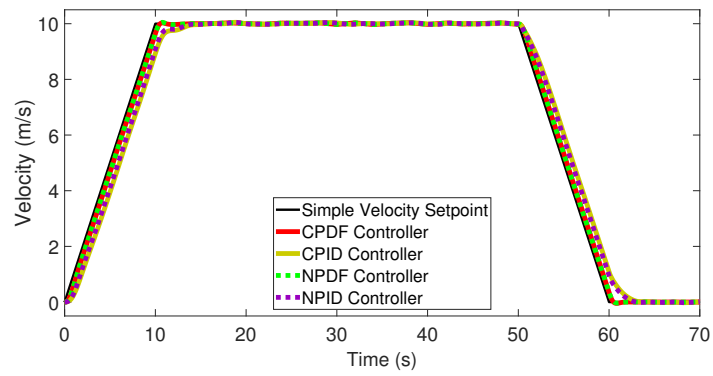


Figure 4.2: Velocity response of the 3200 kg cabins – Elevator A

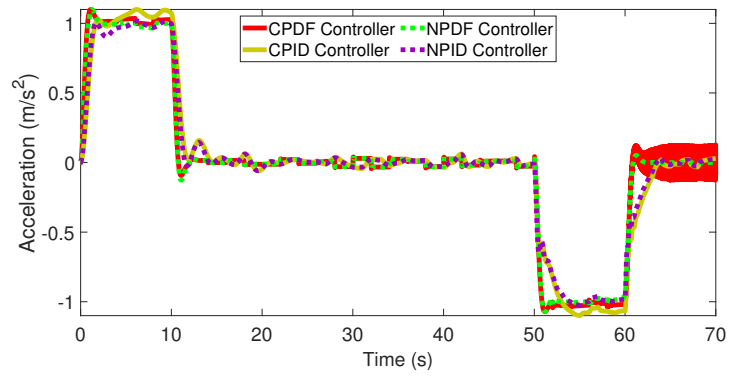


Figure 4.3: Acceleration response of the 3200 kg cabins – Elevator A

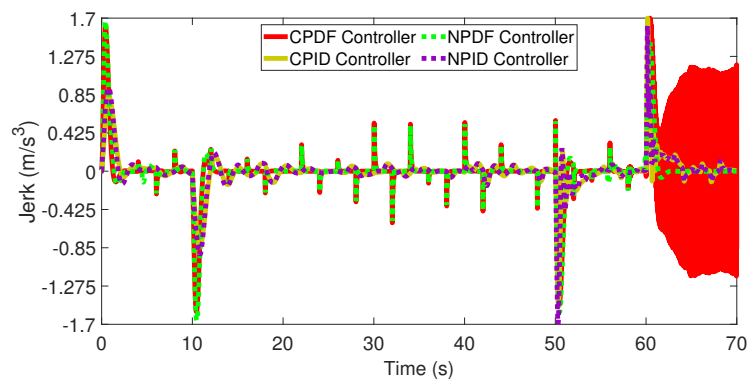


Figure 4.4: Jerk response of the 3200 kg cabins – Elevator A

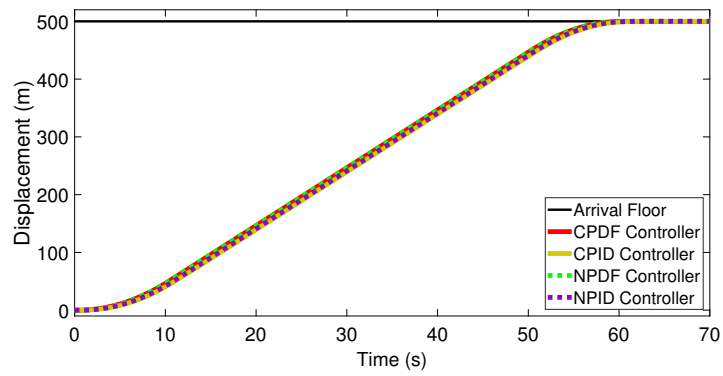


Figure 4.5: Displacement response of the 3200 kg cabins – Elevator A

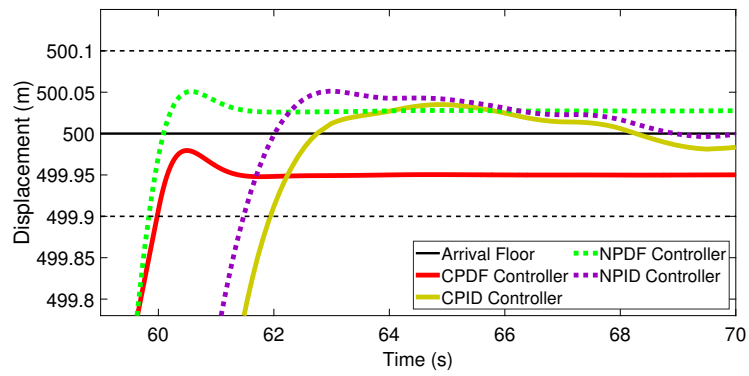


Figure 4.6: Displacement response of the 3200 kg cabins (zoomed into the moment of arrival) – Elevator A

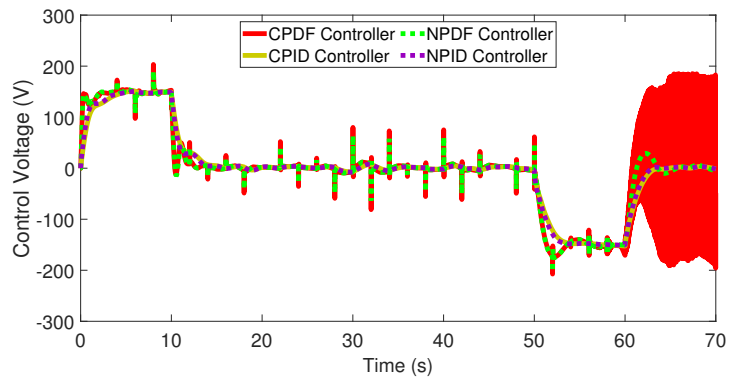


Figure 4.7: Control voltage output for control of the 3200 kg cabins – Elevator A

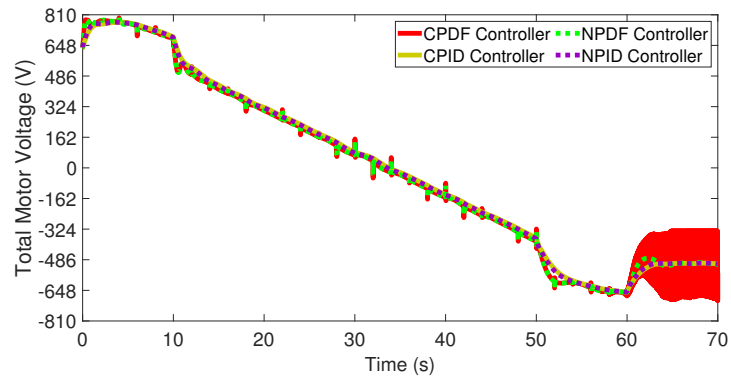


Figure 4.8: Total motor voltage during control of the 3200 kg cabins – Elevator A

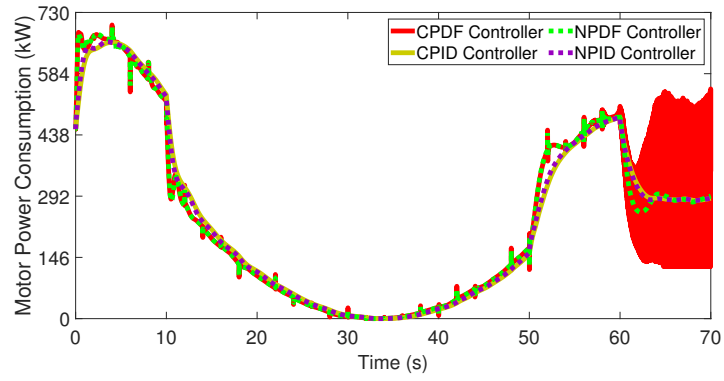


Figure 4.9: Total motor power consumption during control of the 3200 kg cabins – Elevator A

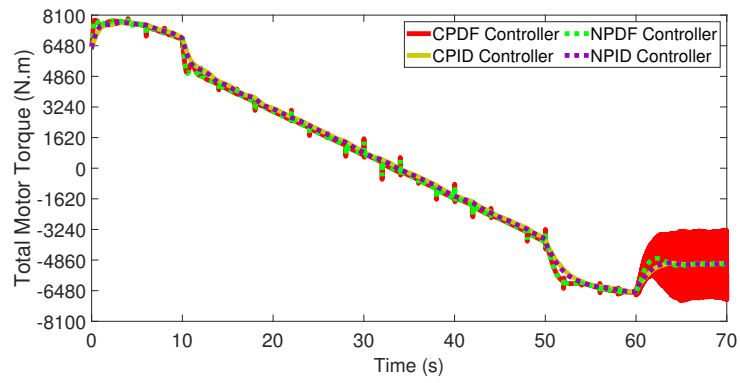


Figure 4.10: Total motor torque for actuation of the 3200 kg cabins – Elevator A

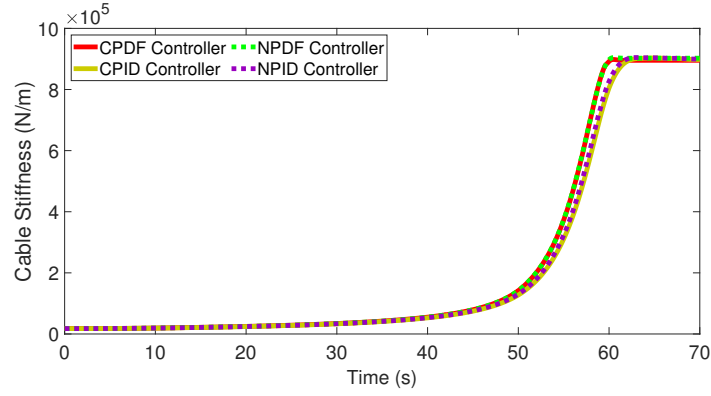


Figure 4.11: Change in the cabin-side cable stiffness (k_c) during control of the 3200 kg cabins – Elevator A

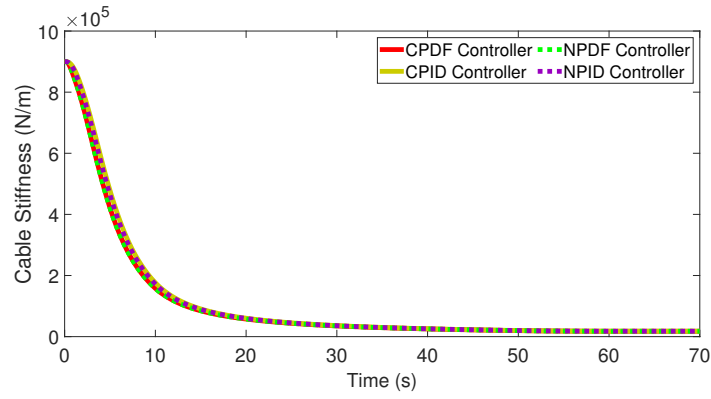


Figure 4.12: Change in the counterweight-side cable stiffness (k_w) during control of the 3200 kg cabins – Elevator A

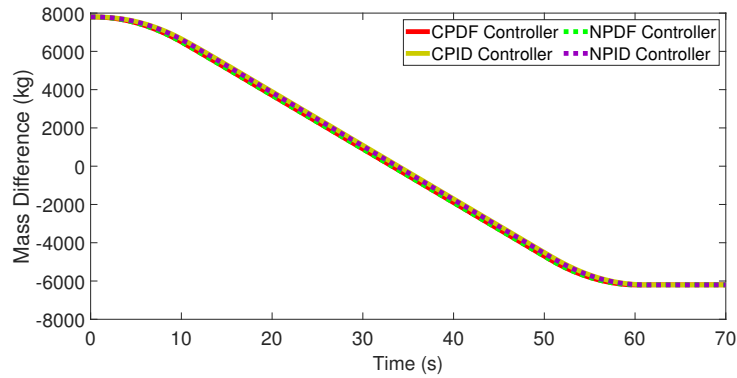


Figure 4.13: Difference between the total mass on the cabin and counterweight-side of the sheave during control of the 3200 kg cabins – Elevator A

4.5 Robustness Analysis for Elevator A

4.5.1 Robustness analysis – CPID and NPID controllers for Elevator A

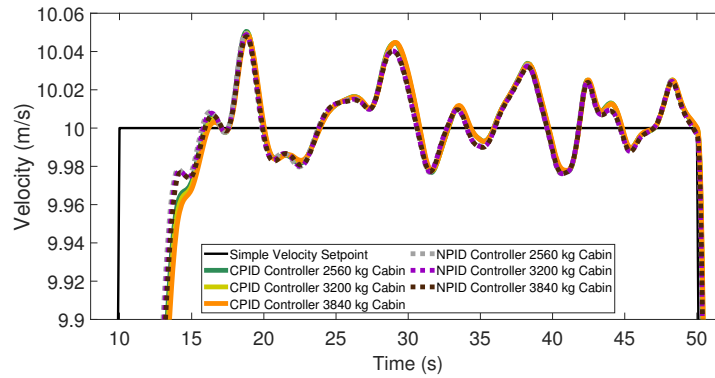


Figure 4.14: Velocity response of the CPID and NPID-controlled cabins following a $\pm 20\%$ variation in cabin mass (zoomed into the period of steady-state travel) – Elevator A

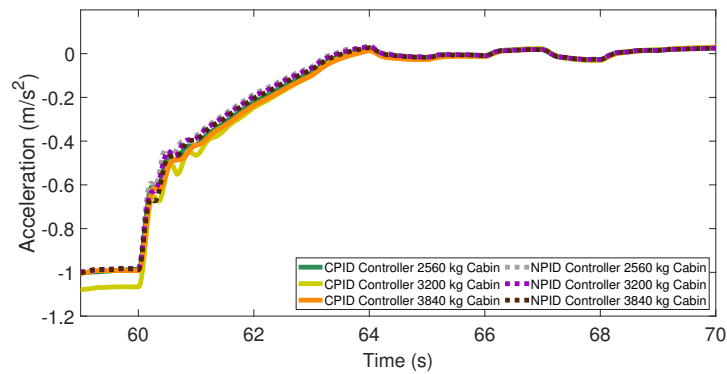


Figure 4.15: Acceleration response of the CPID and NPID-controlled cabins following a $\pm 20\%$ variation in cabin mass (zoomed into the moment of arrival) – Elevator A

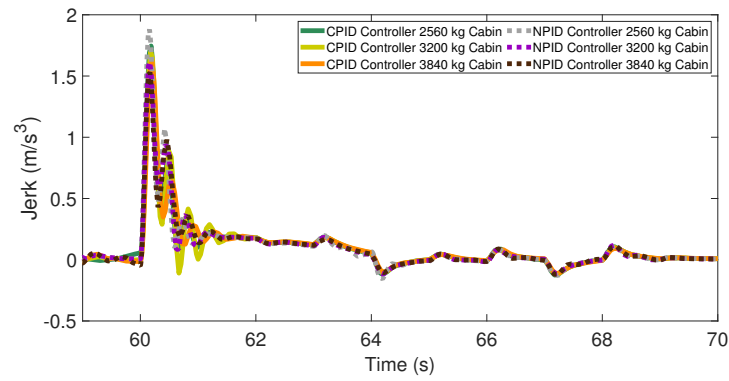


Figure 4.16: Jerk response of the CPID and NPID-controlled cabins following a $\pm 20\%$ variation in cabin mass (zoomed into the moment of arrival) – Elevator A

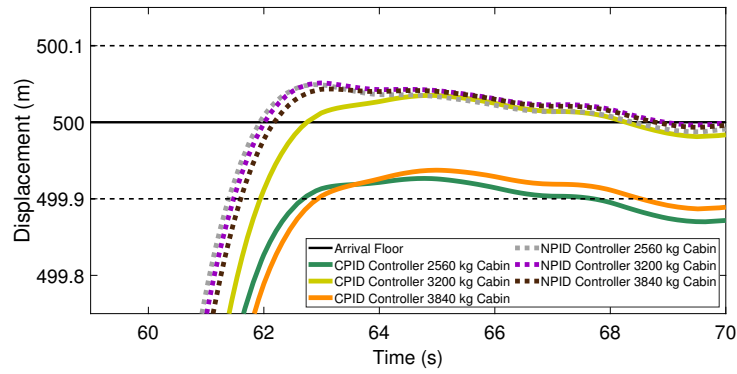


Figure 4.17: Displacement response of the CPID and NPID-controlled cabins following a $\pm 20\%$ variation in cabin mass (zoomed into the moment of arrival) – Elevator A

4.5.2 Robustness analysis – CPDF and NPDF controllers for Elevator A

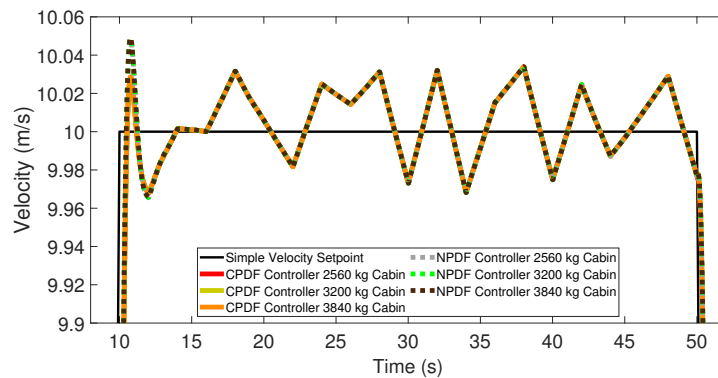


Figure 4.18: Velocity response of the CPDF and NPDF-controlled cabins following a $\pm 20\%$ variation in cabin mass (zoomed into the period of steady-state travel) – Elevator A

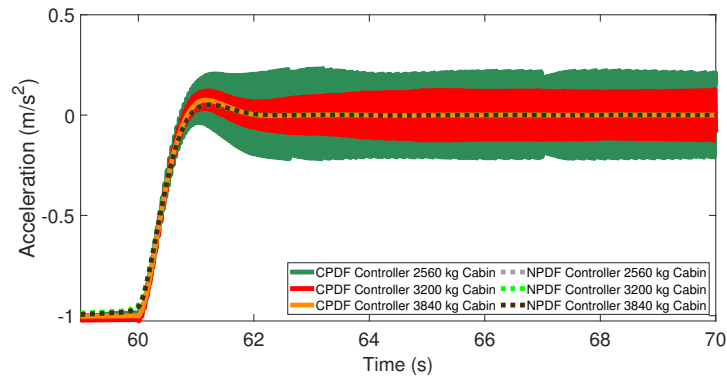


Figure 4.19: Acceleration response of the CPDF and NPDP-controlled cabins following a $\pm 20\%$ variation in cabin mass (zoomed into the moment of arrival) – Elevator A

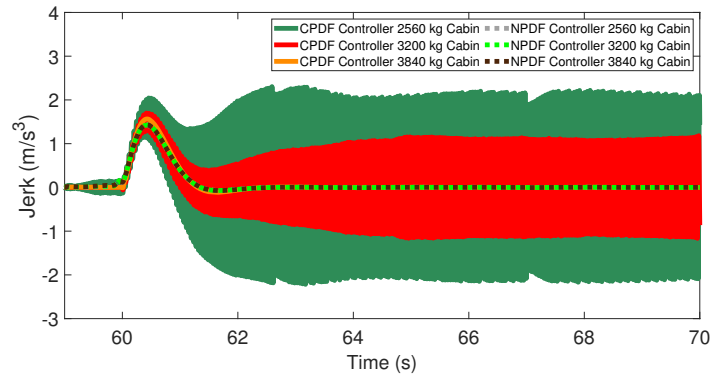


Figure 4.20: Jerk response of the CPDF and NPDP-controlled cabins following a $\pm 20\%$ variation in cabin mass (zoomed into the moment of arrival) – Elevator A

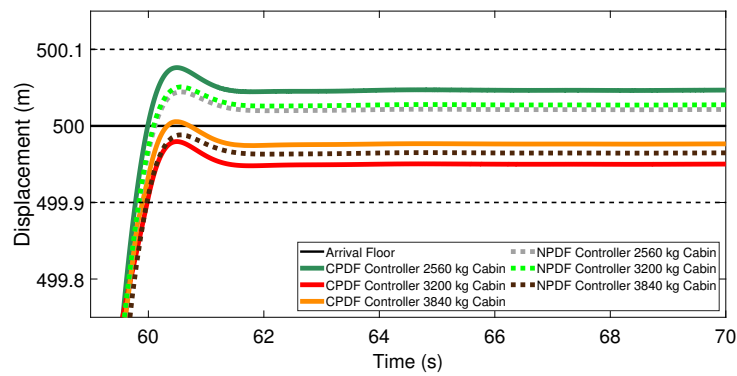


Figure 4.21: Displacement response of the CPDF and NPDP-controlled cabins following a $\pm 20\%$ variation in cabin mass (zoomed into the moment of arrival) – Elevator A

5 Numerical Simulations for Control of Elevator B

5.1 Chapter Outline

Three separate fitness function structures are evaluated in this chapter. Balanced – which does not prioritise any specific aspect of control; comfort-oriented – which prioritises minimising acceleration and jerk; and sustainability-oriented – which focuses on reducing power consumption. A performance-oriented function is not implemented in this chapter, as it is already used for optimisation of the controllers for Elevators A and C. Prior to the simulations detailed in this chapter, a set of preliminary simulations were performed to determine the optimal setpoint for each of the CPID, CPDF, NPID and NPDF controllers; as well as to ascertain suitable search spaces for the FSMC and SSMC parameters to avoid chattering. The robustness of the control systems is analysed by varying cabin mass, travel distance and travel direction; which is done for each of the fitness function configurations.

5.2 Balanced Fitness Function for Evaluation of the Controllers for Elevator B

The weighting factors in [Equation 3.39](#) are selected in order to obtain a balanced cost function; with performance, ride comfort and power consumption all being of equal importance. The relevant parameters of the cost function are listed in [Table 5.1](#).

Table 5.1: Balanced cost function parameters for evaluation of the controllers for Elevator B

Parameter	Value
β_{J-B}	1
γ_{J-B}	1
ϵ_{J-B}	1
η_{J-B}	1
κ_{J-B}	1
ξ_{J-B}	0.01

Hence, the balanced cost function for simulation of any cabin mass-travel direction combination can be written as:

$$J_{B-bal} = \frac{0.01}{120} \int_0^{120} \left[(v_d - v_c)^2 + (d_d - d_c)^2 + \left(\frac{\dot{v}_c}{1.1} \right)^2 + \left(\frac{\ddot{v}_c}{1.6} \right)^2 + \left(\frac{P_{m_{tot}}}{351} \right)^2 \right] dt \quad (5.1)$$

with $J_{B-bal-combined}$ subsequently obtained using [Equation 3.45](#).

Finally, the combined balanced fitness function ($F_{B-bal-combined}$) is written as:

$$F_{B-bal-combined} = [J_{B-bal-combined}]^{-1} \quad (5.2)$$

5.2.1 GA parameters for optimisation of the controllers for Elevator B (balanced fitness function)

In order to improve the run time of the optimisation processes, multiple GA parameters are to be altered from those used for optimisation of Elevator A (refer to [Table 4.1](#)). The population sizes (M_{GA}) for optimisation of the CPID and CPDF controllers are reduced from 30 to 16, while the maximum number of iterations ($k_{GA_{max}}$) are halved from 1000 to 500. The minimum number of generations before convergence can be assumed ($k_{GA_{min}}$) are reduced from 500 to 200, with θ_{GA} being decreased from 200 to 50. The search space sizes of the CPID controller gains are increased significantly, as preliminary simulations indicated that a suitable solution could not be found by utilising the same search space bounds used for Elevator A. The search space bounds for the CPDF controller integral gain (K_I) are shifted upwards by a value of 5000.

In order to evaluate the effects of a positive α_I value, the corresponding upper bound for the NPID controller is increased from 0 to 2. Regarding the NPDF controller, the lower bounds of the nonlinear α term search spaces have been increased to 0.7, with the upper limits reduced from a value of 2 to a value of 1.3. The reduction of ψ_{α_D} in particular should reduce optimisation time, as higher values of α_D tend to induce higher-frequency oscillations in the solution, subsequently prolonging the

simulation. In order to evaluate the effects of reducing the linear area within the nonlinear functions, the maximum allowable values of the nonlinear δ terms are decreased from 10 to 2 for both the NPID and NPDF controllers.

During the preliminary analyses of the controllers, unacceptably excessive run times were recorded for both SMC variants, each taking an average of over two minutes to simulate 10 individuals within a population. In an attempt to counter this, the population sizes are set at 10 individuals for both the FSMC and SSMC. Additionally, the values of $k_{GA_{max}}$, $k_{GA_{min}}$ and θ_{GA} are all significantly reduced from those selected for the CPID, CPDF, NPID and NPDF control systems. For the initial analyses, the lower bounds of the search spaces of the SMC saturation function parameters (ρ) were set at 0. This was done to allow the functions to approach the structure of a sign function, should suitable control without excessive chattering be obtainable. This occurred for both the FSMC and SSMC, converging to small ρ values and significantly fitter solutions than the other controllers. While the hypothesis that a low ρ value would induce chattering in the jerk response was partially correct, the amplitude of the responses remained relatively low. However, it was observed that motor torque was the parameter that experienced problematic chattering; with the responses fluctuating at unacceptably high frequency and amplitude. While this led to effective control in simulation, such a response in the real world would result in significant damage to the actuator. In order to prevent similar chattering in future, the search space of ρ (ψ_ρ) is set to 0.35 – 0.7 for both controllers. The GA parameters used for optimisation of the controllers are provided in [Table 5.2](#).

Table 5.2: GA parameters for optimisation of the controllers for Elevator B (balanced fitness function)

Parameter	CPID Controller	CPDF Controller	NPID Controller	NPDF Controller	FSMC	SSMC
Population Size (M_{GA})	16	16	30	30	10	10
Probability of Crossover (P_{GA_c})	0.8	0.8	0.8	0.8	0.8	0.8
Probability of Mutation (P_{GA_m})	0.1	0.1	0.1	0.1	0.1	0.1
K_P Search Space (ψ_{K_P})	0 – 999	0 – 9999	0 – 999	0 – 9999	-	-
K_I Search Space (ψ_{K_I})	0 – 999	0 – 15000	0 – 999	0 – 15000	-	-
K_D Search Space (ψ_{K_D})	0 – 999	0 – 9999	0 – 999	0 – 9999	-	-
α_P Search Space (ψ_{α_P})	-	-	0 – 2	0.7 – 1.3	-	-
α_I Search Space (ψ_{α_I})	-	-	-2 – 2	0.7 – 1.3	-	-
α_D Search Space (ψ_{α_D})	-	-	0 – 2	0.7 – 1.3	-	-
δ_P Search Space (ψ_{δ_P})	-	-	0.01 – 2	0.01 – 2	-	-
δ_I Search Space (ψ_{δ_I})	-	-	0.01 – 2	0.01 – 2	-	-
δ_D Search Space (ψ_{δ_D})	-	-	0.01 – 2	0.01 – 2	-	-
ρ Search Space (ψ_{ρ})	-	-	-	-	0.35 – 0.7	0.35 – 0.7
K_R Search Space (ψ_{K_R})	-	-	-	-	10 – 200	10 – 200
λ_0 Search Space (ψ_{λ_0})	-	-	-	-	0.01 – 999	0.01 – 999
λ_1 Search Space (ψ_{λ_1})	-	-	-	-	0.01 – 999	0.01 – 999
λ_2 Search Space (ψ_{λ_2})	-	-	-	-	0.01 – 999	0.01 – 999
GA Stopping Condition 1 ($k_{GA_{max}}$)	500	500	500	500	200	200
GA Stopping Condition 2.1 ($k_{GA_{min}}$)	200	200	200	200	100	100
GA Stopping Condition 2.2 (θ_{GA})	50	50	50	50	20	20

5.2.2 Solution repeatability for Elevator B (balanced fitness function)

Table 5.3: Solution repeatability of controller optimisation for Elevator B (balanced fitness function)

Parameter	CPID Controller		CPDF Controller		NPID Controller		NPDF Controller		FSMC		SSMC	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Proportional Gain (K_P)	104.91	20.87	5574.08	1375.74	336.04	49.05	5239.46	837.19	-	-	-	-
Integral Gain (K_I)	603.87	70.05	10126.85	2508.23	729.12	78.02	8401.19	1329.62	-	-	-	-
Derivative Gain (K_D)	364.81	26.95	1624.83	325.76	759.18	67.76	1264.34	298.23	-	-	-	-
Proportional Alpha Term (α_P)	-	-	-	-	0.6038	0.6323	1.1150	0.0497	-	-	-	-
Integral Alpha Term (α_I)	-	-	-	-	-0.5700	0.4381	1.1659	0.0417	-	-	-	-
Derivative Alpha Term (α_D)	-	-	-	-	0.3676	0.1394	1.2097	0.0548	-	-	-	-
Proportional Delta Term (δ_P)	-	-	-	-	1.1029	0.4343	1.2697	0.4505	-	-	-	-
Integral Delta Term (δ_I)	-	-	-	-	1.0521	0.1332	1.3632	0.4861	-	-	-	-
Derivative Delta Term (δ_D)	-	-	-	-	0.3661	0.0542	0.2465	0.2944	-	-	-	-
Saturation Function Coefficient (ρ)	-	-	-	-	-	-	-	-	0.4815	0.0470	0.5469	0.0789
Reaching Law Gain (K_R)	-	-	-	-	-	-	-	-	14.14	5.32	11.83	2.37
λ_0 Coefficient	-	-	-	-	-	-	-	-	813.09	85.68	611.96	209.29
λ_1 Coefficient	-	-	-	-	-	-	-	-	419.38	133.39	332.59	78.68
λ_2 Coefficient	-	-	-	-	-	-	-	-	229.26	57.99	172.01	43.43
Fitness Value ($F_{B-bal-combined}$)	1.54e-17	3.23e-19	423.180	0.358	419.880	0.492	427.537	0.962	421.991	0.293	421.972	0.143
GA Iterations (k_{GA})	313	122	228	34	235	47	225	17	120	19	118	17
GA Run Time [s]	19478	5931	51739	15941	35984	9096	50825	8341	103721	20613	73533	14883
GA Run Time/10 Individuals [s]	40.15	4.13	140.42	32.18	50.80	4.93	76.15	14.68	865.20	90.14	622.64	111.18

5.2.3 Comparison of control results for Elevator B (balanced fitness function)

Table 5.4: Controller performance summary – Elevator B (balanced fitness function)

Parameter	CPID Controller	CPDF Controller	NPID Controller	NPDF Controller	FSMC	SSMC
Proportional Gain (K_P)	78.46	7425	199.57	4985	-	-
Integral Gain (K_I)	519.73	13687	680.31	8647.20	-	-
Derivative Gain (K_D)	315.10	2161.40	771.67	1174.10	-	-
Proportional Alpha Term (α_P)	-	-	1.111	1.1762	-	-
Integral Alpha Term (α_I)	-	-	-0.4455	1.2135	-	-
Derivative Alpha Term (α_D)	-	-	0.4067	1.2424	-	-
Proportional Delta Term (δ_P)	-	-	1.7113	0.7470	-	-
Integral Delta Term (δ_I)	-	-	0.9806	1.0996	-	-
Derivative Delta Term (δ_D)	-	-	0.4123	0.2086	-	-
Saturation Function Coefficient (ρ)	-	-	-	-	0.4518	0.5863
Reaching Law Gain (K_R)	-	-	-	-	10.06	10.01
λ_0 Coefficient	-	-	-	-	683.59	383.59
λ_1 Coefficient	-	-	-	-	374.59	245.30
λ_2 Coefficient	-	-	-	-	206.88	124.18
Fitness Value ($F_{B-bal-combined}$)	1.61e-17	423.590	420.692	428.733	422.323	422.234
GA Iterations (k_{GA})	433	200	262	236	148	101
GA Run Time [s]	26444	51024	35291	46213	128252	64729
GA Run Time/10 Individuals [s]	38.17	159.45	44.90	65.27	866.57	640.88
Rise Time [s] (3200 kg Cabin, 1000 m Upwards Travel)	8.84	8.94	8.92	8.92	8.86	8.87
Settling Time [s] (3200 kg Cabin, 1000 m Upwards Travel)	10.13	10.36	10.16	10.38	10.10	10.10
Velocity Overshoot [%] (3200 kg Cabin, 1000 m Upwards Travel)	0.84	0.64	0.76	0.64	0.65	0.64

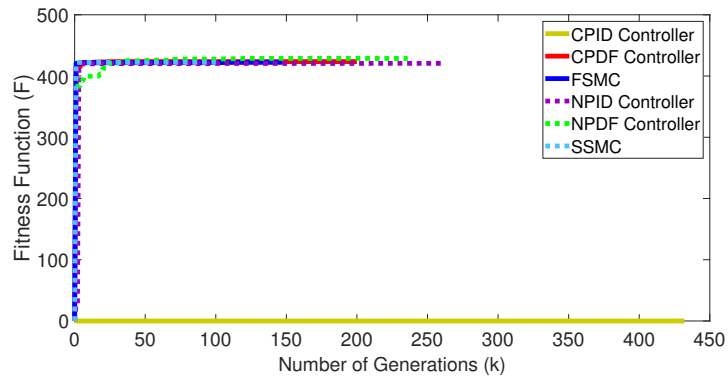


Figure 5.1: Evolution of the fitness function ($F_{B-bal-combined}$) vs. the number of population generations in the GA (k_{GA}) – Elevator B (balanced fitness function)

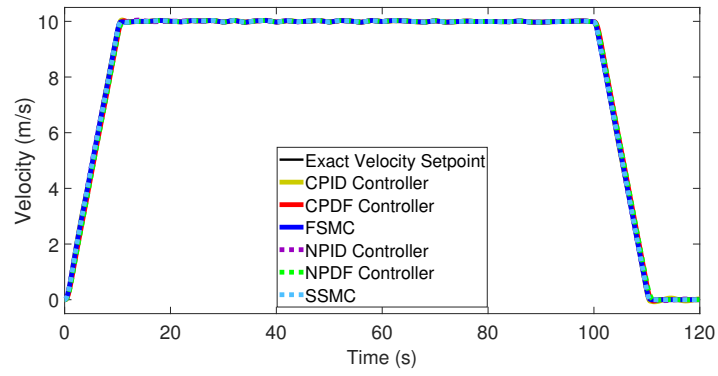


Figure 5.2: Velocity response of the 3200 kg cabins – Elevator B (balanced fitness function). Refer to Figures 10.1 and 10.2 for more detail.

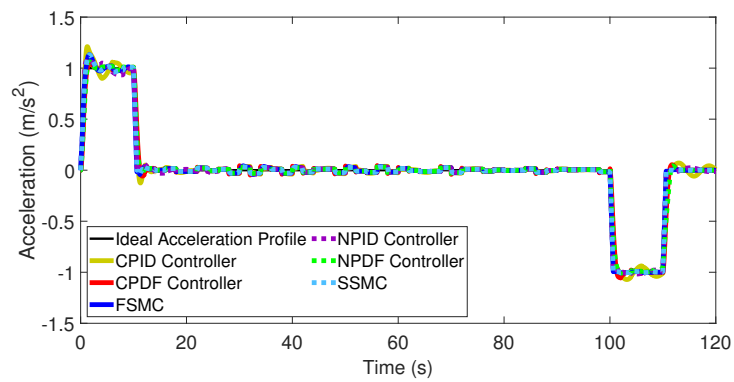


Figure 5.3: Acceleration response of the 3200 kg cabins – Elevator B (balanced fitness function). Refer to Figures 10.3 – 10.5 for more detail.

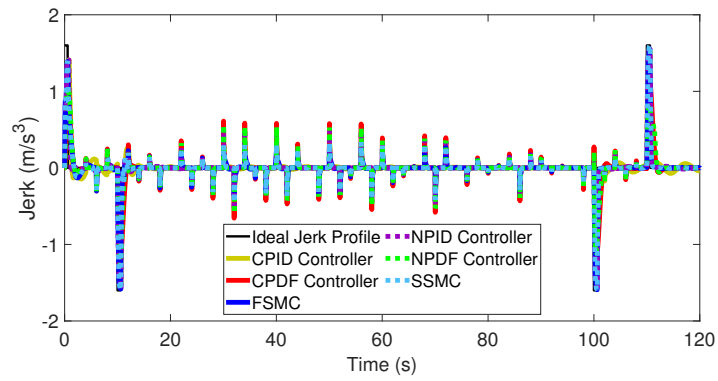


Figure 5.4: Jerk response of the 3200 kg cabins – Elevator B (balanced fitness function). Refer to Figures 10.6 – 10.8 for more detail.

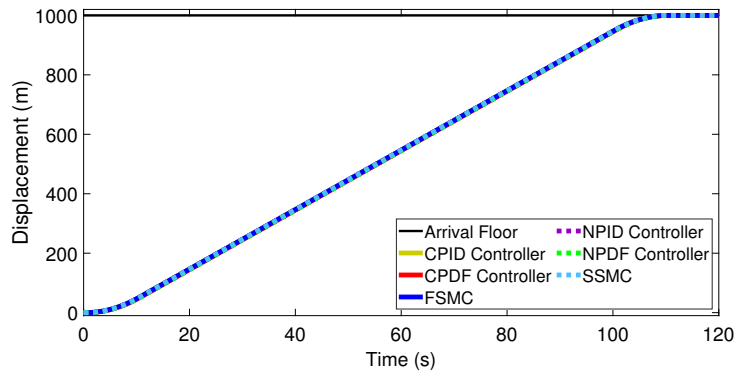


Figure 5.5: Displacement response of the 3200 kg cabins – Elevator B (balanced fitness function)

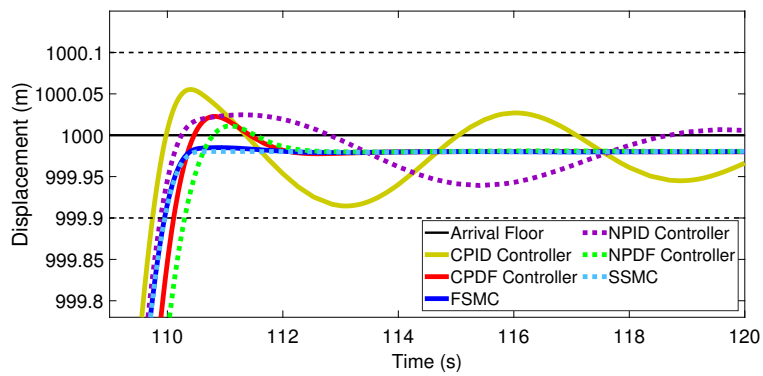


Figure 5.6: Displacement response of the 3200 kg cabins (zoomed into the moment of arrival) – Elevator B (balanced fitness function)

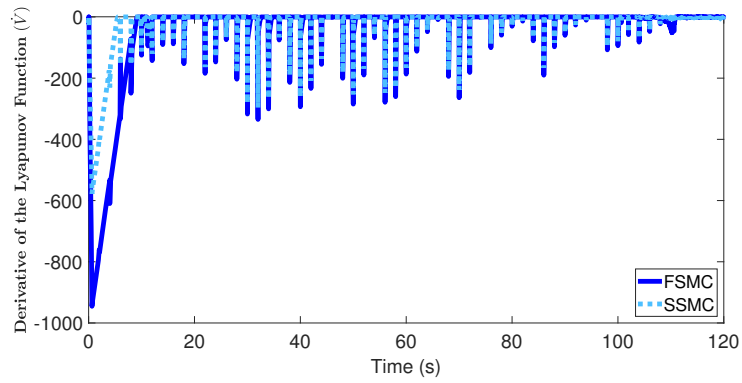


Figure 5.7: Derivative of the Lyapunov function ($\dot{V}$) during SMC control of the 3200 kg cabins – Elevator B (balanced fitness function)

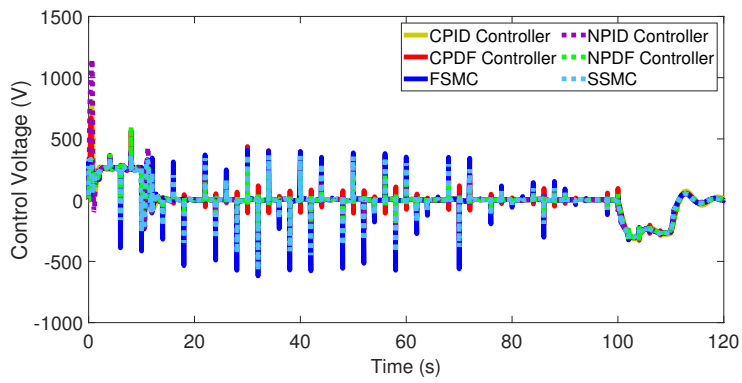


Figure 5.8: Control voltage output during control of the 3200 kg cabins – Elevator B (balanced fitness function)

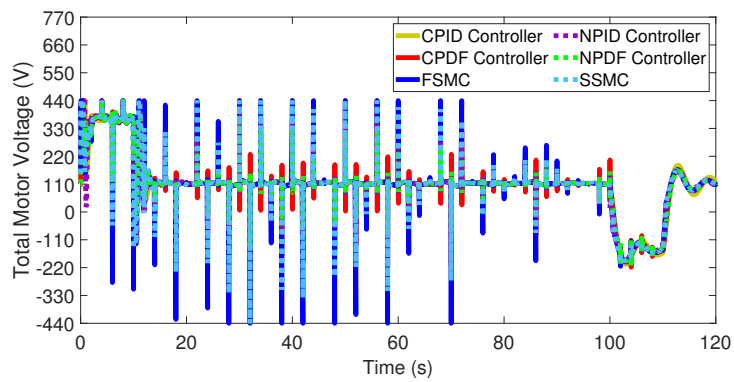


Figure 5.9: Total motor voltage during control of the 3200 kg cabins – Elevator B (balanced fitness function)

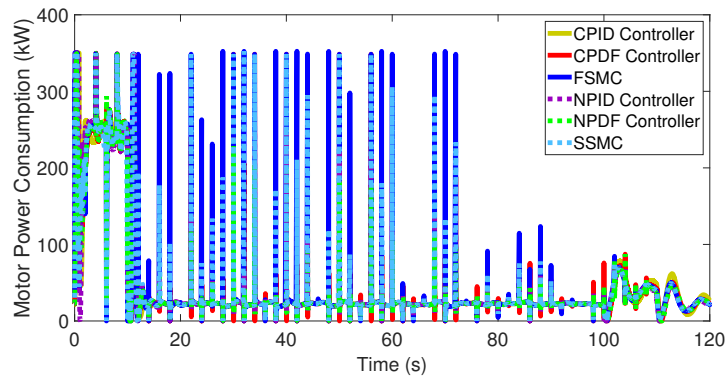


Figure 5.10: Total motor power consumption during control of the 3200 kg cabins – Elevator B (balanced fitness function)

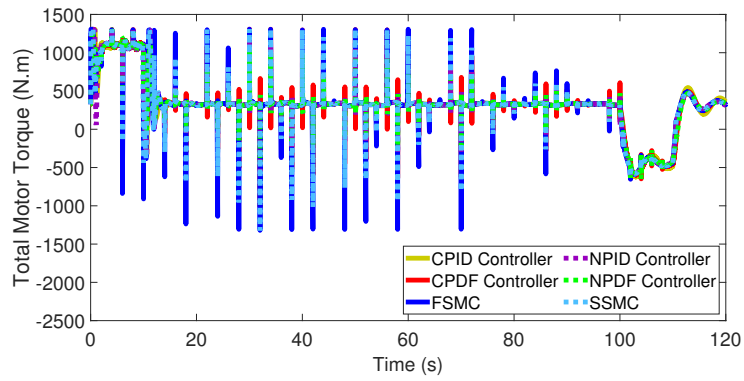


Figure 5.11: Total motor torque during actuation of the 3200 kg cabins – Elevator B (balanced fitness function)

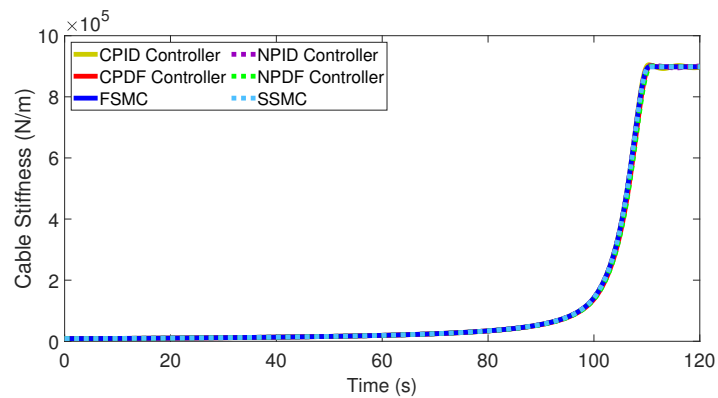


Figure 5.12: Change in the cabin-side cable stiffness (k_c) during control of the 3200 kg cabin – Elevator B (balanced fitness function)

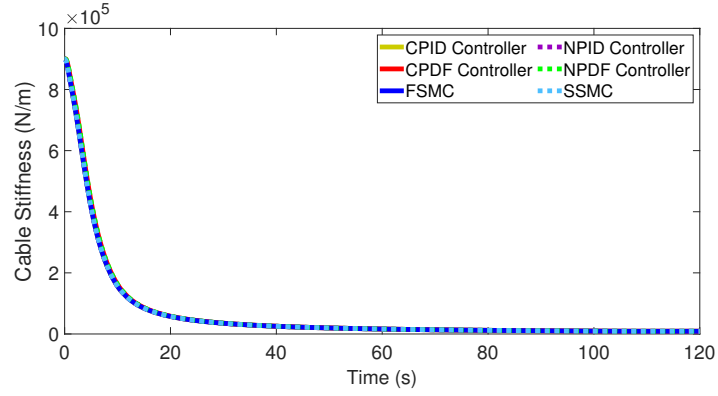


Figure 5.13: Change in the counterweight-side cable stiffness (k_w) during control of the 3200 kg cabin – Elevator B (balanced fitness function)

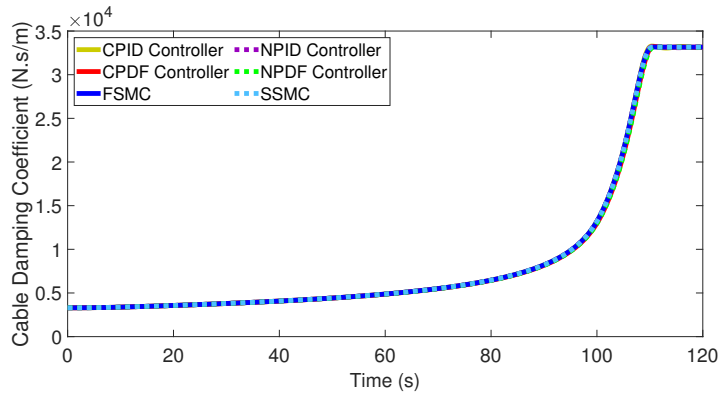


Figure 5.14: Change in the cabin-side cable damping coefficient (c_c) during control of the 3200 kg cabin – Elevator B (balanced fitness function)

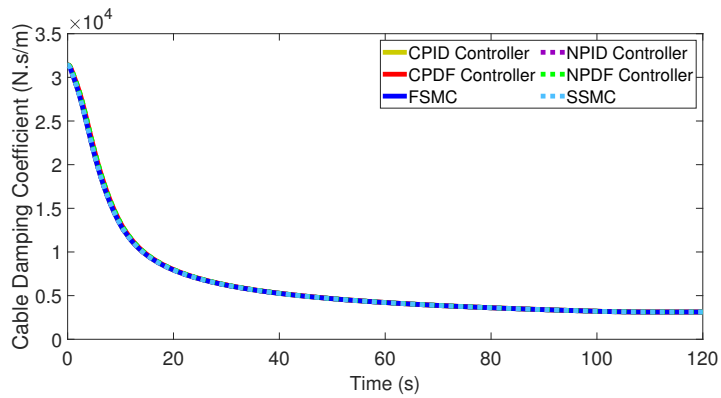


Figure 5.15: Change in the counterweight-side cable damping coefficient (c_w) during control of the 3200 kg cabin – Elevator B (balanced fitness function)

5.2.4 Robustness analysis for Elevator B (balanced fitness function)

5.2.4.1 Robustness analysis – CPID controller for Elevator B (balanced fitness function)

Table 5.5: Robustness analysis – CPID controller for control of Elevator B (balanced fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	176.881	193.964	169.344	143.722	115.002
	Pass	Pass	Pass	Pass	Pass
400 m	2.60e-08	2.86e-08	2.50e-08	2.10e-08	1.65e-08
	D (+0.17m)	D (+0.17m)	D (+0.17m)	D (+0.17m)	D (+0.18m)
600 m	3.34e-08	3.68e-08	3.20e-08	2.67e-08	2.07e-08
	D (+0.30m)	D (+0.30m)	D (+0.30m)	D (+0.30m)	D (+0.31m)
800 m	4.17e-08	4.59e-08	3.98e-08	3.29e-08	2.50e-08
	D (+0.20m)	D (+0.20m)	D (+0.20m)	D (+0.20m)	D (+0.20m)
1000 m	4.92e-08	5.41e-08	470.829	384.532	286.277
	J (+0.15m/s ³)	J (+0.15m/s ³)	Pass	Pass	Pass
-1000 m	4.90e-08	5.41e-08	4.71e-08	3.86e-08	2.89e-08
	J (+0.15m/s ³)	J (+0.14m/s ³)	J (+0.09m/s ³)	J (+0.07m/s ³)	J (+0.05m/s ³)
-800 m	4.15e-08	4.59e-08	3.98e-08	3.29e-08	2.50e-08
	D (-0.18m)	D (-0.19m)	D (-0.19m)	D (-0.19m)	D (-0.19m)
-600 m	3.33e-08	3.67e-08	3.21e-08	2.69e-08	2.08e-08
	D (-0.29m)	D (-0.30m)	D (-0.30m)	D (-0.30m)	D (-0.30m)
-400 m	2.59e-08	2.86e-08	2.51e-08	2.11e-08	1.66e-08
	D (-0.16m)	D (-0.17m)	D (-0.17m)	D (-0.17m)	D (-0.17m)
-200 m	176.578	193.842	169.698	144.284	115.653
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.2.4.2 Robustness analysis – CPDF controller for Elevator B (balanced fitness function)

Table 5.6: Robustness analysis – CPDF controller for control of Elevator B (balanced fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	176.198	192.770	168.729	143.564	115.184
	Pass	Pass	Pass	Pass	Pass
400 m	2.58e-08	2.83e-08	2.48e-08	2.09e-08	1.64e-08
	D (+0.16m)	D (+0.16m)	D (+0.16m)	D (+0.16m)	D (+0.16m)
600 m	3.31e-08	3.64e-08	3.18e-08	2.66e-08	2.05e-08
	D (+0.29m)	D (+0.29m)	D (+0.29m)	D (+0.29m)	D (+0.29m)
800 m	4.16e-08	4.58e-08	3.97e-08	3.27e-08	2.45e-08
	D (+0.17m)	D (+0.18m)	D (+0.18m)	D (+0.18m)	D (+0.18m)
1000 m	494.446	549.199	475.577	388.154	288.000
	Pass	Pass	Pass	Pass	Pass
-1000 m	492.364	548.28	475.186	388.513	288.477
	Pass	Pass	Pass	Pass	Pass
-800 m	4.13e-08	4.58e-08	3.98e-08	3.28e-08	2.48e-08
	D (-0.17m)	D (-0.17m)	D (-0.17m)	D (-0.17m)	D (-0.17m)
-600 m	3.30e-08	3.64e-08	3.19e-08	2.67e-08	2.07e-08
	D (-0.28m)	D (-0.28m)	D (-0.28m)	D (-0.28m)	D (-0.28m)
-400 m	2.58e-08	2.84e-08	2.49e-08	2.10e-08	1.66e-08
	D (-0.16m)	D (-0.16m)	D (-0.16m)	D (-0.16m)	D (-0.16m)
-200 m	175.996	192.894	169.354	144.343	116.013
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.2.4.3 Robustness analysis – NPID controller for Elevator B (balanced fitness function)

Table 5.7: Robustness analysis – NPID controller for control of Elevator B (balanced fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	178.708 Pass	195.744 Pass	170.66 Pass	144.732 Pass	115.732 Pass
400 m	2.63e-08 D (+0.15m)	2.88e-08 D (+0.16m)	2.51e-08 D (+0.16m)	2.11e-08 D (+0.16m)	1.65e-08 D (+0.16m)
600 m	3.37e-08 D (+0.28m)	3.70e-08 D (+0.28m)	3.21e-08 D (+0.28m)	2.68e-08 D (+0.28m)	2.07e-08 D (+0.29m)
800 m	4.22e-08 D (+0.18m)	4.61e-08 D (+0.18m)	3.99e-08 D (+0.18m)	3.29e-08 D (+0.18m)	2.48e-08 D (+0.18m)
1000 m	499.145 Pass	5.47e-08 J (+0.18m/s ³)	470.160 Pass	382.298 Pass	283.588 Pass
-1000 m	496.667 Pass	5.45e-08 J (+0.01m/s ³)	4.72e-08 J (+0.03m/s ³)	386.378 Pass	288.545 Pass
-800 m	4.20e-08 D (-0.17m)	4.63e-08 D (-0.17m)	3.99e-08 D (-0.18m)	3.29e-08 D (-0.18m)	2.49e-08 D (-0.17m)
-600 m	3.36e-08 D (-0.28m)	3.70e-08 D (-0.28m)	3.22e-08 D (-0.28m)	2.69e-08 D (-0.29m)	2.08e-08 D (-0.27m)
-400 m	2.62e-08 D (-0.15m)	2.89e-08 D (-0.16m)	2.52e-08 D (-0.16m)	2.12e-08 D (-0.16m)	1.67e-08 D (-0.16m)
-200 m	178.509 Pass	195.887 Pass	171.313 Pass	145.544 Pass	116.549 Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.2.4.4 Robustness analysis – NPDF controller for Elevator B (balanced fitness function)

Table 5.8: Robustness analysis – NPDF controller for control of Elevator B (balanced fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	178.815	195.262	170.428	144.806	116.037
	Pass	Pass	Pass	Pass	Pass
400 m	2.62e-08	2.87e-08	2.51e-08	2.11e-08	1.66e-08
	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.15m)
600 m	3.37e-08	3.69e-08	3.22e-08	2.69e-08	2.07e-08
	D (+0.27m)	D (+0.27m)	D (+0.27m)	D (+0.27m)	D (+0.27m)
800 m	4.23e-08	4.66e-08	4.02e-08	3.31e-08	2.48e-08
	D (+0.16m)	D (+0.16m)	D (+0.16m)	D (+0.16m)	D (+0.16m)
1000 m	502.984	557.532	480.846	392.137	291.070
	Pass	Pass	Pass	Pass	Pass
-1000 m	498.45	556.053	482.918	395.62	292.714
	Pass	Pass	Pass	Pass	Pass
-800 m	4.19e-08	4.65e-08	4.07e-08	3.38e-08	2.56e-08
	D (-0.16m)	D (-0.16m)	D (-0.16m)	D (-0.16m)	D (-0.16m)
-600 m	3.34e-08	3.70e-08	3.25e-08	2.73e-08	2.12e-08
	D (-0.27m)	D (-0.27m)	D (-0.27m)	D (-0.27m)	D (-0.27m)
-400 m	2.61e-08	2.88e-08	2.53e-08	2.14e-08	1.69e-08
	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.14m)
-200 m	177.831	195.399	172.038	146.766	117.946
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.2.4.5 Robustness analysis – FSMC for Elevator B (balanced fitness function)

Table 5.9: Robustness analysis – FSMC for control of Elevator B (balanced fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	178.350	195.346	170.361	144.487	115.57
	Pass	Pass	Pass	Pass	Pass
400 m	2.62e-08	2.88e-08	2.51e-08	2.10e-08	1.65e-08
	D (+0.11m)	D (+0.11m)	D (+0.11m)	D (+0.11m)	D (+0.11m)
600 m	3.36e-08	3.69e-08	3.21e-08	2.68e-08	2.07e-08
	D (+0.24m)	D (+0.24m)	D (+0.24m)	D (+0.24m)	D (+0.24m)
800 m	4.20e-08	4.58e-08	4.01e-08	3.30e-08	2.50e-08
	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)
1000 m	497.717	5.46e-08	472.069	383.843	285.367
	Pass	J (+0.02m/s ³)	Pass	Pass	Pass
-1000 m	494.424	543.624	477.746	390.98	291.326
	Pass	Pass	Pass	Pass	Pass
-800 m	4.18e-08	4.60e-08	3.99e-08	3.29e-08	2.49e-08
	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.14m)
-600 m	3.35e-08	3.69e-08	3.22e-08	2.69e-08	2.08e-08
	D (-0.24m)	D (-0.24m)	D (-0.24m)	D (-0.24m)	D (-0.24m)
-400 m	2.62e-08	2.88e-08	2.52e-08	2.12e-08	1.67e-08
	D (-0.11m)	D (-0.11m)	D (-0.11m)	D (-0.11m)	D (-0.11m)
-200 m	178.182	195.493	171.022	145.312	116.394
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.2.4.6 Robustness analysis – SSMC for Elevator B (balanced fitness function)

Table 5.10: Robustness analysis – SSMC for control of Elevator B (balanced fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	178.420	195.416	170.426	144.55	115.626
	Pass	Pass	Pass	Pass	Pass
400 m	2.62e-08	2.88e-08	2.51e-08	2.11e-08	1.65e-08
	D (+0.11m)	D (+0.11m)	D (+0.11m)	D (+0.11m)	D (+0.11m)
600 m	3.37e-08	3.69e-08	3.21e-08	2.68e-08	2.07e-08
	D (+0.24m)	D (+0.24m)	D (+0.24m)	D (+0.24m)	D (+0.24m)
800 m	4.20e-08	4.59e-08	4.01e-08	3.30e-08	2.50e-08
	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)
1000 m	497.013	5.45e-08	471.657	384.324	285.507
	Pass	J (+0.04m/s ³)	Pass	Pass	Pass
-1000 m	494.705	544.715	478.108	391.489	291.846
	Pass	Pass	Pass	Pass	Pass
-800 m	4.18e-08	4.60e-08	3.99e-08	3.29e-08	2.49e-08
	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.14m)
-600 m	3.36e-08	3.69e-08	3.22e-08	2.69e-08	2.08e-08
	D (-0.24m)	D (-0.24m)	D (-0.24m)	D (-0.24m)	D (-0.24m)
-400 m	2.62e-08	2.88e-08	2.52e-08	2.12e-08	1.67e-08
	D (-0.11m)	D (-0.11m)	D (-0.11m)	D (-0.11m)	D (-0.11m)
-200 m	178.241	195.551	171.077	145.385	116.458
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.3 Comfort-Oriented Fitness Function for Evaluation of the Controllers for Elevator B

The weighting factors in Equation 3.39 are selected to prioritise the minimisation of acceleration and jerk experienced by the occupants. The values of the terms are summarised in Table 5.11.

Table 5.11: Comfort-oriented cost function parameters for evaluation of the controllers for Elevator B

Parameter	Value
β_{J-B}	1
γ_{J-B}	1
ϵ_{J-B}	10000
η_{J-B}	10000
κ_{J-B}	1
ξ_{J-B}	1e-05

Hence, the comfort-oriented cost function for simulation of any cabin mass-travel direction combination is defined by:

$$J_{B-com} = \frac{10^{-5}}{120} \int_0^{120} \left[(v_d - v_c)^2 + (d_d - d_c)^2 + 10000 \left(\frac{\dot{v}_c}{1.1} \right)^2 + 10000 \left(\frac{\ddot{v}_c}{1.6} \right)^2 + \left(\frac{P_{m_{tot}}}{351} \right)^2 \right] dt \quad (5.3)$$

with $J_{B-com-combined}$ calculated using Equation 3.45.

The combined comfort-oriented fitness function ($F_{B-com-combined}$) takes the form:

$$F_{B-com-combined} = [J_{B-com-combined}]^{-1} \quad (5.4)$$

5.3.1 GA parameters for optimisation of the controllers for Elevator B (comfort-oriented fitness function)

Following the failure of the CPID controller highlighted in Table 5.5, the K_P , K_I and K_D gain search spaces for both the CPID and NPID controllers are increased. Conversely, the controller gain search spaces for optimisation of the CPDF and NPDF controllers are truncated to ensure more effective convergence. The bounds of the nonlinear α and δ terms, as well as all FSMC and SSMC parameters, remain unchanged. Following the observation of excessive run times, the stopping conditions $k_{GA_{max}}$, $k_{GA_{min}}$ and θ_{GA} are lowered. The full set of parameters may be found in Table 5.12.

Table 5.12: GA parameters for optimisation of the controllers for Elevator B (comfort-oriented fitness function)

Parameter	CPID Controller	CPDF Controller	NPID Controller	NPDF Controller	FSMC	SSMC
Population Size (M_{GA})	16	16	30	30	10	10
Probability of Crossover (P_{GA_c})	0.8	0.8	0.8	0.8	0.8	0.8
Probability of Mutation (P_{GA_m})	0.1	0.1	0.1	0.1	0.1	0.1
K_P Search Space (ψ_{K_P})	0 – 3000	5000 – 20000	0 – 3000	5000 – 20000	-	-
K_I Search Space (ψ_{K_I})	0 – 5000	5000 – 15000	0 – 5000	5000 – 15000	-	-
K_D Search Space (ψ_{K_D})	0 – 9999	0 – 1000	0 – 9999	0 – 1000	-	-
α_P Search Space (ψ_{α_P})	-	-	0 – 2	0.7 – 1.3	-	-
α_I Search Space (ψ_{α_I})	-	-	-2 – 2	0.7 – 1.3	-	-
α_D Search Space (ψ_{α_D})	-	-	0 – 2	0.7 – 1.3	-	-
δ_P Search Space (ψ_{δ_P})	-	-	0.01 – 2	0.01 – 2	-	-
δ_I Search Space (ψ_{δ_I})	-	-	0.01 – 2	0.01 – 2	-	-
δ_D Search Space (ψ_{δ_D})	-	-	0.01 – 2	0.01 – 2	-	-
ρ Search Space (ψ_{ρ})	-	-	-	-	0.35 – 0.7	0.35 – 0.7
K_R Search Space (ψ_{K_R})	-	-	-	-	10 – 200	10 – 200
λ_0 Search Space (ψ_{λ_0})	-	-	-	-	0.01 – 999	0.01 – 999
λ_1 Search Space (ψ_{λ_1})	-	-	-	-	0.01 – 999	0.01 – 999
λ_2 Search Space (ψ_{λ_2})	-	-	-	-	0.01 – 999	0.01 – 999
GA Stopping Condition 1 ($k_{GA_{max}}$)	100	250	100	250	100	100
GA Stopping Condition 2.1 ($k_{GA_{min}}$)	50	100	50	100	50	50
GA Stopping Condition 2.2 (θ_{GA})	20	50	20	50	20	20

5.3.2 Solution repeatability for Elevator B (comfort-oriented fitness function)

Table 5.13: Solution repeatability of controller optimisation for Elevator B (comfort-oriented fitness function)

Parameter	CPID Controller		CPDF Controller		NPID Controller		NPDF Controller		FSMC		SSMC	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Proportional Gain (K_P)	1666.09	279.25	14105	2695.89	1616.61	594.9941	12898.95	1558.79	-	-	-	-
Integral Gain (K_I)	2933.82	445.28	11367.90	2155.52	2814.08	979.4647	12347.43	1685.92	-	-	-	-
Derivative Gain (K_D)	7377.00	1124.83	267.45	43.58	7071.86	2269.739	596.00	193.75	-	-	-	-
Proportional Alpha Term (α_P)	-	-	-	-	1.0540	0.3800	1.1269	0.1029	-	-	-	-
Integral Alpha Term (α_I)	-	-	-	-	0.2500	0.7948	1.0521	0.0952	-	-	-	-
Derivative Alpha Term (α_D)	-	-	-	-	1.0444	0.4404	0.8550	0.1715	-	-	-	-
Proportional Delta Term (δ_P)	-	-	-	-	0.9154	0.5841	0.7997	0.4284	-	-	-	-
Integral Delta Term (δ_I)	-	-	-	-	1.3261	0.6491	0.9955	0.4935	-	-	-	-
Derivative Delta Term (δ_D)	-	-	-	-	0.7890	0.5718	0.8304	0.4564	-	-	-	-
Saturation Function Coefficient (ρ)	-	-	-	-	-	-	-	-	0.6084	0.0479	0.5584	0.1100
Reaching Law Gain (K_R)	-	-	-	-	-	-	-	-	72.92	31.35	87.44	23.81
λ_0 Coefficient	-	-	-	-	-	-	-	-	363.25	143.03	362.80	104.77
λ_1 Coefficient	-	-	-	-	-	-	-	-	400.37	188.83	393.64	133.05
λ_2 Coefficient	-	-	-	-	-	-	-	-	742.97	239.62	782.46	146.93
Fitness Value ($F_{B-com-combined}$)	65.542	0.009	78.818	0.063	65.565	0.024	80.585	0.149	65.855	0.028	65.868	0.012
GA Iterations (k_{GA})	58	15	135	28	56	10	137	39	66	19	75	11
GA Run Time [s]	38132	13115	25219	9359	46084	19214	47589	22351	45334	13109	44401	7938
GA Run Time/10 Individuals [s]	402.85	49.02	115.71	29.82	271.21	101.21	112.50	31.14	689.85	68.21	593.83	33.45

5.3.3 Comparison of control results for Elevator B (comfort-oriented fitness function)

Table 5.14: Controller performance summary – Elevator B (comfort-oriented fitness function)

Parameter	CPID Controller	CPDF Controller	NPID Controller	NPDF Controller	FSMC	SSMC
Proportional Gain (K_P)	1560.30	18588	1158	14077	-	-
Integral Gain (K_I)	2835	14973	1334.20	13313	-	-
Derivative Gain (K_D)	7478.80	345.19	5953.30	648.17	-	-
Proportional Alpha Term (α_P)	-	-	1.2780	1.0828	-	-
Integral Alpha Term (α_I)	-	-	1.1647	1.0118	-	-
Derivative Alpha Term (α_D)	-	-	1.2714	0.8407	-	-
Proportional Delta Term (δ_P)	-	-	0.1226	1.2400	-	-
Integral Delta Term (δ_I)	-	-	1.9733	1.7236	-	-
Derivative Delta Term (δ_D)	-	-	0.0190	1.3000	-	-
Saturation Function Coefficient (ρ)	-	-	-	-	0.6451	0.4096
Reaching Law Gain (K_R)	-	-	-	-	64.63	113.46
λ_0 Coefficient	-	-	-	-	315.65	309.29
λ_1 Coefficient	-	-	-	-	351.87	302.59
λ_2 Coefficient	-	-	-	-	708.66	748.94
Fitness Value ($F_{B-com-combined}$)	65.553	78.905	65.623	80.767	65.883	65.883
GA Iterations (k_{GA})	50	155	76	127	70	81
GA Run Time [s]	30036	21033	79185	48430	47321	52729
GA Run Time/10 Individuals [s]	375.45	84.81	347.30	127.11	676.01	650.98
Rise Time [s] (3200 kg Cabin, 1000 m Upwards Travel)	8.92	9.77	8.92	10.30	8.89	8.89
Settling Time [s] (3200 kg Cabin, 1000 m Upwards Travel)	10.15	12.21	10.15	12.86	10.16	10.16
Velocity Overshoot [%] (3200 kg Cabin, 1000 m Upwards Travel)	0.66	0.64	0.65	0.64	0.66	0.65

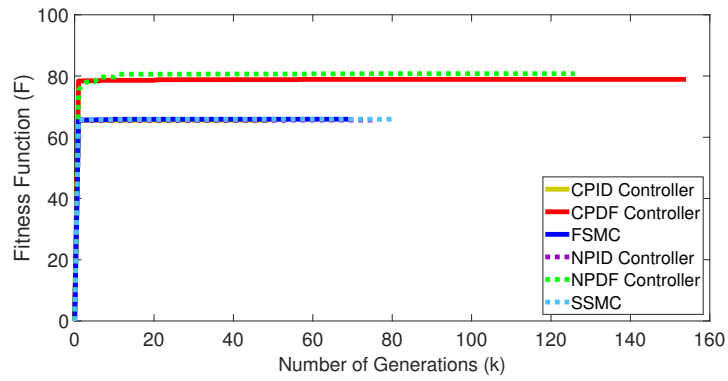


Figure 5.16: Evolution of the fitness function ($F_{B-combined}$) vs. the number of population generations in the GA (k_{GA}) – Elevator B (comfort-oriented fitness function)

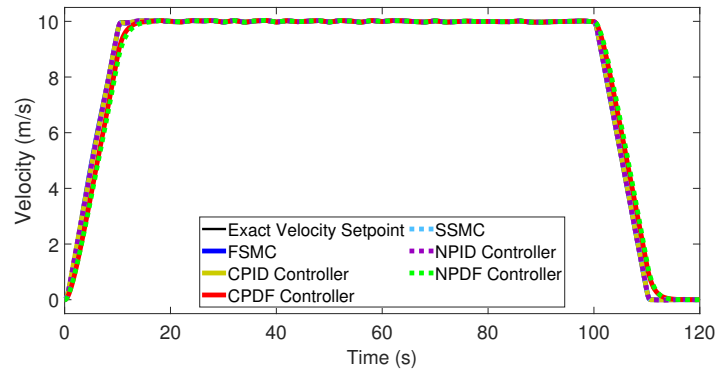


Figure 5.17: Velocity response of the 3200 kg cabins – Elevator B (comfort-oriented fitness function). Refer to Figures 10.9 and 10.10 for more detail.

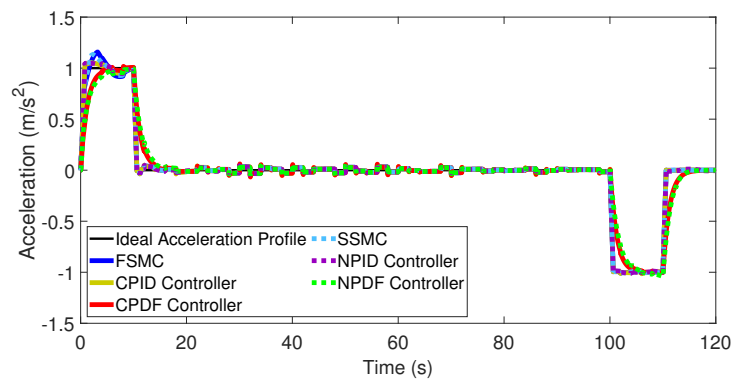


Figure 5.18: Acceleration response of the 3200 kg cabins – Elevator B (comfort-oriented fitness function). Refer to Figures 10.11 – 10.13 for more detail.

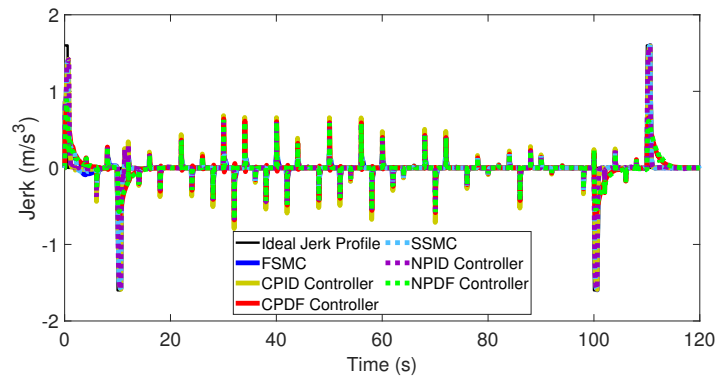


Figure 5.19: Jerk response of the 3200 kg cabins – Elevator B (comfort-oriented fitness function). Refer to Figures 10.14 – 10.16 for more detail.

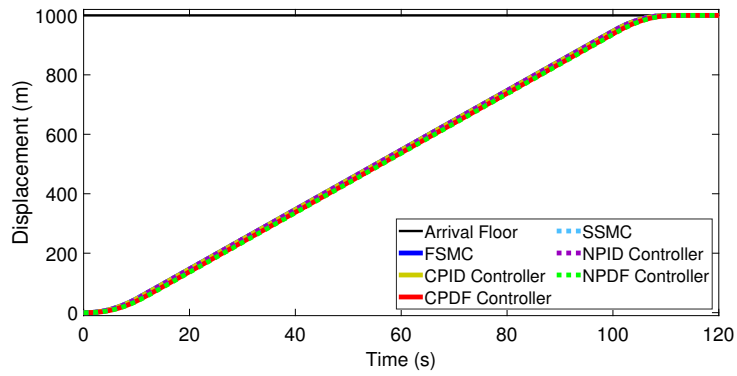


Figure 5.20: Displacement response of the 3200 kg cabins – Elevator B (comfort-oriented fitness function)

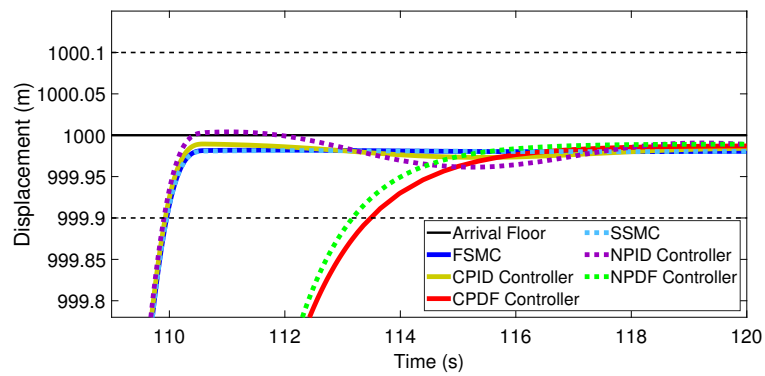


Figure 5.21: Displacement response of the 3200 kg cabins (zoomed into the moment of arrival) – Elevator B (comfort-oriented fitness function)

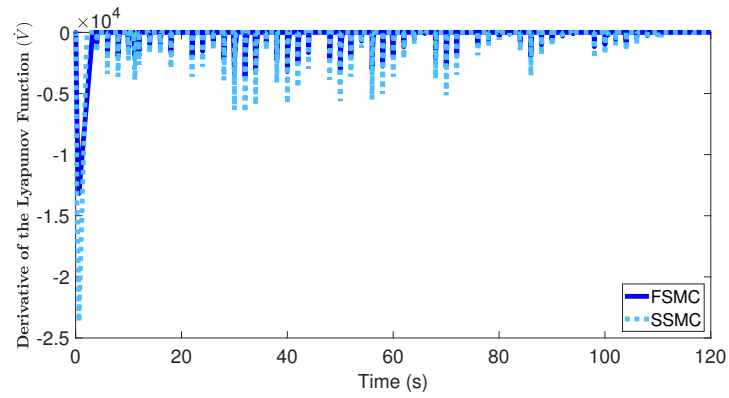


Figure 5.22: Derivative of the Lyapunov function ($\dot{V}$) during SMC control of the 3200 kg cabins – Elevator B (comfort-oriented fitness function)

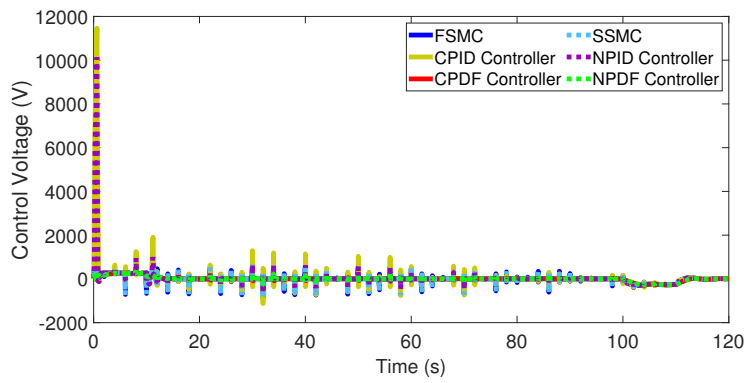


Figure 5.23: Control voltage output during control of the 3200 kg cabins – Elevator B (comfort-oriented fitness function)

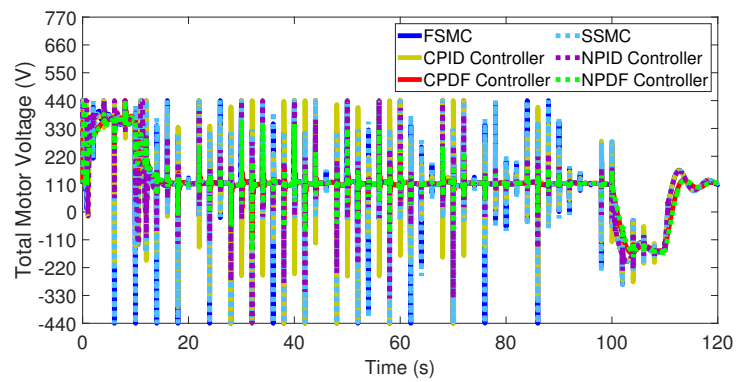


Figure 5.24: Total motor voltage during control of the 3200 kg cabins – Elevator B (comfort-oriented fitness function)

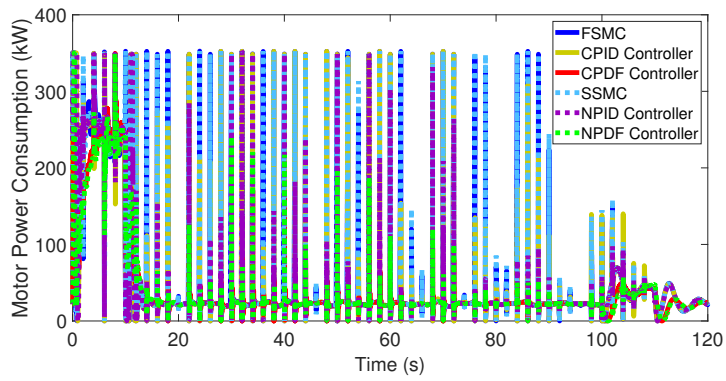


Figure 5.25: Total motor power consumption during control of the 3200 kg cabins – Elevator B (comfort-oriented fitness function)

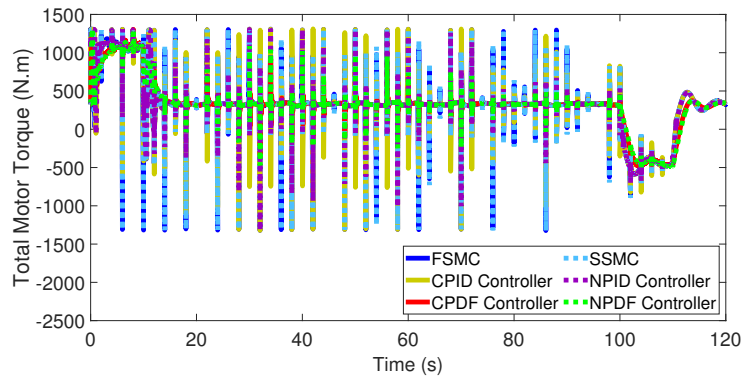


Figure 5.26: Total motor torque during actuation of the 3200 kg cabins – Elevator B (comfort-oriented fitness function)

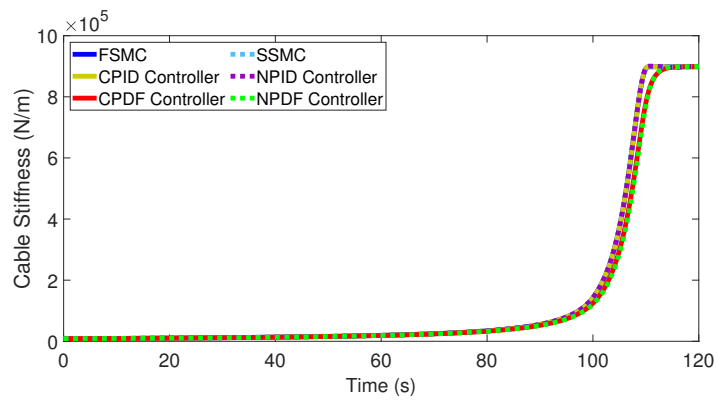


Figure 5.27: Change in the cabin-side cable stiffness (k_c) during control of the 3200 kg cabin – Elevator B (comfort-oriented fitness function)

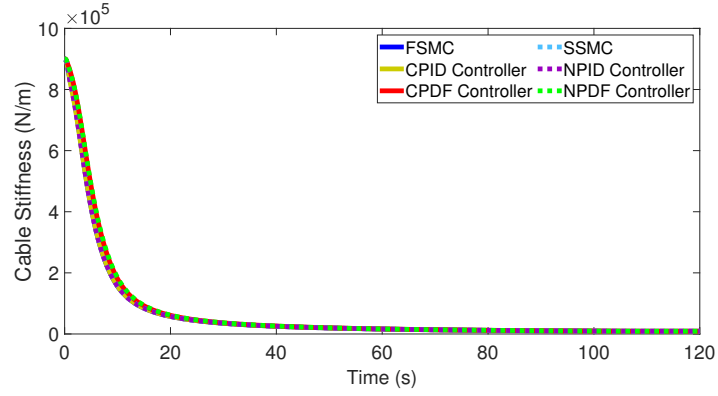


Figure 5.28: Change in the counterweight-side cable stiffness (k_w) during control of the 3200 kg cabin – Elevator B (comfort-oriented fitness function)

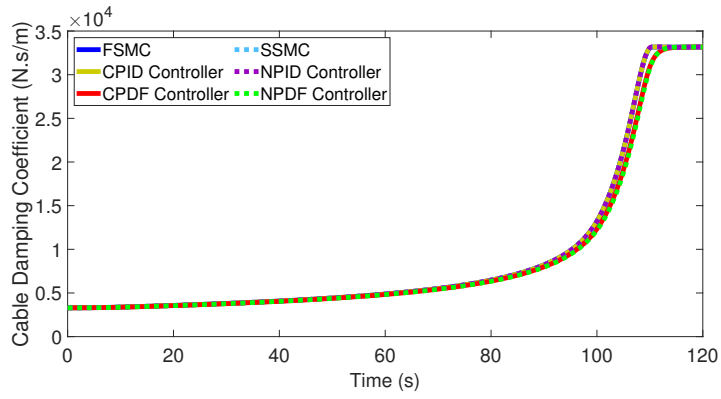


Figure 5.29: Change in the cabin-side cable damping coefficient (c_c) during control of the 3200 kg cabin – Elevator B (comfort-oriented fitness function)

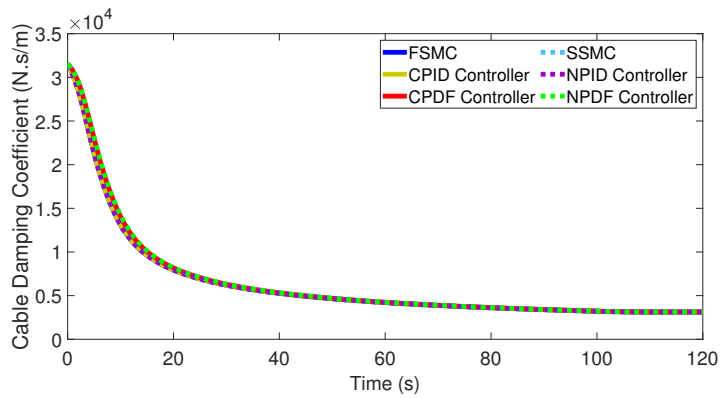


Figure 5.30: Change in the counterweight-side cable damping coefficient (c_w) during control of the 3200 kg cabin – Elevator B (comfort-oriented fitness function)

5.3.4 Robustness analysis for Elevator B (comfort-oriented fitness function)

5.3.4.1 Robustness analysis – CPID controller for Elevator B (comfort-oriented fitness function)

Table 5.15: Robustness analysis – CPID controller for control of Elevator B (comfort-oriented fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	21.870	21.870	21.870	21.869	21.869
	Pass	Pass	Pass	Pass	Pass
400 m	3.28e-09	3.28e-09	3.28e-09	3.28e-09	3.29e-09
	D (+0.12m)	D (+0.12m)	D (+0.12m)	D (+0.12m)	D (+0.12m)
600 m	4.36e-09	4.36e-09	4.37e-09	4.37e-09	4.37e-09
	D (+0.25m)	D (+0.25m)	D (+0.25m)	D (+0.25m)	D (+0.25m)
800 m	5.44e-09	5.44e-09	5.48e-09	5.48e-09	5.48e-09
	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)
1000 m	65.352	6.53e-09	65.572	65.606	65.613
	Pass	J (+0.20m/s ³)	Pass	Pass	Pass
-1000 m	65.349	65.419	65.738	65.766	65.787
	Pass	Pass	Pass	Pass	Pass
-800 m	5.44e-09	5.44e-09	5.46e-09	5.47e-09	5.47e-09
	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.16m)	D (-0.18m)
-600 m	4.36e-09	4.36e-09	4.36e-09	4.36e-09	4.37e-09
	D (-0.25m)	D (-0.25m)	D (-0.25m)	D (-0.25m)	D (-0.25m)
-400 m	3.28e-09	3.28e-09	3.28e-09	3.28e-09	3.28e-09
	D (-0.12m)	D (-0.12m)	D (-0.12m)	D (-0.12m)	D (-0.12m)
-200 m	21.869	21.869	21.869	21.869	21.868
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.3.4.2 Robustness analysis – CPDF controller for Elevator B (comfort-oriented fitness function)

Table 5.16: Robustness analysis – CPDF controller for control of Elevator B (comfort-oriented fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	26.505	26.504	26.503	26.501	26.499
	Pass	Pass	Pass	Pass	Pass
400 m	3.96e-09	3.96e-09	3.96e-09	3.96e-09	3.96e-09
	D (+0.12m)	D (+0.12m)	D (+0.12m)	D (+0.12m)	D (+0.12m)
600 m	5.26e-09	5.26e-09	5.26e-09	5.26e-09	5.26e-09
	D (+0.25m)	D (+0.25m)	D (+0.25m)	D (+0.25m)	D (+0.25m)
800 m	6.57e-09	6.57e-09	6.57e-09	6.57e-09	6.57e-09
	D (+0.13m)	D (+0.13m)	D (+0.13m)	D (+0.13m)	D (+0.13m)
1000 m	78.918	78.911	78.901	78.895	78.885
	Pass	Pass	Pass	Pass	Pass
-1000 m	78.933	78.927	78.918	78.912	78.904
	Pass	Pass	Pass	Pass	Pass
-800 m	6.57e-09	6.57e-09	6.57e-09	6.57e-09	6.57e-09
	D (-0.13m)	D (-0.13m)	D (-0.13m)	D (-0.13m)	D (-0.13m)
-600 m	5.26e-09	5.26e-09	5.26e-09	5.26e-09	5.26e-09
	D (-0.25m)	D (-0.25m)	D (-0.25m)	D (-0.25m)	D (-0.25m)
-400 m	3.96e-09	3.96e-09	3.96e-09	3.96e-09	3.96e-09
	D (-0.12m)	D (-0.12m)	D (-0.12m)	D (-0.12m)	D (-0.12m)
-200 m	26.506	26.505	26.503	26.502	26.500
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.3.4.3 Robustness analysis – NPID controller for Elevator B (comfort-oriented fitness function)

Table 5.17: Robustness analysis – NPID controller for control of Elevator B (comfort-oriented fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	21.889	21.890	21.891	21.891	21.891
	Pass	Pass	Pass	Pass	Pass
400 m	3.29e-09	3.29e-09	3.29e-09	3.29e-09	3.29e-09
	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)
600 m	4.37e-09	4.37e-09	4.37e-09	4.38e-09	4.38e-09
	D (+0.26m)	D (+0.26m)	D (+0.26m)	D (+0.27m)	D (+0.27m)
800 m	5.45e-09	5.45e-09	5.48e-09	5.49e-09	5.48e-09
	D (+0.16m)	D (+0.16m)	D (+0.16m)	D (+0.16m)	D (+0.16m)
1000 m	65.430	6.53e-09	65.651	65.684	65.683
	Pass	J (+0.20m/s ³)	Pass	Pass	Pass
-1000 m	65.427	65.483	65.786	65.799	65.783
	Pass	Pass	Pass	Pass	Pass
-800 m	5.45e-09	5.45e-09	5.47e-09	5.48e-09	5.47e-09
	D (-0.16m)	D (-0.16m)	D (-0.16m)	D (-0.15m)	D (-0.17m)
-600 m	4.37e-09	4.37e-09	4.37e-09	4.37e-09	4.37e-09
	D (-0.26m)	D (-0.26m)	D (-0.27m)	D (-0.27m)	D (-0.25m)
-400 m	3.29e-09	3.29e-09	3.29e-09	3.29e-09	3.29e-09
	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.14m)
-200 m	21.888	21.890	21.891	21.891	21.891
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.3.4.4 Robustness analysis – NPDF controller for Elevator B (comfort-oriented fitness function)

Table 5.18: Robustness analysis – NPDF controller for control of Elevator B (comfort-oriented fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	27.116	27.115	27.113	27.112	27.110
	Pass	Pass	Pass	Pass	Pass
400 m	4.05e-09	4.05e-09	4.05e-09	4.05e-09	4.05e-09
	D (+0.13m)	D (+0.13m)	D (+0.13m)	D (+0.13m)	D (+0.13m)
600 m	5.38e-09	5.38e-09	5.38e-09	5.38e-09	5.38e-09
	D (+0.25m)	D (+0.25m)	D (+0.25m)	D (+0.25m)	D (+0.25m)
800 m	6.73e-09	6.73e-09	6.73e-09	6.73e-09	6.73e-09
	D (+0.13m)	D (+0.13m)	D (+0.13m)	D (+0.13m)	D (+0.13m)
1000 m	80.781	80.775	80.766	80.748	80.712
	Pass	Pass	Pass	Pass	Pass
-1000 m	80.804	80.801	80.795	80.790	80.783
	Pass	Pass	Pass	Pass	Pass
-800 m	6.73e-09	6.73e-09	6.73e-09	6.73e-09	6.73e-09
	D (-0.13m)	D (-0.13m)	D (-0.13m)	D (-0.13m)	D (-0.13m)
-600 m	5.38e-09	5.38e-09	5.38e-09	5.38e-09	5.38e-09
	D (-0.25m)	D (-0.25m)	D (-0.25m)	D (-0.25m)	D (-0.25m)
-400 m	4.05e-09	4.05e-09	4.05e-09	4.05e-09	4.05e-09
	D (-0.13m)	D (-0.13m)	D (-0.13m)	D (-0.13m)	D (-0.13m)
-200 m	27.117	27.116	27.114	27.113	27.111
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.3.4.5 Robustness analysis – FSMC for Elevator B (comfort-oriented fitness function)

Table 5.19: Robustness analysis – FSMC for control of Elevator B (comfort-oriented fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	21.878	21.878	21.878	21.877	21.880
	Pass	Pass	Pass	Pass	Pass
400 m	3.29e-09	3.29e-09	3.29e-09	3.29e-09	3.30e-09
	D (+0.11m)	D (+0.11m)	D (+0.11m)	D (+0.11m)	D (+0.11m)
600 m	4.37e-09	4.37e-09	4.38e-09	4.39e-09	4.39e-09
	D (+0.24m)	D (+0.24m)	D (+0.24m)	D (+0.24m)	D (+0.24m)
800 m	5.45e-09	5.45e-09	5.50e-09	5.51e-09	5.50e-09
	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)
1000 m	65.524	6.55e-09	65.967	65.968	65.899
	Pass	J (+0.01m/s ³)	Pass	Pass	Pass
-1000 m	65.521	65.666	66.168	66.156	66.083
	Pass	Pass	Pass	Pass	Pass
-800 m	5.45e-09	5.45e-09	5.48e-09	5.49e-09	5.50e-09
	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.15m)	D (-0.16m)
-600 m	4.37e-09	4.37e-09	4.37e-09	4.38e-09	4.38e-09
	D (-0.24m)	D (-0.24m)	D (-0.24m)	D (-0.24m)	D (-0.25m)
-400 m	3.29e-09	3.29e-09	3.29e-09	3.29e-09	3.29e-09
	D (-0.11m)	D (-0.11m)	D (-0.11m)	D (-0.11m)	D (-0.11m)
-200 m	21.878	21.878	21.878	21.877	21.877
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.3.4.6 Robustness analysis – SSMC for Elevator B (comfort-oriented fitness function)

Table 5.20: Robustness analysis – SSMC for control of Elevator B (comfort-oriented fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	21.877	21.877	21.877	21.877	21.879
	Pass	Pass	Pass	Pass	Pass
400 m	3.29e-09	3.29e-09	3.29e-09	3.29e-09	3.30e-09
	D (+0.11m)	D (+0.11m)	D (+0.11m)	D (+0.11m)	D (+0.11m)
600 m	4.37e-09	4.37e-09	4.38e-09	4.39e-09	4.39e-09
	D (+0.24m)	D (+0.24m)	D (+0.24m)	D (+0.24m)	D (+0.24m)
800 m	5.45e-09	5.45e-09	5.50e-09	5.51e-09	5.51e-09
	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)
1000 m	65.498	6.54e-09	65.960	65.980	65.932
	Pass	J (+0.06m/s ³)	Pass	Pass	Pass
-1000 m	65.495	65.630	66.171	66.176	66.150
	Pass	Pass	Pass	Pass	Pass
-800 m	5.45e-09	5.45e-09	5.48e-09	5.49e-09	5.50e-09
	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.15m)	D (-0.16m)
-600 m	4.37e-09	4.37e-09	4.37e-09	4.38e-09	4.38e-09
	D (-0.24m)	D (-0.24m)	D (-0.24m)	D (-0.24m)	D (-0.25m)
-400 m	3.29e-09	3.29e-09	3.29e-09	3.29e-09	3.29e-09
	D (-0.11m)	D (-0.11m)	D (-0.11m)	D (-0.11m)	D (-0.11m)
-200 m	21.878	21.878	21.877	21.876	21.876
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.4 Sustainability-Oriented Fitness Function for Evaluation of the Controllers for Elevator B

The parameters of the sustainability-oriented cost function, designed for the minimisation of power consumption, are given in [Table 5.21](#). The resulting cost function is defined in [Equation 5.5](#).

Table 5.21: Sustainability-oriented cost function parameters for evaluation of the controllers for Elevator B

Parameter	Value
β_{J-B}	1
γ_{J-B}	1
ϵ_{J-B}	1
η_{J-B}	1
κ_{J-B}	10000
ξ_{J-B}	0.001

$$J_{B-sus} = \frac{0.001}{120} \int_0^{120} \left[(v_d - v_c)^2 + (d_d - d_c)^2 + \left(\frac{\dot{v}_c}{1.1} \right)^2 + \left(\frac{\ddot{v}_c}{1.6} \right)^2 + 10000 \left(\frac{P_{m_{tot}}}{351} \right)^2 \right] dt \quad (5.5)$$

$J_{B-sus-combined}$ is computed using [Equation 3.45](#).

The combined sustainability-oriented fitness function ($F_{B-sus-combined}$) is obtained using the following equation:

$$F_{B-sus-combined} = [J_{B-sus-combined}]^{-1} \quad (5.6)$$

5.4.1 GA parameters for optimisation of the controllers for Elevator B (sustainability-oriented fitness function)

As the optimal controller parameters for reducing power consumption are likely to be similar to those for the minimisation of acceleration and jerk, the search space parameters of the GA are left unchanged from those defined in [Table 5.12](#).

5.4.2 Solution repeatability for Elevator B (sustainability-oriented fitness function)

Table 5.22: Solution repeatability of controller optimisation for Elevator B (sustainability-oriented fitness function)

Parameter	CPID Controller		CPDF Controller		NPID Controller		NPDF Controller		FSMC		SSMC	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Proportional Gain (K_P)	554.40	261.40	14619	2708.43	481.28	182.59	11288.60	2617.94	-	-	-	-
Integral Gain (K_I)	3981.36	707.47	11903.80	2151.03	3780.25	1671.44	11662.23	2466.06	-	-	-	-
Derivative Gain (K_D)	2163.15	376.19	555.36	74.21	2380.81	459.50	738.54	235.88	-	-	-	-
Proportional Alpha Term (α_P)	-	-	-	-	0.7839	0.7193	1.0324	0.0814	-	-	-	-
Integral Alpha Term (α_I)	-	-	-	-	1.5845	0.2963	0.9467	0.0766	-	-	-	-
Derivative Alpha Term (α_D)	-	-	-	-	1.1623	0.5427	1.1585	0.1366	-	-	-	-
Proportional Delta Term (δ_P)	-	-	-	-	1.2745	0.5946	1.0147	0.4920	-	-	-	-
Integral Delta Term (δ_I)	-	-	-	-	0.4425	0.4832	1.3443	0.5761	-	-	-	-
Derivative Delta Term (δ_D)	-	-	-	-	1.0916	0.5988	0.6252	0.4521	-	-	-	-
Saturation Function Coefficient (ρ)	-	-	-	-	-	-	-	-	0.5126	0.0963	0.6162	0.0625
Reaching Law Gain (K_R)	-	-	-	-	-	-	-	-	20.82	7.86	17.28	4.39
λ_0 Coefficient	-	-	-	-	-	-	-	-	688.39	262.68	819.27	201.71
λ_1 Coefficient	-	-	-	-	-	-	-	-	298.77	105.73	365.37	99.21
λ_2 Coefficient	-	-	-	-	-	-	-	-	193.51	61.19	228.85	69.95
Fitness Value ($F_{B-sus-combined}$)	1.308	0.005	1.596	0.002	1.313	0.003	1.641	0.010	1.336	0.002	1.335	0.003
GA Iterations (k_{GA})	84	19	134	34	67	15	144	30	80	18	87	16
GA Run Time [s]	47304	15100	31178	7119	47656	25940	40413	11724	50603	13624	48743	12671
GA Run Time/10 Individuals [s]	351.99	70.96	148.29	26.64	226.68	83.86	92.15	11.35	633.39	66.14	556.17	90.39

5.4.3 Comparison of control results for Elevator B (sustainability-oriented fitness function)

Table 5.23: Controller performance summary – Elevator B (sustainability-oriented fitness function)

Parameter	CPID Controller	CPDF Controller	NPID Controller	NPDF Controller	FSMC	SSMC
Proportional Gain (K_P)	366.63	17429	345.10	7500	-	-
Integral Gain (K_I)	3419	14110	3141.20	8354	-	-
Derivative Gain (K_D)	1818.30	499.20	2009.10	955.10	-	-
Proportional Alpha Term (α_P)	-	-	0.9882	1.0750	-	-
Integral Alpha Term (α_I)	-	-	1.2879	0.9652	-	-
Derivative Alpha Term (α_D)	-	-	0.7374	1.2652	-	-
Proportional Delta Term (δ_P)	-	-	1.9709	0.7147	-	-
Integral Delta Term (δ_I)	-	-	0.1319	1.8624	-	-
Derivative Delta Term (δ_D)	-	-	1.9214	0.3251	-	-
Saturation Function Coefficient (ρ)	-	-	-	-	0.5781	0.6688
Reaching Law Gain (K_R)	-	-	-	-	21.46	12.02
λ_0 Coefficient	-	-	-	-	401	360
λ_1 Coefficient	-	-	-	-	161.77	213.46
λ_2 Coefficient	-	-	-	-	116.08	97.58
Fitness Value ($F_{B-sus-combined}$)	1.314	1.598	1.318	1.659	1.340	1.340
GA Iterations (k_{GA})	84	134	100	134	97	100
GA Run Time [s]	41708	35373	92026	31720	60796	53906
GA Run Time/10 Individuals [s]	310.33	164.99	306.75	78.91	626.76	539.06
Rise Time [s] (3200 kg Cabin, 1000 m Upwards Travel)	8.93	9.75	8.88	10.27	8.87	8.88
Settling Time [s] (3200 kg Cabin, 1000 m Upwards Travel)	10.14	12.17	10.11	12.82	10.10	10.10
Velocity Overshoot [%] (3200 kg Cabin, 1000 m Upwards Travel)	0.64	0.64	0.64	0.64	0.64	0.64

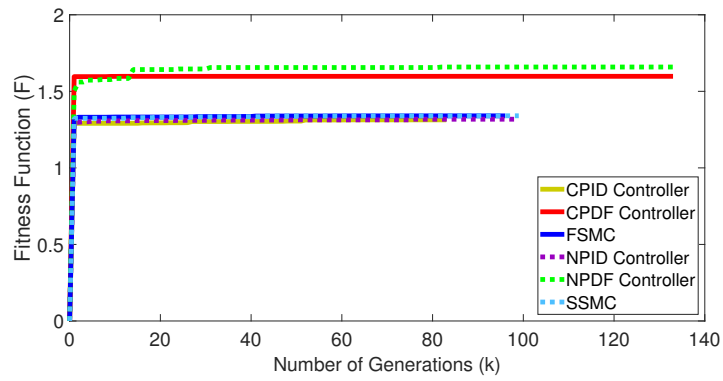


Figure 5.31: Evolution of the fitness function ($F_{B-sus-combined}$) vs. the number of population generations in the GA (k_{GA}) – Elevator B (sustainability-oriented fitness function)

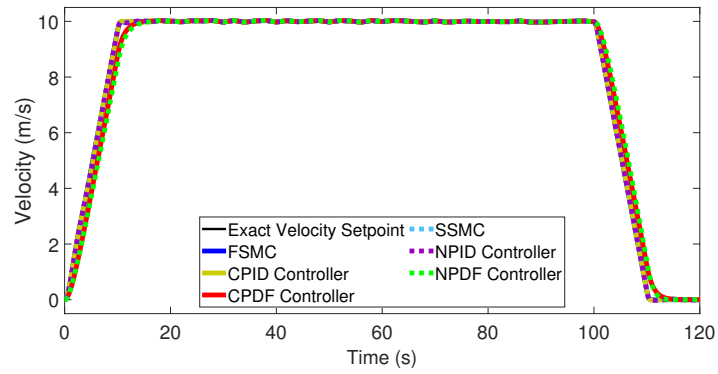


Figure 5.32: Velocity response of the 3200 kg cabins – Elevator B (sustainability-oriented fitness function). Refer to Figures 10.17 and 10.18 for more detail.

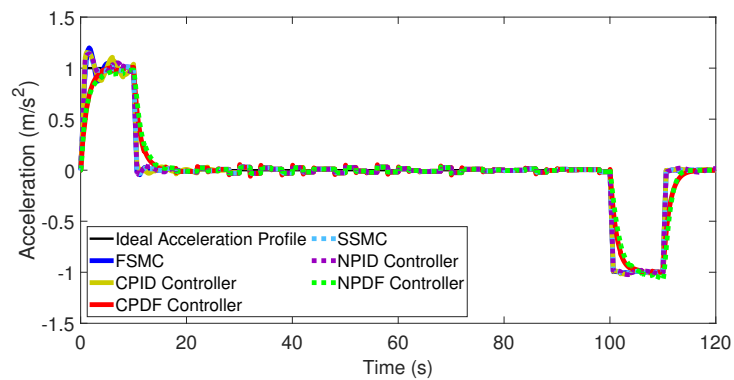


Figure 5.33: Acceleration response of the 3200 kg cabins – Elevator B (sustainability-oriented fitness function). Refer to Figures 10.19 – 10.21 for more detail.

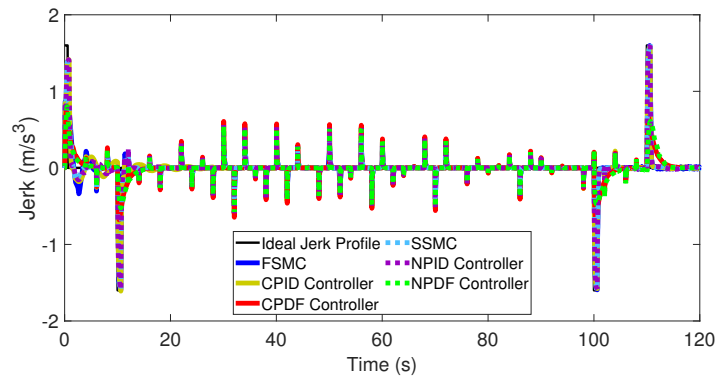


Figure 5.34: Jerk response of the 3200 kg cabins – Elevator B (sustainability-oriented fitness function). Refer to Figures 10.22 – 10.24 for more detail.

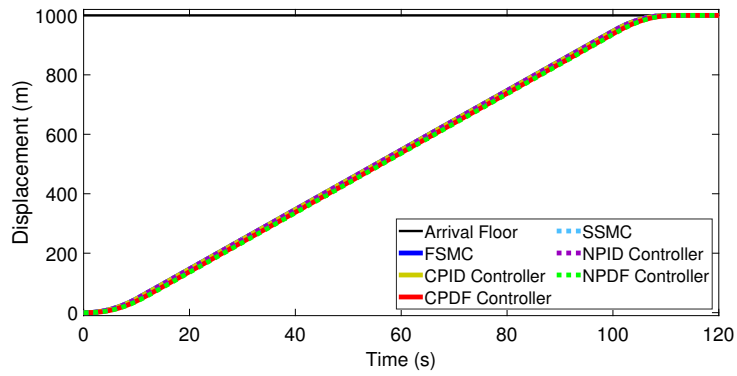


Figure 5.35: Displacement response of the 3200 kg cabins – Elevator B (sustainability-oriented fitness function)

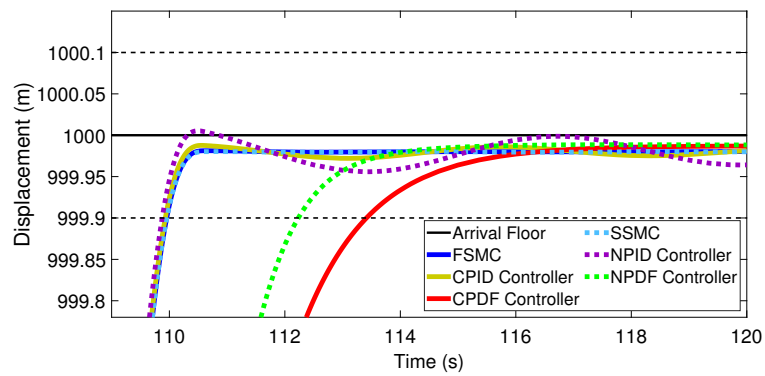


Figure 5.36: Displacement response of the 3200 kg cabins (zoomed into the moment of arrival) – Elevator B (sustainability-oriented fitness function)

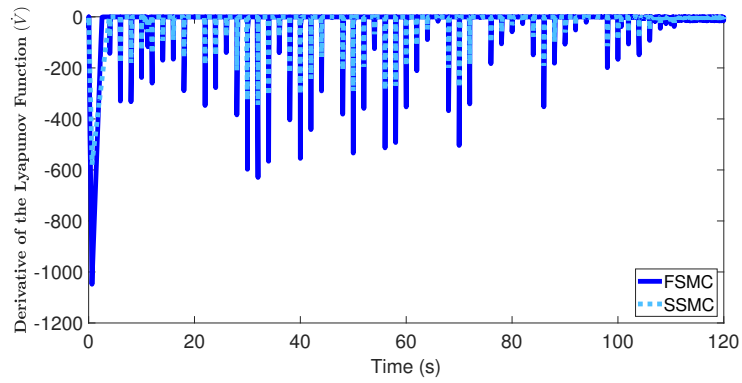


Figure 5.37: Derivative of the Lyapunov function ($\dot{V}$) during SMC control of the 3200 kg cabins – Elevator B (sustainability-oriented fitness function)

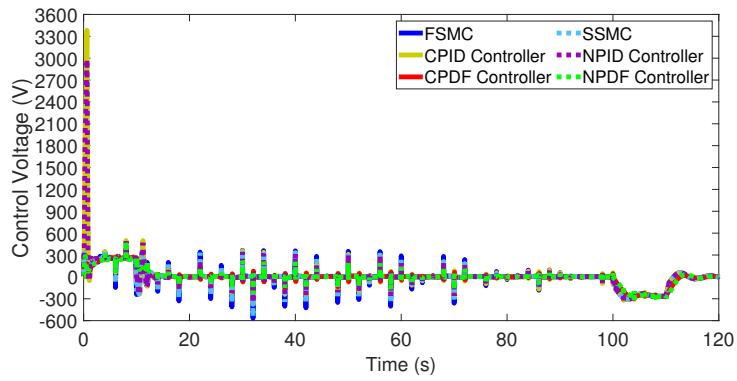


Figure 5.38: Control voltage output during control of the 3200 kg cabins – Elevator B (sustainability-oriented fitness function)

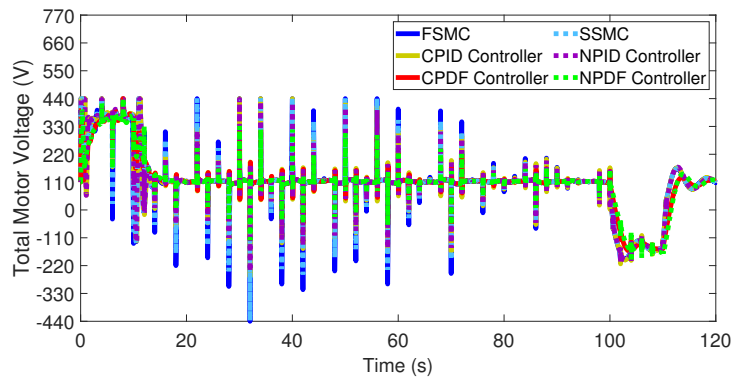


Figure 5.39: Total motor voltage during control of the 3200 kg cabins – Elevator B (sustainability-oriented fitness function)

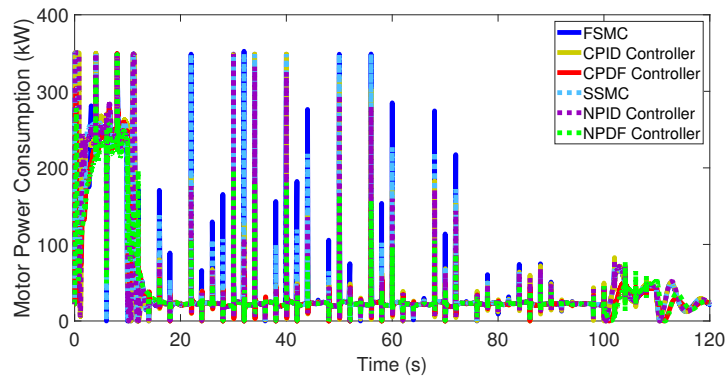


Figure 5.40: Total motor power consumption during control of the 3200 kg cabins – Elevator B (sustainability-oriented fitness function)

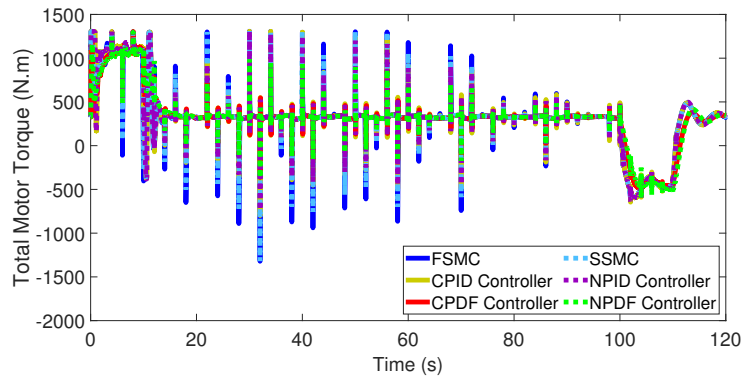


Figure 5.41: Total motor torque during actuation of the 3200 kg cabins – Elevator B (sustainability-oriented fitness function)

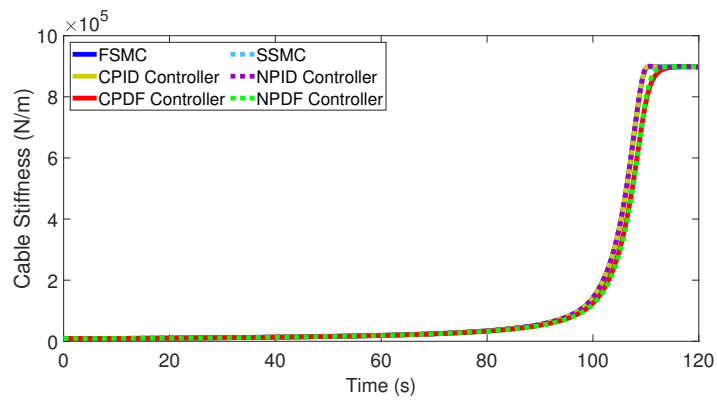


Figure 5.42: Change in the cabin-side cable stiffness (k_c) during control of the 3200 kg cabin – Elevator B (sustainability-oriented fitness function)

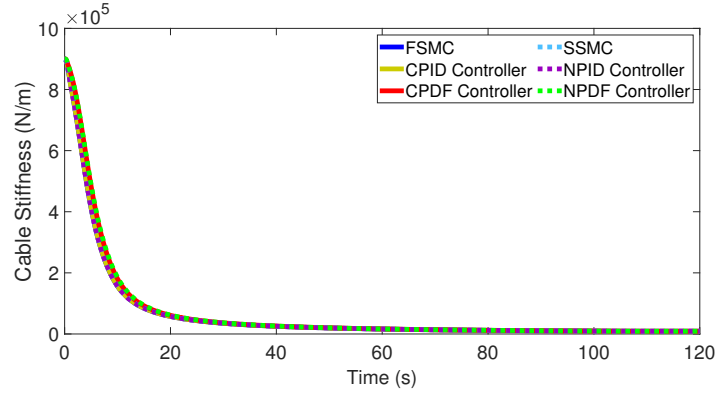


Figure 5.43: Change in the counterweight-side cable stiffness (k_w) during control of the 3200 kg cabin – Elevator B (sustainability-oriented fitness function)

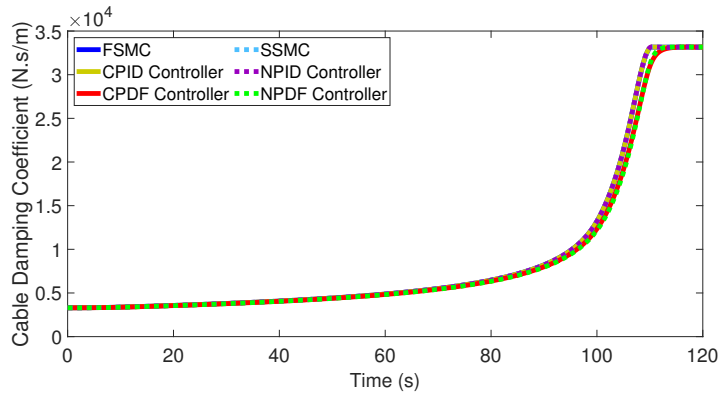


Figure 5.44: Change in the cabin-side cable damping coefficient (c_c) during control of the 3200 kg cabin – Elevator B (sustainability-oriented fitness function)

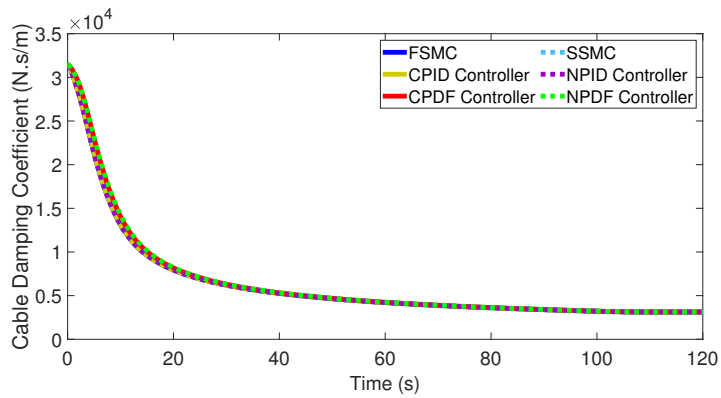


Figure 5.45: Change in the counterweight-side cable damping coefficient (c_w) during control of the 3200 kg cabin – Elevator B (sustainability-oriented fitness function)

5.4.4 Robustness analysis for Elevator B (sustainability-oriented fitness function)

5.4.4.1 Robustness analysis – CPID controller for Elevator B (sustainability-oriented fitness function)

Table 5.24: Robustness analysis – CPID controller for control of Elevator B (sustainability-oriented fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	1.039	2.108	0.816	0.440	0.250
	Pass	Pass	Pass	Pass	Pass
400 m	1.50e-10	3.07e-10	1.18e-10	6.22e-11	3.43e-11
	D (+0.12m)	D (+0.12m)	D (+0.12m)	D (+0.12m)	D (+0.12m)
600 m	1.92e-10	3.90e-10	1.49e-10	7.71e-11	4.17e-11
	D (+0.25m)	D (+0.25m)	D (+0.25m)	D (+0.25m)	D (+0.25m)
800 m	2.28e-10	4.32e-10	1.74e-10	9.00e-11	4.80e-11
	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)
1000 m	2.562	4.73e-10	1.955	0.999	0.525
	Pass	J (+0.22m/s ³)	Pass	Pass	Pass
-1000 m	2.492	4.521	2.005	1.032	0.541
	Pass	Pass	Pass	Pass	Pass
-800 m	2.22e-10	4.47e-10	1.74e-10	8.98e-11	4.80e-11
	D (-0.14m)	D (-0.14m)	D (-0.15m)	D (-0.15m)	D (-0.15m)
-600 m	1.88e-10	3.95e-10	1.53e-10	7.87e-11	4.23e-11
	D (-0.25m)	D (-0.25m)	D (-0.25m)	D (-0.25m)	D (-0.25m)
-400 m	1.48e-10	3.10e-10	1.21e-10	6.37e-11	3.50e-11
	D (-0.12m)	D (-0.12m)	D (-0.12m)	D (-0.12m)	D (-0.12m)
-200 m	1.032	2.123	0.832	0.447	0.254
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.4.4.2 Robustness analysis – CPDF controller for Elevator B (sustainability-oriented fitness function)

Table 5.25: Robustness analysis – CPDF controller for control of Elevator B (sustainability-oriented fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	1.187	2.573	0.943	0.496	0.277
	Pass	Pass	Pass	Pass	Pass
400 m	1.71e-10	3.83e-10	1.39e-10	7.09e-11	3.82e-11
	D (+0.12m)	D (+0.12m)	D (+0.12m)	D (+0.12m)	D (+0.12m)
600 m	2.21e-10	5.09e-10	1.82e-10	9.01e-11	4.70e-11
	D (+0.25m)	D (+0.25m)	D (+0.25m)	D (+0.25m)	D (+0.25m)
800 m	2.69e-10	6.33e-10	2.23e-10	1.07e-10	5.44e-11
	D (+0.13m)	D (+0.13m)	D (+0.13m)	D (+0.13m)	D (+0.13m)
1000 m	3.111	7.360	2.570	1.214	0.603
	Pass	Pass	Pass	Pass	Pass
-1000 m	3.046	7.389	2.641	1.248	0.619
	Pass	Pass	Pass	Pass	Pass
-800 m	2.63e-10	6.25e-10	2.26e-10	9.18e-11	5.54e-11
	D (-0.13m)	D (-0.13m)	D (-0.13m)	D (-0.13m)	D (-0.13m)
-600 m	2.18e-10	5.07e-10	1.85e-10	9.14e-11	4.77e-11
	D (-0.25m)	D (-0.25m)	D (-0.25m)	D (-0.25m)	D (-0.25m)
-400 m	1.70e-10	3.86e-10	1.42e-10	7.21e-11	3.88e-11
	D (-0.12m)	D (-0.12m)	D (-0.12m)	D (-0.12m)	D (-0.12m)
-200 m	1.183	2.609	0.964	0.504	0.281
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.4.4.3 Robustness analysis – NPID controller for Elevator B (sustainability-oriented fitness function)

Table 5.26: Robustness analysis – NPID controller for control of Elevator B (sustainability-oriented fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	1.039	2.104	0.814	0.439	0.249
	Pass	Pass	Pass	Pass	Pass
400 m	1.50e-10	3.07e-10	1.18e-10	6.21e-11	3.42e-11
	D (+0.13m)	D (+0.13m)	D (+0.13m)	D (+0.13m)	D (+0.13m)
600 m	1.92e-10	3.89e-10	1.49e-10	7.70e-11	4.17e-11
	D (+0.26m)	D (+0.26m)	D (+0.26m)	D (+0.26m)	D (+0.26m)
800 m	2.29e-10	4.33e-10	1.73e-10	8.99e-11	4.80e-11
	D (+0.16m)	D (+0.16m)	D (+0.16m)	D (+0.16m)	D (+0.16m)
1000 m	2.569	4.75e-10	1.963	1.003	0.527
	Pass	J (+0.20m/s ³)	Pass	Pass	Pass
-1000 m	2.500	4.527	2.005	1.033	0.543
	Pass	Pass	Pass	Pass	Pass
-800 m	2.23e-10	4.47e-10	1.74e-10	8.98e-11	4.80e-11
	D (-0.15m)	D (-0.15m)	D (-0.15m)	D (-0.15m)	D (-0.15m)
-600 m	1.88e-10	3.95e-10	1.52e-10	7.86e-11	4.23e-11
	D (-0.26m)	D (-0.26m)	D (-0.26m)	D (-0.26m)	D (-0.26m)
-400 m	1.48e-10	3.10e-10	1.21e-10	6.36e-11	3.49e-11
	D (-0.13m)	D (-0.13m)	D (-0.13m)	D (-0.13m)	D (-0.13m)
-200 m	1.029	2.119	0.831	0.447	0.253
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.4.4.4 Robustness analysis – NPDF controller for Elevator B (sustainability-oriented fitness function)

Table 5.27: Robustness analysis – NPDF controller for control of Elevator B (sustainability-oriented fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	1.141	2.606	1.005	0.523	0.289
	Pass	Pass	Pass	Pass	Pass
400 m	1.65e-10	3.88e-10	1.48e-10	7.44e-11	3.96e-11
	D (+0.13m)	D (+0.13m)	D (+0.13m)	D (+0.13m)	D (+0.13m)
600 m	2.13e-10	5.15e-10	1.91e-10	9.43e-11	4.86e-11
	D (+0.25m)	D (+0.25m)	D (+0.25m)	D (+0.25m)	D (+0.25m)
800 m	2.61e-10	6.40e-10	2.35e-10	1.12e-10	5.60e-11
	D (+0.13m)	D (+0.13m)	D (+0.13m)	D (+0.13m)	D (+0.13m)
1000 m	3.020	7.546	2.756	1.279	0.626
	Pass	Pass	Pass	Pass	Pass
-1000 m	3.242	7.738	2.632	1.245	0.619
	Pass	Pass	Pass	Pass	Pass
-800 m	2.79e-10	6.44e-10	2.20e-10	1.07e-10	5.48e-11
	D (-0.13m)	D (-0.13m)	D (-0.13m)	D (-0.13m)	D (-0.13m)
-600 m	2.32e-10	5.21e-10	1.79e-10	8.93e-11	4.69e-11
	D (-0.25m)	D (-0.25m)	D (-0.25m)	D (-0.25m)	D (-0.25m)
-400 m	1.81e-10	3.94e-10	1.37e-10	7.02e-11	3.80e-11
	D (-0.13m)	D (-0.13m)	D (-0.13m)	D (-0.13m)	D (-0.13m)
-200 m	1.260	2.660	0.930	0.490	0.275
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.4.4.5 Robustness analysis – FSMC for Elevator B (sustainability-oriented fitness function)

Table 5.28: Robustness analysis – FSMC for control of Elevator B (sustainability-oriented fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	1.042	2.118	0.818	0.440	0.250
	Pass	Pass	Pass	Pass	Pass
400 m	1.51e-10	3.09e-10	1.18e-10	6.23e-11	3.43e-11
	D (+0.11m)	D (+0.11m)	D (+0.11m)	D (+0.11m)	D (+0.11m)
600 m	1.93e-10	3.89e-10	1.49e-10	7.71e-11	4.16e-11
	D (+0.24m)	D (+0.24m)	D (+0.24m)	D (+0.24m)	D (+0.24m)
800 m	2.29e-10	4.28e-10	1.82e-10	9.26e-11	4.87e-11
	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)
1000 m	2.564	4.69e-10	2.005	1.021	0.533
	Pass	J (+0.12m/s ³)	Pass	Pass	Pass
-1000 m	2.501	4.572	2.114	1.070	0.554
	Pass	Pass	Pass	Pass	Pass
-800 m	2.24e-10	4.41e-10	1.75e-10	9.06e-11	4.83e-11
	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.14m)
-600 m	1.90e-10	3.93e-10	1.52e-10	7.86e-11	4.22e-11
	D (-0.24m)	D (-0.24m)	D (-0.24m)	D (-0.24m)	D (-0.24m)
-400 m	1.49e-10	3.12e-10	1.22e-10	6.38e-11	3.51e-11
	D (-0.11m)	D (-0.11m)	D (-0.11m)	D (-0.11m)	D (-0.11m)
-200 m	1.036	2.134	0.833	0.448	0.254
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

5.4.4.6 Robustness analysis – SSMC for Elevator B (sustainability-oriented fitness function)

Table 5.29: Robustness analysis – SSMC for control of Elevator B (sustainability-oriented fitness function)

Lifting Height	Mass of Elevator B Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	1.043	2.120	0.818	0.440	0.250
	Pass	Pass	Pass	Pass	Pass
400 m	1.51e-10	3.10e-10	1.19e-10	6.24e-11	3.43e-11
	D (+0.11m)	D (+0.11m)	D (+0.11m)	D (+0.11m)	D (+0.11m)
600 m	1.93e-10	3.91e-10	1.49e-10	7.73e-11	4.18e-11
	D (+0.24m)	D (+0.24m)	D (+0.24m)	D (+0.24m)	D (+0.24m)
800 m	2.30e-10	4.30e-10	1.79e-10	9.16e-11	4.84e-11
	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)
1000 m	2.573	4.76e-10	2.008	1.021	0.533
	Pass	J (+0.08m/s ³)	Pass	Pass	Pass
-1000 m	2.509	4.632	2.112	1.069	0.553
	Pass	Pass	Pass	Pass	Pass
-800 m	2.24e-10	4.45e-10	1.76e-10	9.09e-11	4.81e-11
	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.14m)
-600 m	1.90e-10	3.95e-10	1.53e-10	7.87e-11	4.22e-11
	D (-0.24m)	D (-0.24m)	D (-0.24m)	D (-0.24m)	D (-0.24m)
-400 m	1.49e-10	3.12e-10	1.22e-10	6.39e-11	3.51e-11
	D (-0.11m)	D (-0.11m)	D (-0.11m)	D (-0.11m)	D (-0.11m)
-200 m	1.036	2.136	0.834	0.448	0.254
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

6 Numerical Simulations for Control of Elevator C

6.1 Chapter Outline

The performance of the RBFNN-SMC is analysed in this chapter, with the control system being compared with the NPID, NPDE, FSMC and SSMC architectures. The parameters of each of the controllers are optimised using the GA-code as before; however, unlike in previous chapters, manual tuning is performed prior to the optimisation procedure in order to determine highly-fit initial guesses. As the RBFNN-SMC was designed using the SSMC as the baseline, the optimised SMC parameters of the SSMC are applied to the RBFNN-SMC. A brief GA-optimisation of the RBFNN parameters (namely the number of hidden layer neurons (n_n), initial connection weights (w_0), first RBFNN centre (c_1), RBFNN centre spread (b) and the adaptive law parameter (γ)) is then performed in order to evaluate the effects on the solution fitness.

Following optimisation and a thorough analysis of the pre-re-levelling control results, adaptive re-levelling is implemented to each of the controllers. The response to re-levelling is evaluated for a 3200 kg cabin travelling upwards for a distance of 1000 m, in addition to the travel procedure that exhibited the worst performance during the robustness analysis.

After completion of the simulations, the chattering behaviour of six SMC architectures is examined. The six controller types are – FSMC (saturation function), FSMC (sign function), SSMC (saturation function), SSMC (sign function), RBFNN-SMC (saturation function) and RBFNN-SMC (sign function). The SMC parameters K_R , λ_0 , λ_1 and λ_2 are identical for all six SMC variants, with the parameters taken from the GA-optimised SSMC. Three of the SMCs inherit the saturation function parameter (ρ) of the GA-optimised SSMC, while the remaining three controllers utilise a sign function. The two RBFNN-SMCs have the RBFNN parameters taken from the GA-optimised RBFNN-SMC.

6.2 GA Parameters for Optimisation of the Controllers for Elevator C

The search space parameters for GA-optimisation of the controllers for Elevator C were determined through manual tuning, as well as using knowledge gained from the procedures in previous chapters. The optimisation process for the RBFNN-SMC is set to run for exactly 25 iterations due to the high run time of the control architecture. Hence, there is no θ_{GA} term for GA-optimisation of the RBFNN-SMC. The GA parameters are given in Table 6.1, while the initial guesses, obtained through the manual tuning procedure, are provided in Table 6.2.

Table 6.1: GA parameters for optimisation of the controllers for Elevator C

Parameter	NPID Controller	NPDF Controller	FSMC	SSMC	RBFNN-SMC
Population Size (M_{GA})	30	30	10	10	10
Probability of Crossover (P_{GA_c})	0.8	0.8	0.8	0.8	0.8
Probability of Mutation (P_{GA_m})	0.1	0.1	0.1	0.1	0.1
K_P Search Space (ψ_{K_P})	5000 – 9999	5000 – 15000	-	-	-
K_I Search Space (ψ_{K_I})	0 – 5000	5000 – 30000	-	-	-
K_D Search Space (ψ_{K_D})	0 – 9999	0 – 5000	-	-	-
α_P Search Space (ψ_{α_P})	0 – 2	0.7 – 1.1	-	-	-
α_I Search Space (ψ_{α_I})	-2 – 2	0.7 – 1.1	-	-	-
α_D Search Space (ψ_{α_D})	0 – 2	0.7 – 1.1	-	-	-
δ_P Search Space (ψ_{δ_P})	0.01 – 2	0.01 – 10	-	-	-
δ_I Search Space (ψ_{δ_I})	0.01 – 2	0.01 – 10	-	-	-
δ_D Search Space (ψ_{δ_D})	0.01 – 2	0.01 – 10	-	-	-
ρ Search Space (ψ_{ρ})	-	-	0.35 – 0.7	0.35 – 0.7	-
K_R Search Space (ψ_{K_R})	-	-	10 – 200	10 – 200	-
λ_0 Search Space (ψ_{λ_0})	-	-	0.01 – 999	0.01 – 999	-
λ_1 Search Space (ψ_{λ_1})	-	-	0.01 – 999	0.01 – 999	-
λ_2 Search Space (ψ_{λ_2})	-	-	0.01 – 999	0.01 – 999	-
n_n Search Space (ψ_{n_n})	-	-	-	-	3 – 10
w_0 Search Space (ψ_{w_0})	-	-	-	-	-100 – 100
c_1 Search Space (ψ_{c_1})	-	-	-	-	-2000 – -1400
b Search Space (ψ_b)	-	-	-	-	1000 – 3000
γ Search Space (ψ_{γ})	-	-	-	-	100000 – 200000
GA Stopping Condition 1 ($k_{GA_{max}}$)	100	250	100	100	25
GA Stopping Condition 2.1 ($k_{GA_{min}}$)	50	100	50	50	25
GA Stopping Condition 2.2 (θ_{GA})	20	50	20	20	-

Table 6.2: Initial parameter guesses for GA-optimisation of the controllers for Elevator C

Parameter	NPID Controller	NPDF Controller	FSMC	SSMC	RBFNN-SMC
K_P Initial Guess	5437	10140	-	-	-
K_I Initial Guess	2114	19330	-	-	-
K_D Initial Guess	3640	1290	-	-	-
α_P Initial Guess	1.81	0.77	-	-	-
α_I Initial Guess	0.74	0.82	-	-	-
α_D Initial Guess	1.65	0.7	-	-	-
δ_P Initial Guess	0.7	3.05	-	-	-
δ_I Initial Guess	1.74	4.51	-	-	-
δ_D Initial Guess	0.09	7.63	-	-	-
ρ Initial Guess	-	-	0.70	0.70	-
K_R Initial Guess	-	-	173	173	-
λ_0 Initial Guess	-	-	500	500	-
λ_1 Initial Guess	-	-	60	60	-
λ_2 Initial Guess	-	-	800	800	-
n_n Initial Guess	-	-	-	-	7
w_0 Initial Guess	-	-	-	-	0
c_1 Initial Guess	-	-	-	-	-1400
b Initial Guess	-	-	-	-	1500
γ Initial Guess	-	-	-	-	130000
Initial Fitness Value (F_C)	106.305	101.344	106.121	106.120	106.201

6.3 Solution Repeatability for Elevator C

Table 6.3: Solution repeatability of controller optimisation for Elevator C

Parameter	NPID Controller		NPDF Controller		FSMC		SSMC		RBFNN-SMC	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Proportional Gain (K_P)	6375.57	1134.25	10140	0	-	-	-	-	-	-
Integral Gain (K_I)	772.20	563.76	19330	0	-	-	-	-	-	-
Derivative Gain (K_D)	4821.79	2034.13	1290	0	-	-	-	-	-	-
Proportional Alpha Term (α_P)	1.18	0.54	0.7700	0	-	-	-	-	-	-
Integral Alpha Term (α_I)	0.65	1.08	0.8200	0	-	-	-	-	-	-
Derivative Alpha Term (α_D)	1.64	0.19	0.7000	0	-	-	-	-	-	-
Proportional Delta Term (δ_P)	0.69	0.42	3.1890	0.2142	-	-	-	-	-	-
Integral Delta Term (δ_I)	1.33	0.54	4.2280	0.5914	-	-	-	-	-	-
Derivative Delta Term (δ_D)	0.05	0.03	7.6400	0.0300	-	-	-	-	-	-
Saturation Function Coefficient (ρ)	-	-	-	-	0.5825	0.0818	0.5805	0.0792	-	-
Reaching Law Gain (K_R)	-	-	-	-	153.19	31.70	137.16	43.92	-	-
λ_0 Coefficient	-	-	-	-	65.63	56.94	310.85	300.02	-	-
λ_1 Coefficient	-	-	-	-	177.65	278.10	382.69	380.95	-	-
λ_2 Coefficient	-	-	-	-	521.80	351.35	304.44	226.53	-	-
Number of Hidden Layer Neurons (n_n)	-	-	-	-	-	-	-	-	7.80	0.75
Initial Hidden Layer Neuron Connection Weights (w_0)	-	-	-	-	-	-	-	-	-15.34	62.80
First Hidden Layer Neuron Radial Centre (c_1)	-	-	-	-	-	-	-	-	-1558.90	140.94
Hidden Layer Neurons Radial Centre Spread (b)	-	-	-	-	-	-	-	-	1403.97	52.35
RBFNN-SMC Adaptive Law Parameter (γ)	-	-	-	-	-	-	-	-	144740	19021.57
Fitness Value (F_C)	106.554	0.016	101.452	0.212	106.237	0.075	106.147	0.016	106.202	0
GA Iterations (k_{GA})	57	8	111	23	60	12	57	15	25	0
GA Run Time [s]	27529	10031	14932	2421	40053	6711	30279	9368	164585	4614
GA Run Time/10 Individuals [s]	163.77	66.23	45.53	5.78	679.64	123.26	532.74	51.77	6583.42	184.54

6.4 Comparison of Control Results for Elevator C

Table 6.4: Controller performance summary – Elevator C

Parameter	NPID Controller	NPDF Controller	FSMC	SSMC	RBFNN-SMC
Proportional Gain (K_P)	6935.60	10140	-	-	-
Integral Gain (K_I)	644.20	19330	-	-	-
Derivative Gain (K_D)	3699.70	1290	-	-	-
Proportional Alpha Term (α_P)	0.0810	0.7700	-	-	-
Integral Alpha Term (α_I)	1.7802	0.8200	-	-	-
Derivative Alpha Term (α_D)	1.5334	0.7000	-	-	-
Proportional Delta Term (δ_P)	1.5399	3.5500	-	-	-
Integral Delta Term (δ_I)	0.6940	2.5100	-	-	-
Derivative Delta Term (δ_D)	0.0202	7.6300	-	-	-
Saturation Function Coefficient (ρ)	-	-	0.6950	0.4539	0.4539*
Reaching Law Gain (K_R)	-	-	105.18	177.23	177.23*
λ_0 Coefficient	-	-	20.47	80.42	80.42*
λ_1 Coefficient	-	-	1.02	20.03	20.03*
λ_2 Coefficient	-	-	746.75	662.75	662.75*
Number of Hidden Layer Neurons (n_n)	-	-	-	-	8
Initial Hidden Layer Neuron Connection Weights (w_0)	-	-	-	-	-1.23
First Hidden Layer Neuron Radial Centre (c_1)	-	-	-	-	-1417
Hidden Layer Neurons Radial Centre Spread (b)	-	-	-	-	1334.40
RBFNN-SMC Adaptive Law Parameter (γ)	-	-	-	-	130000
Fitness Value (F_C)	106.565	102.062	106.353	106.175	106.202
GA Iterations (k_{GA})	67	100	51	51	25
GA Run Time [s]	22919	15496	43372	29612	167940
GA Run Time/10 Individuals [s]	114.02	51.65	850.43	580.63	6717.60
Rise Time [s] (3200 kg Cabin, 1000 m Upwards Travel)	8.99	8.89	8.99	8.99	8.99
Settling Time [s] (3200 kg Cabin, 1000 m Upwards Travel)	10.10	10.12	10.10	10.10	10.10
Velocity Overshoot [%] (3200 kg Cabin, 1000 m Upwards Travel)	0.64	0.70	0.65	0.66	0.64

*SMC parameters taken from the GA-optimised SSMC

As detailed in Table 6.4, the RBFNN takes a 10-8-1 structure; with the network input vector given as $\mathbf{x} = [\dot{v}_c \ v_c \ \dot{v}_w \ v_w \ \dot{x}_c \ x_c \ \dot{x}_w \ x_w \ \dot{i}_m \ \omega_s]^T$. Using Equation 3.30 and Equation 3.31, the network centres are calculated to be $\mathbf{c} = [-1417 \ -1012.14 \ -607.29 \ -202.43 \ 202.43 \ 607.29 \ 1012.14 \ 1417]^T$; while the spread of the centres is $b = 1334.40$. The initial connection weight (w_0) for all eight neurons is set to -1.23, with the adaptive law parameter of $\gamma = 130000$ used for online adjustment of the weights during simulation.

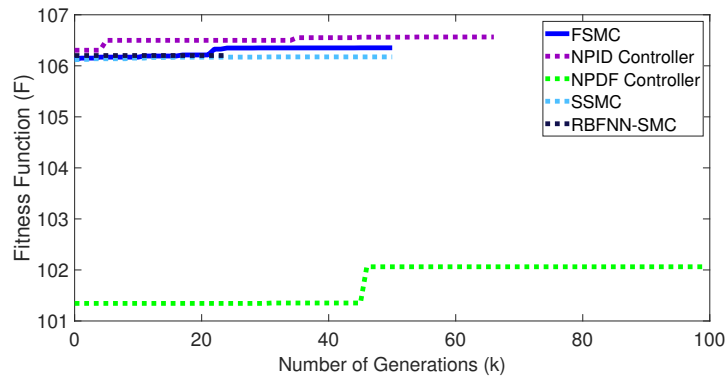


Figure 6.1: Evolution of the fitness function (F_C) vs. the number of population generations in the GA (k_{GA}) – Elevator C

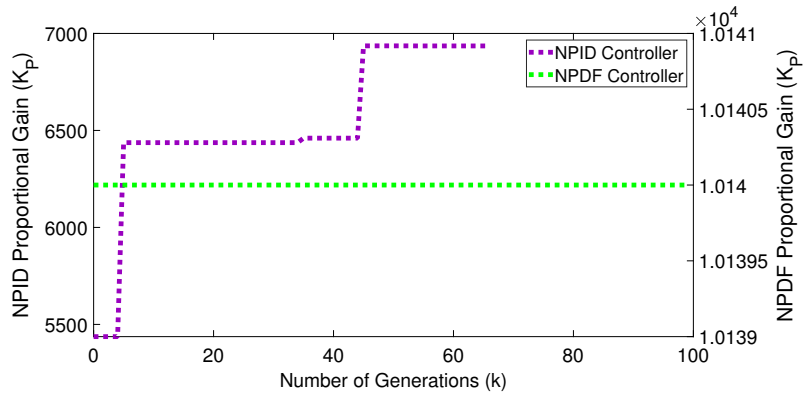


Figure 6.2: Evolution of the proportional gain (K_P) vs. the number of population generations in the GA (k_{GA}) – Elevator C

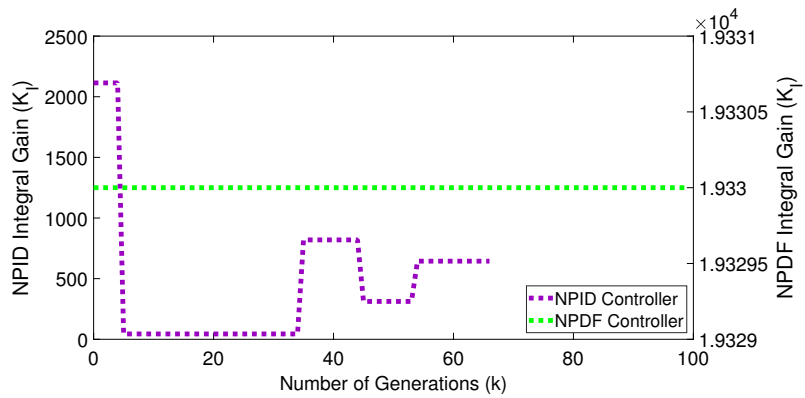


Figure 6.3: Evolution of the integral gain (K_I) vs. the number of population generations in the GA (k_{GA}) – Elevator C

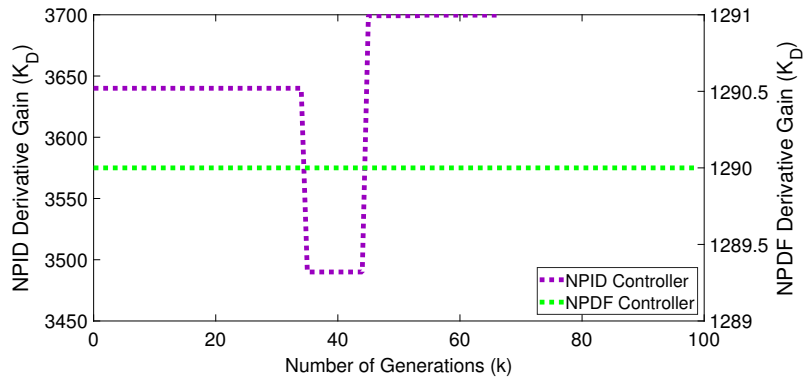


Figure 6.4: Evolution of the derivative gain (K_D) vs. the number of population generations in the GA (k_{GA}) – Elevator C

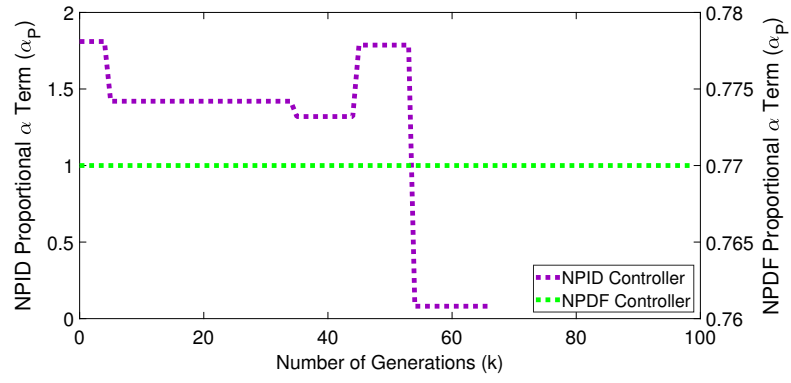


Figure 6.5: Evolution of the proportional nonlinear α term (α_P) vs. the number of population generations in the GA (k_{GA}) – Elevator C

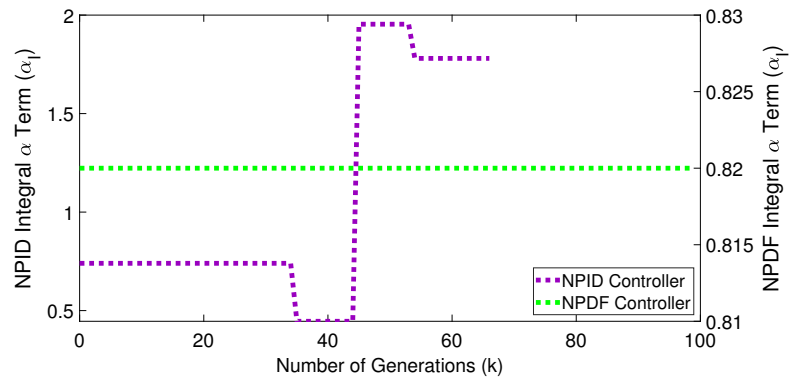


Figure 6.6: Evolution of the integral nonlinear α term (α_I) vs. the number of population generations in the GA (k_{GA}) – Elevator C

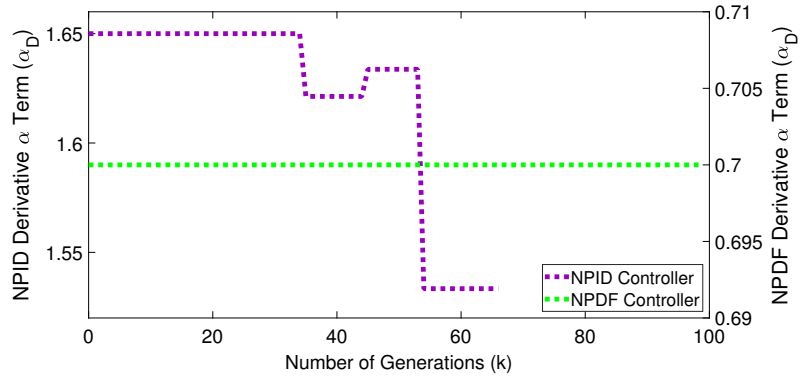


Figure 6.7: Evolution of the derivative nonlinear α term (α_D) vs. the number of population generations in the GA (k_{GA}) – Elevator C

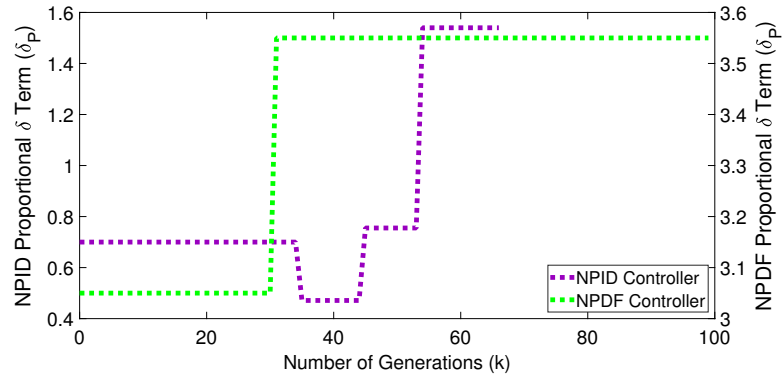


Figure 6.8: Evolution of the proportional nonlinear δ term (δ_P) vs. the number of population generations in the GA (k_{GA}) – Elevator C

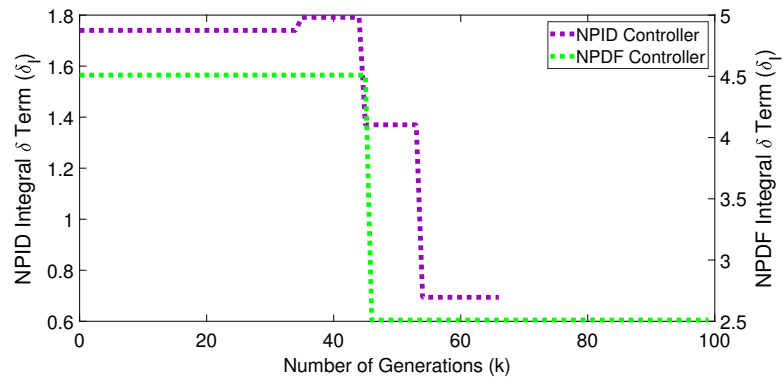


Figure 6.9: Evolution of the integral nonlinear δ term (δ_I) vs. the number of population generations in the GA (k_{GA}) – Elevator C

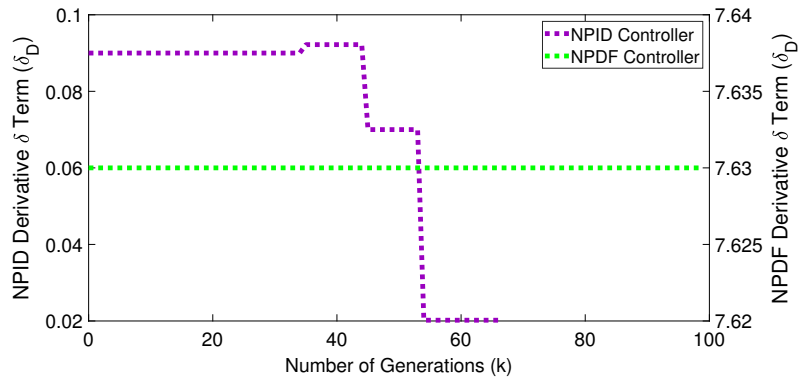


Figure 6.10: Evolution of the derivative nonlinear δ term (δ_D) vs. the number of population generations in the GA (k_{GA}) – Elevator C

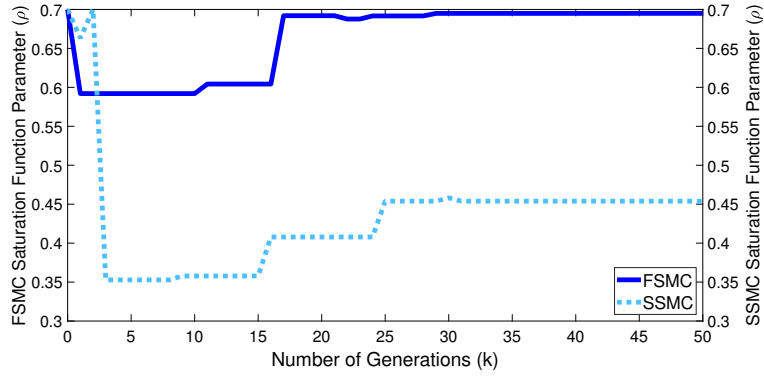


Figure 6.11: Evolution of the SMC saturation function coefficient (ρ) vs. the number of population generations in the GA (k_{GA}) – Elevator C

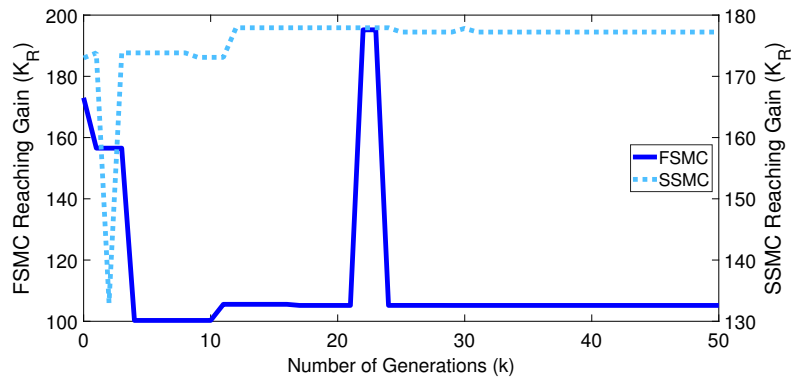


Figure 6.12: Evolution of the SMC reaching law gain (K_R) vs. the number of population generations in the GA (k_{GA}) – Elevator C

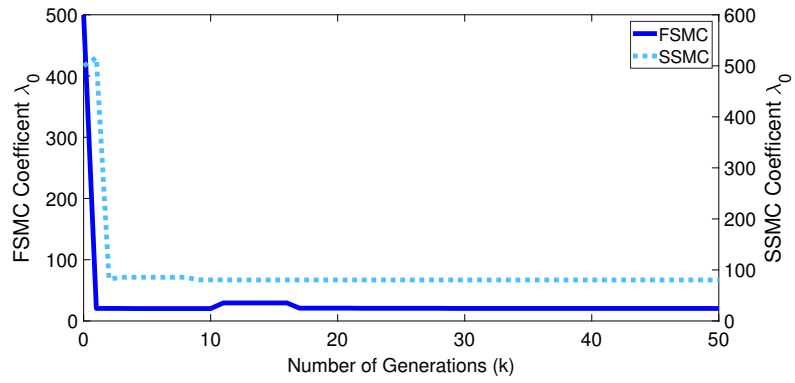


Figure 6.13: Evolution of the SMC coefficient λ_0 vs. the number of population generations in the GA (k_{GA}) – Elevator C

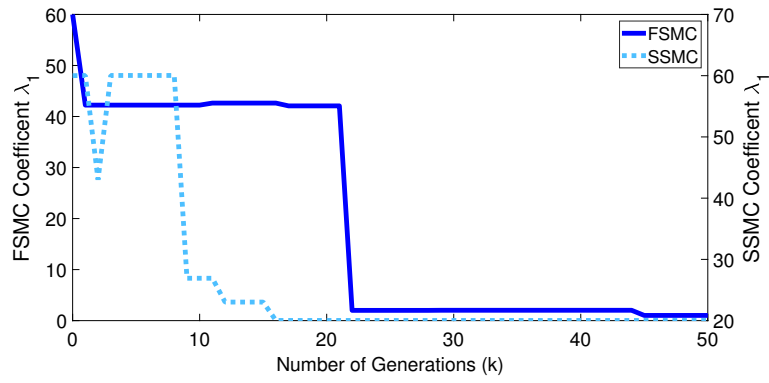


Figure 6.14: Evolution of the SMC coefficient λ_1 vs. the number of population generations in the GA (k_{GA}) – Elevator C

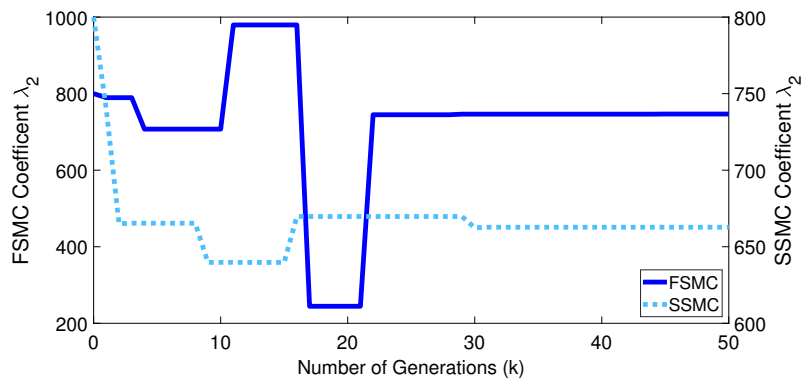


Figure 6.15: Evolution of the SMC coefficient λ_2 vs. the number of population generations in the GA (k_{GA}) – Elevator C

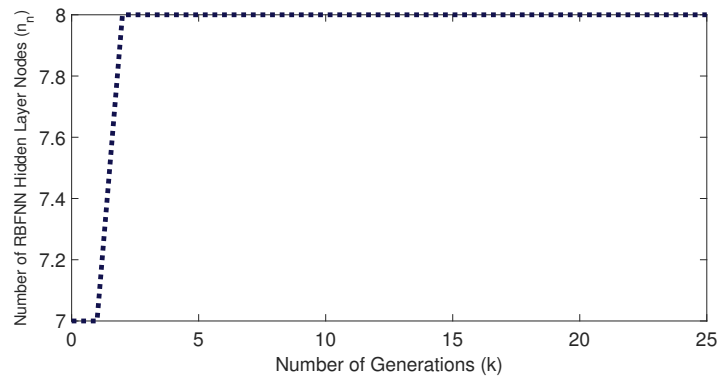


Figure 6.16: Evolution of the number of RBFNN hidden layer neurons (n_n) vs. the number of population generations in the GA (k_{GA}) – Elevator C

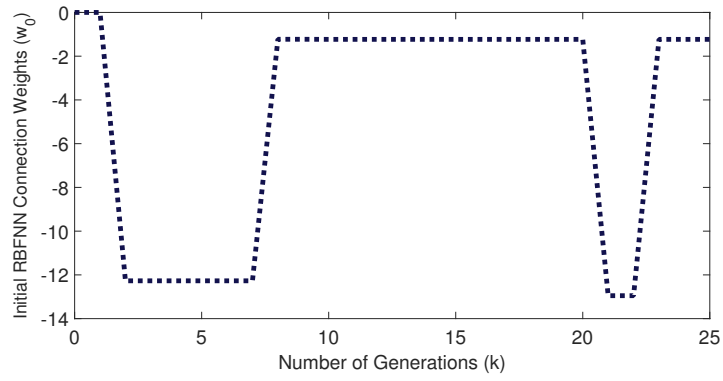


Figure 6.17: Evolution of initial RBFNN connection weights (w_0) vs. the number of population generations in the GA (k_{GA}) – Elevator C

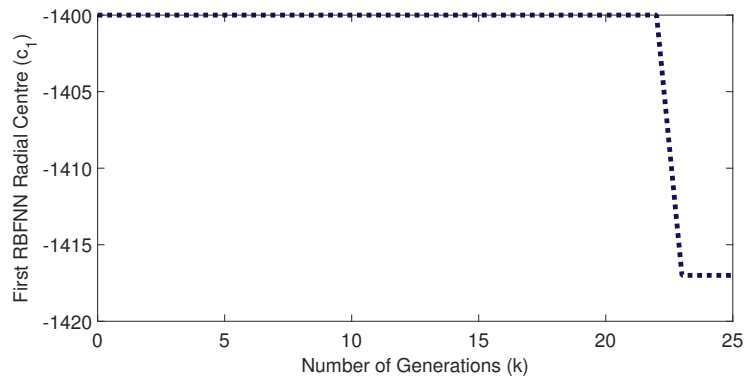


Figure 6.18: Evolution of the radial centre of the first RBFNN hidden layer node (c_1) vs. the number of population generations in the GA (k_{GA}) – Elevator C

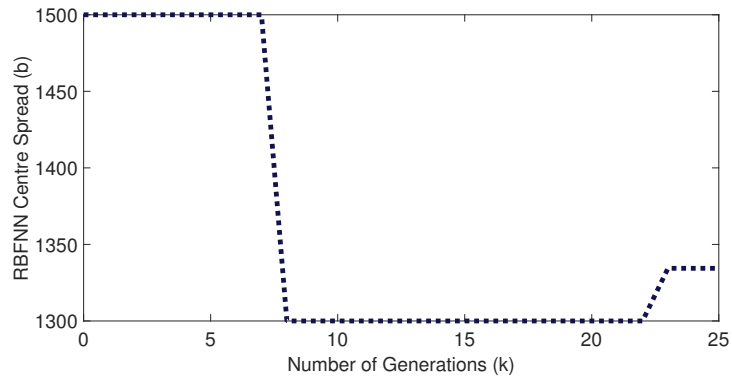


Figure 6.19: Evolution of the spreads of the RBFNN centres (b) vs. the number of population generations in the GA (k_{GA}) – Elevator C

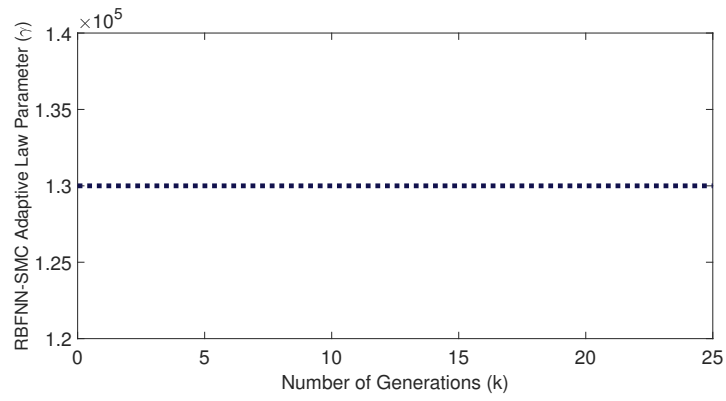


Figure 6.20: Evolution of the RBFNN-SMC adaptive law parameter (γ) vs. the number of population generations in the GA (k_{GA}) – Elevator C

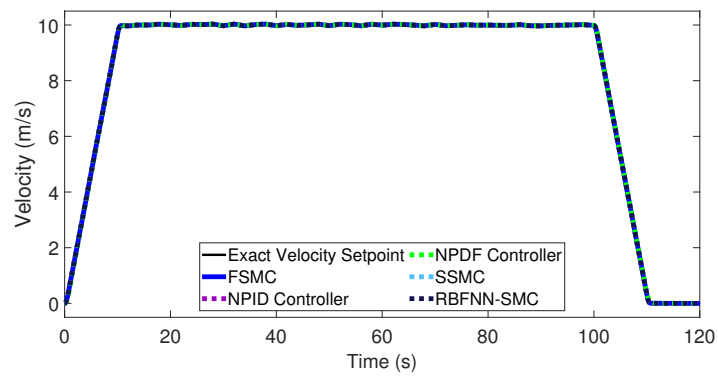


Figure 6.21: Velocity response of the 3200 kg cabins – Elevator C. Refer to Figures 10.25 and 10.26 for more detail.

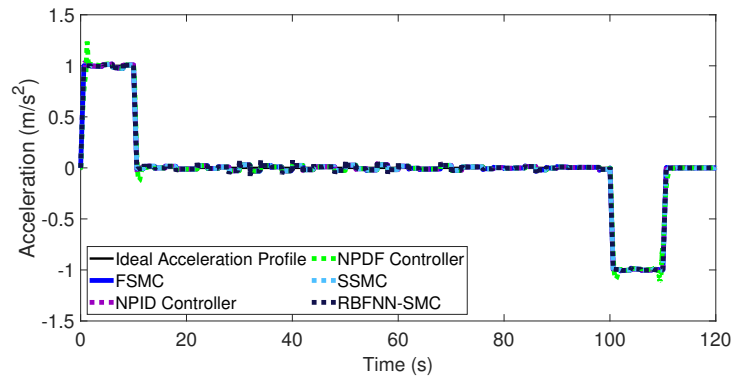


Figure 6.22: Acceleration response of the 3200 kg cabins – Elevator C. Refer to Figures 10.27 – 10.29 for more detail.

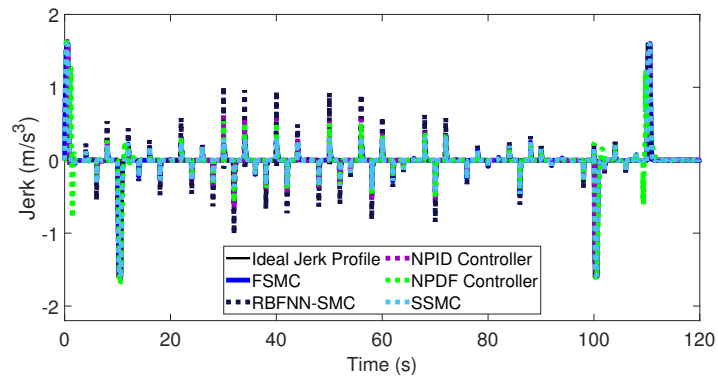


Figure 6.23: Jerk response of the 3200 kg cabins – Elevator C. Refer to Figures 10.30 – 10.32 for more detail.

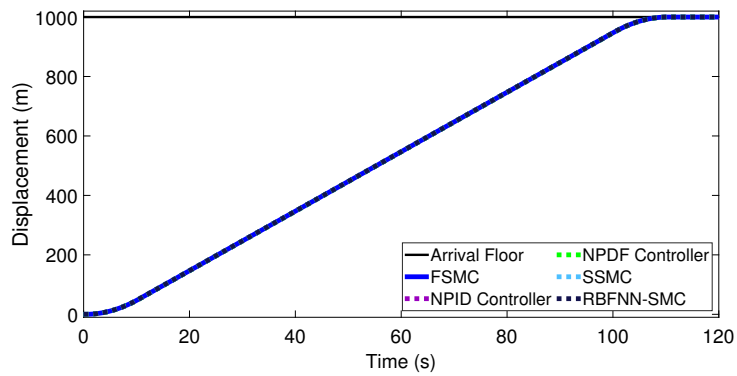


Figure 6.24: Displacement response of the 3200 kg cabins – Elevator C

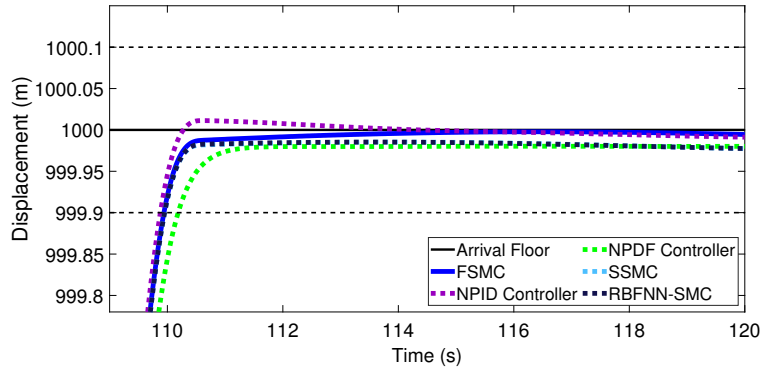


Figure 6.25: Displacement response of the 3200 kg cabins (zoomed into the moment of arrival) – Elevator C

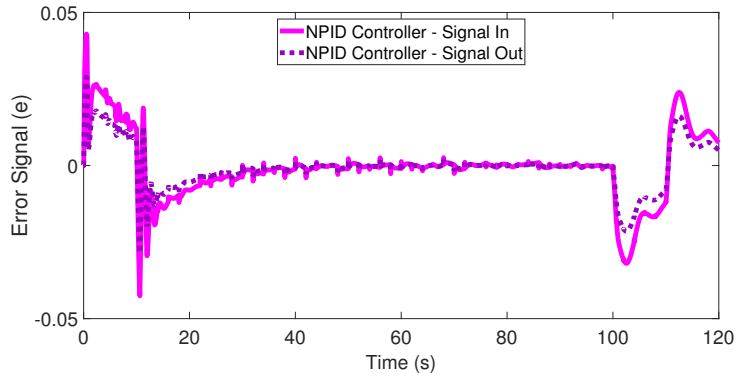


Figure 6.26: Adaptation of the error signal (U_e) as it passes into and out of the NPID controller proportional nonlinear function (Φ_{P-NPID}). Φ_{P-NPID} is defined by $\alpha_P = 0.0810$ and $\delta_P = 1.5399$ – Elevator C

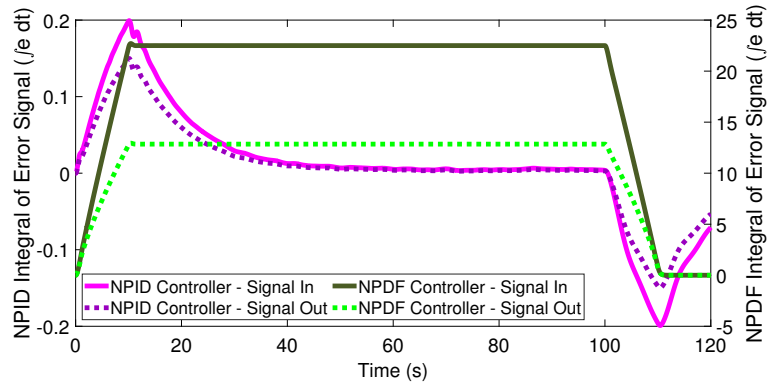


Figure 6.27: Adaptation of the error signal integral ($\int U_e dt$) as it passes into and out of the NPID and NPDF controller integral nonlinear functions (Φ_{I-NPID} and Φ_{I-NPDF}). Φ_{I-NPID} is defined by $\alpha_I = 1.7802$ and $\delta_I = 0.6940$. Φ_{I-NPDF} is defined by $\alpha_I = 0.8200$ and $\delta_I = 2.5100$ – Elevator C

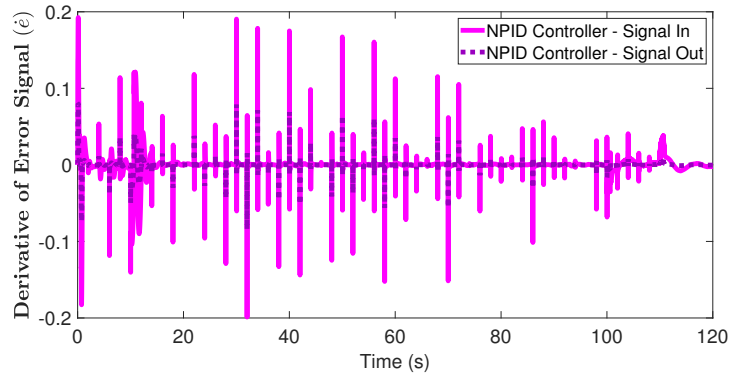


Figure 6.28: Adaptation of the error signal derivative ($\dot{U}_e$) as it passes into and out of the NPID controller derivative nonlinear function (Φ_{D-NPID}). Φ_{D-NPID} is defined by $\alpha_D = 1.5334$ and $\delta_D = 0.0202$ – Elevator C

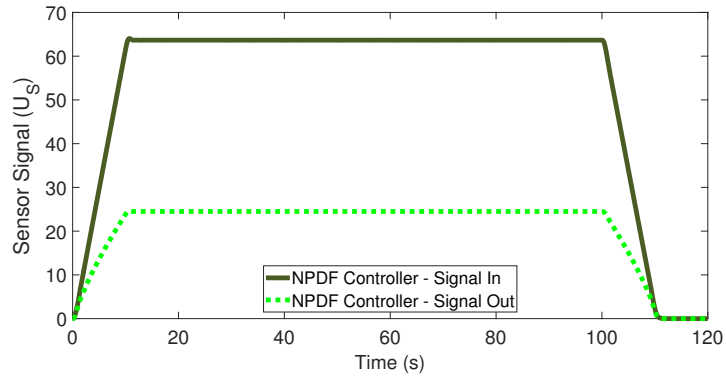


Figure 6.29: Adaptation of the feedback sensor signal (U_s) as it passes into and out of the NPDP controller proportional nonlinear function (Φ_{P-NPDP}). Φ_{P-NPDP} is defined by $\alpha_P = 0.7700$ and $\delta_P = 3.5500$ – Elevator C

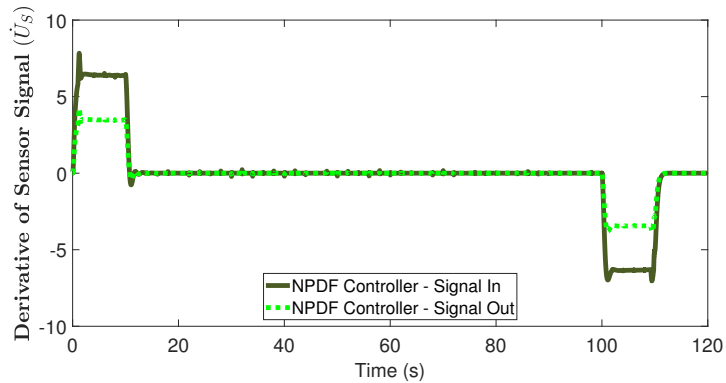


Figure 6.30: Adaptation of the feedback sensor signal derivative ($\dot{U}_s$) as it passes into and out of the NPDP controller derivative nonlinear function (Φ_{D-NPDP}). Φ_{D-NPDP} is defined by $\alpha_D = 0.7000$ and $\delta_D = 7.6300$ – Elevator C

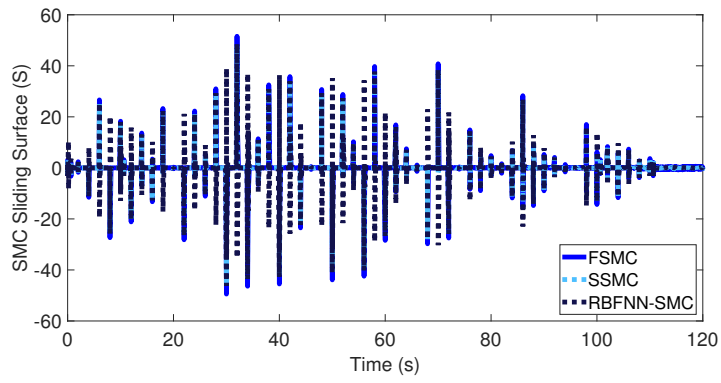


Figure 6.31: SMC sliding surface (S) during SMC control of the 3200 kg cabins – Elevator C

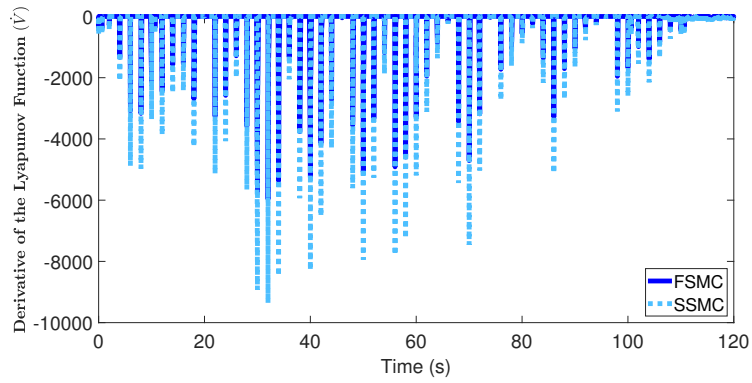


Figure 6.32: Derivative of the Lyapunov function ($\dot{V}$) during SMC control of the 3200 kg cabins – Elevator C

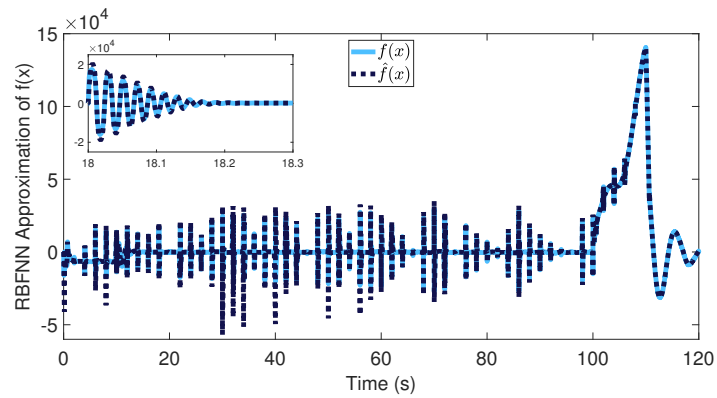


Figure 6.33: RBFNN approximation of $f(x)$ during RBFNN-SMC control of the 3200 kg cabin (featuring an inset zoomed into the period between $t = 18$ s and $t = 18.3$ s) – Elevator C

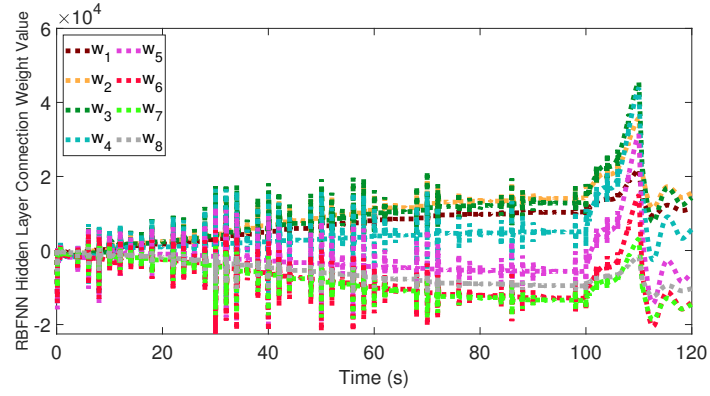


Figure 6.34: Adaptation of the RBFNN hidden layer neuron connection weights $w_1 - w_8$ during RBFNN-SMC control of the 3200 kg cabin – Elevator C

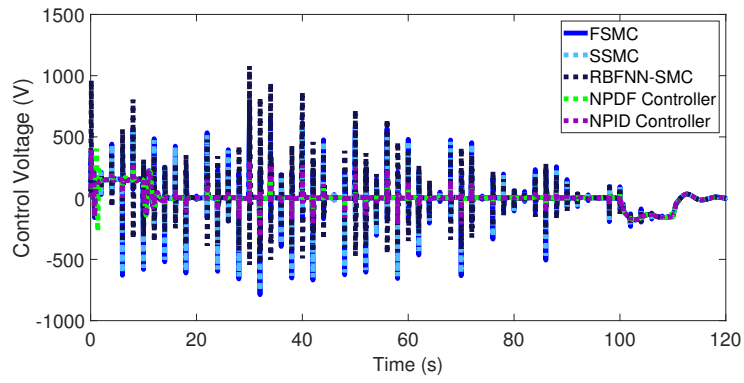


Figure 6.35: Control voltage output during control of the 3200 kg cabins – Elevator C

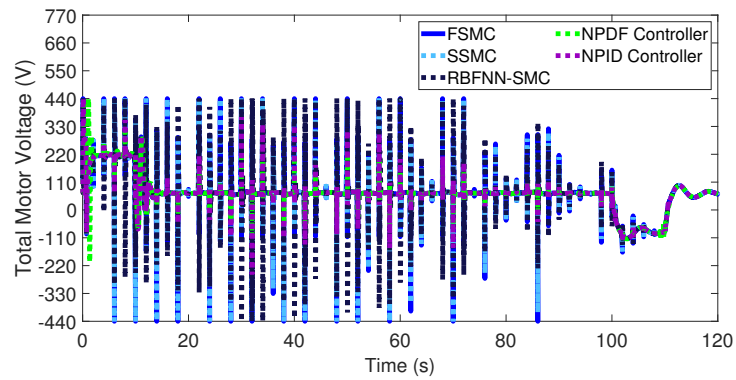


Figure 6.36: Total motor voltage during control of the 3200 kg cabins – Elevator C

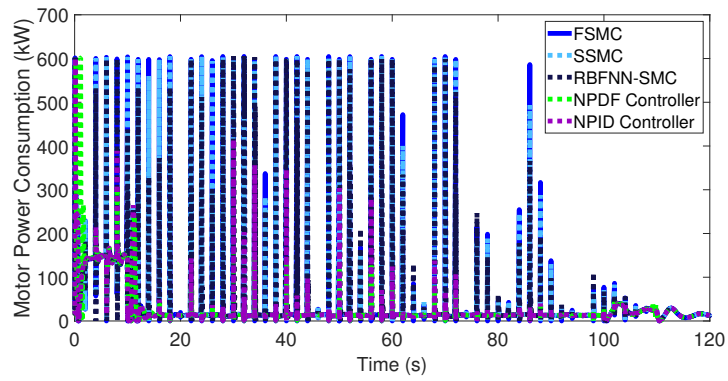


Figure 6.37: Total motor power consumption during control of the 3200 kg cabins – Elevator C

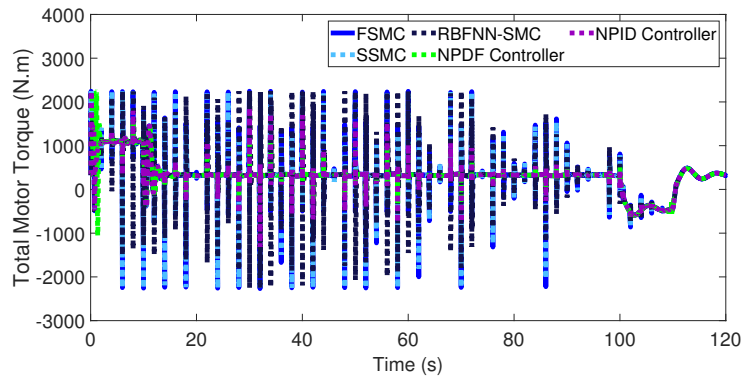


Figure 6.38: Total motor torque during actuation of the 3200 kg cabins – Elevator C

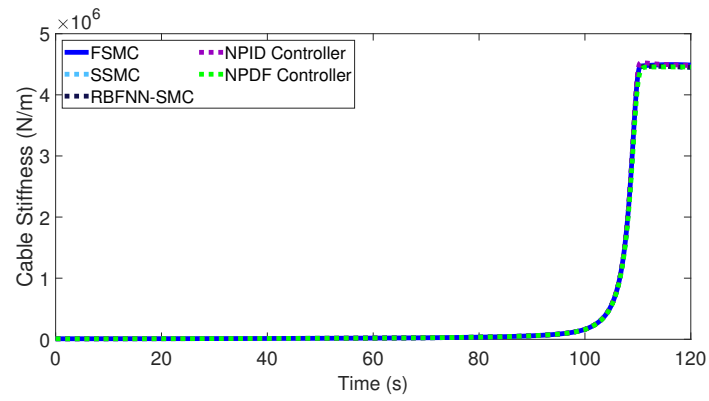


Figure 6.39: Change in the cabin-side cable stiffness (k_c) during control of the 3200 kg cabins – Elevator C

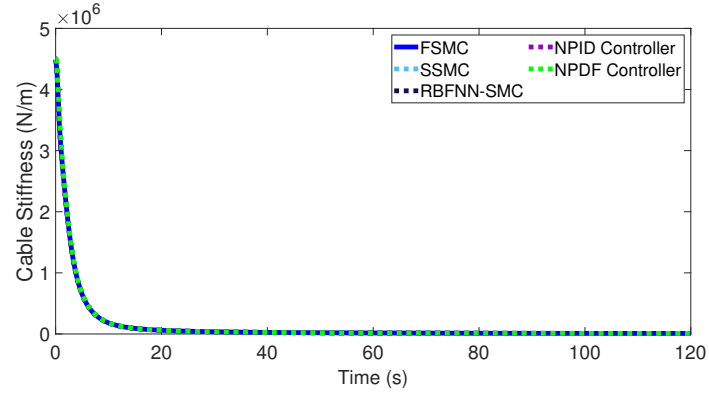


Figure 6.40: Change in the counterweight-side cable stiffness (k_w) during control of the 3200 kg cabins – Elevator C

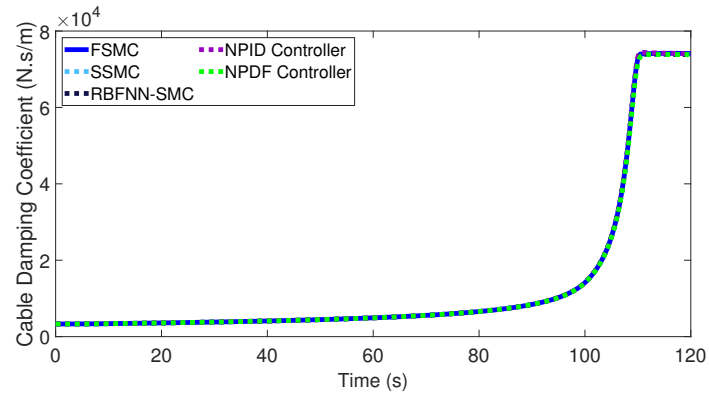


Figure 6.41: Change in the cabin-side cable damping coefficient (c_c) during control of the 3200 kg cabin – Elevator C

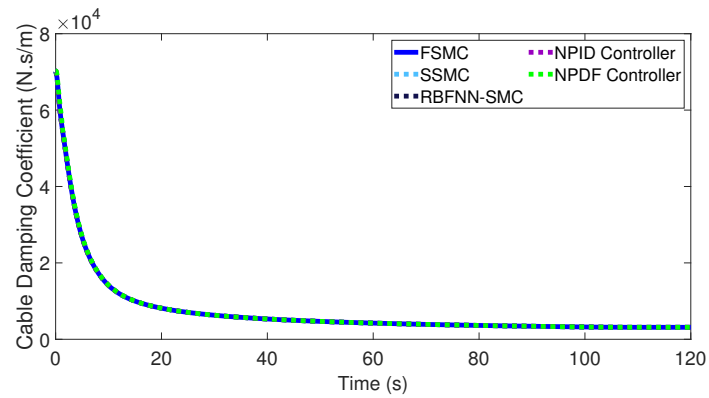


Figure 6.42: Change in the counterweight-side cable damping coefficient (c_w) during control of the 3200 kg cabins – Elevator C

6.5 Robustness Analysis for Elevator C

6.5.1 Robustness analysis – NPID controller for Elevator C

Table 6.5: Robustness analysis – NPID controller for control of Elevator C

Lifting Height	Mass of Elevator C Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	129.653 Pass	129.553 Pass	129.423 Pass	129.342 Pass	129.251 Pass
400 m	8.81e-09 D (+0.14m)	8.78e-09 D (+0.14m)	8.75e-09 D (+0.14m)	8.73e-09 D (+0.14m)	8.72e-09 D (+0.14m)
600 m	5.75e-09 D (+0.27m)	5.73e-09 D (+0.27m)	5.71e-09 D (+0.27m)	5.69e-09 D (+0.27m)	5.69e-09 D (+0.27m)
800 m	8.68e-09 D (+0.16m)	8.66e-09 D (+0.16m)	8.64e-09 D (+0.17m)	8.63e-09 D (+0.17m)	8.62e-09 D (+0.17m)
1000 m	106.568 Pass	106.571 Pass	106.567 Pass	106.555 Pass	106.541 Pass
-1000 m	106.579 Pass	106.584 Pass	106.579 Pass	106.573 Pass	106.559 Pass
-800 m	8.69e-09 D (-0.16m)	8.67e-09 D (-0.16m)	8.65e-09 D (-0.16m)	8.63e-09 D (-0.16m)	8.62e-09 D (-0.17m)
-600 m	5.75e-09 D (-0.27m)	5.73e-09 D (-0.27m)	5.71e-09 D (-0.27m)	5.70e-09 D (-0.27m)	5.69e-09 D (-0.27m)
-400 m	8.82e-09 D (-0.14m)	8.79e-09 D (-0.14m)	8.76e-09 D (-0.14m)	8.74e-09 D (-0.14m)	8.72e-09 D (-0.14m)
-200 m	129.697 Pass	129.605 Pass	129.48 Pass	129.403 Pass	129.309 Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

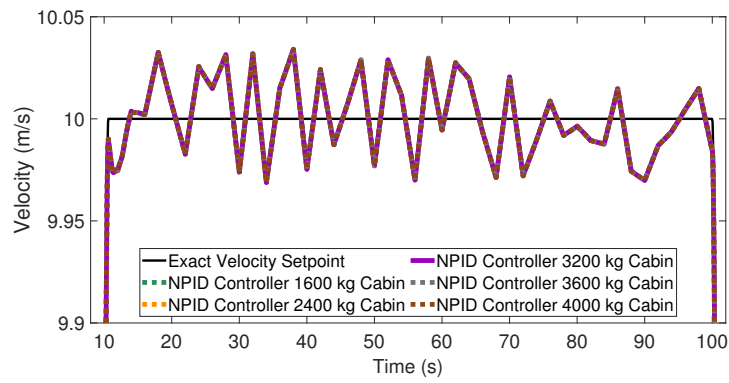


Figure 6.43: Velocity response of NPID-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the period of steady-state travel) – Elevator C

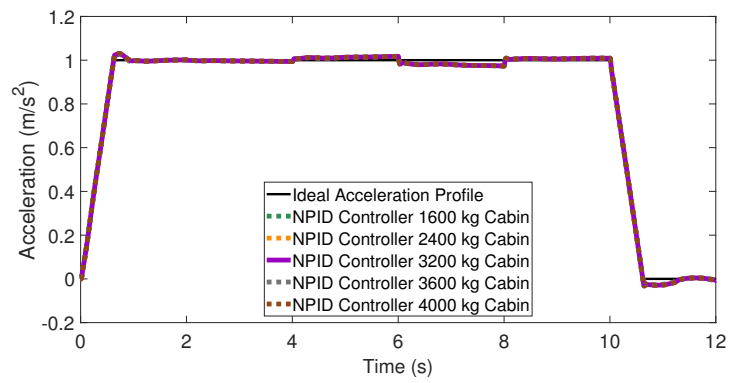


Figure 6.44: Acceleration response of NPID-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the period of acceleration) – Elevator C

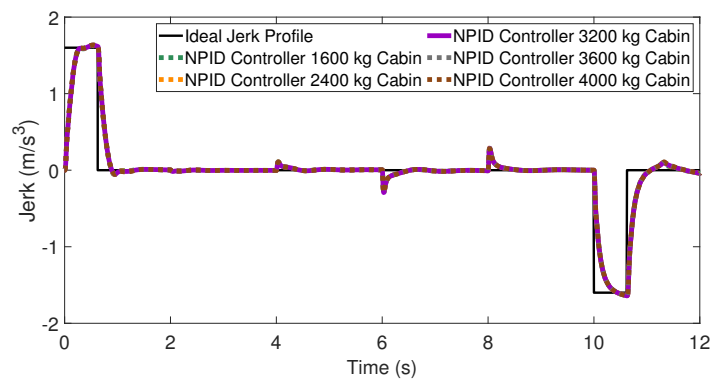


Figure 6.45: Jerk response of NPID-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the period of acceleration) – Elevator C

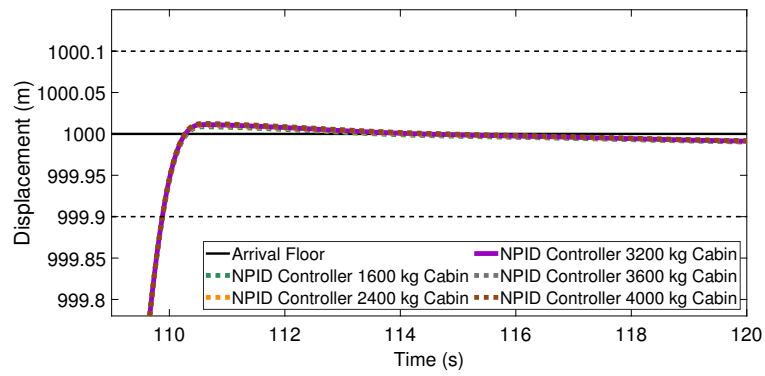


Figure 6.46: Displacement response of NPID-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the moment of arrival) – Elevator C

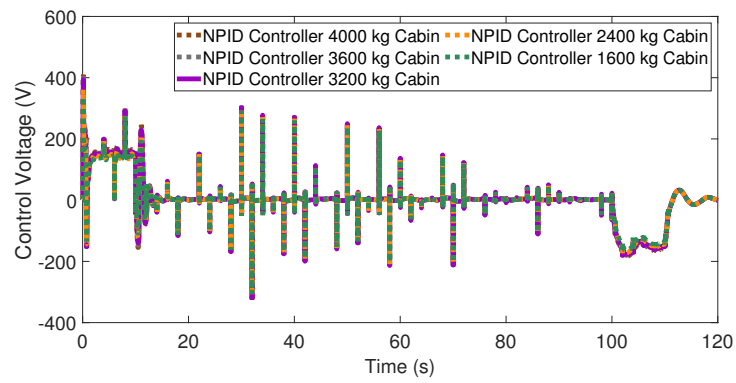


Figure 6.47: Control voltage output during NPID control of cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

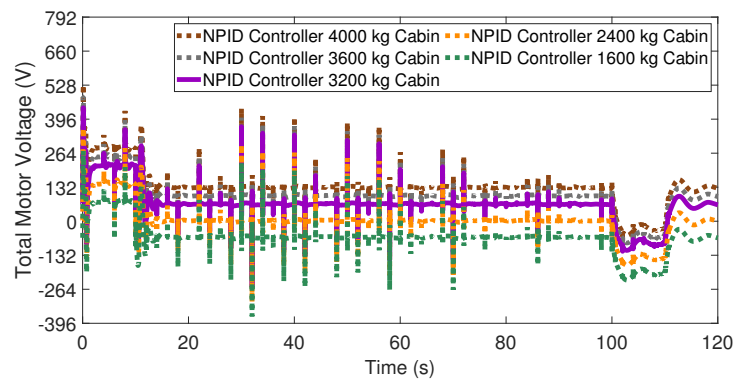


Figure 6.48: Total motor voltage during NPID control of cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

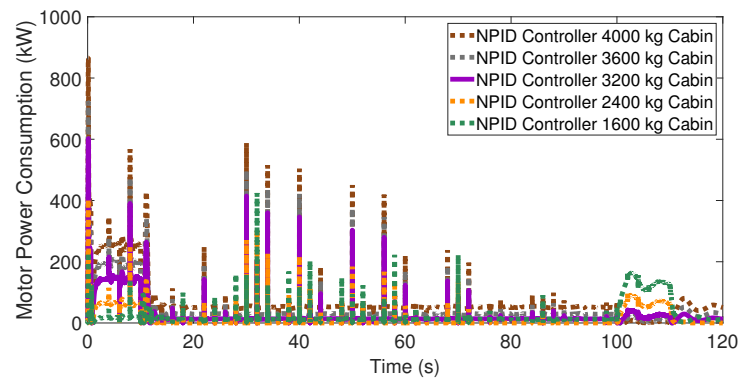


Figure 6.49: Total motor power consumption during NPID control of cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

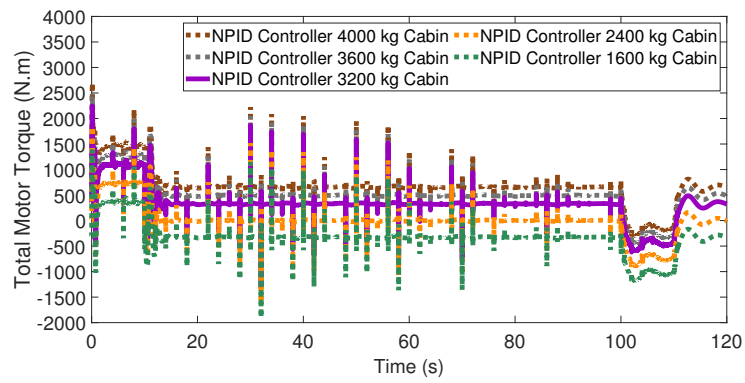


Figure 6.50: Total motor torque during actuation of NPID-controlled cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

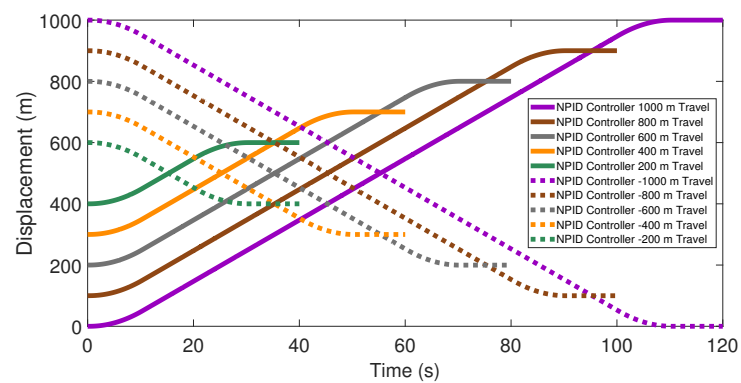


Figure 6.51: Displacement response of NPID-controlled 3200 kg cabins travelling to different floors – Elevator C

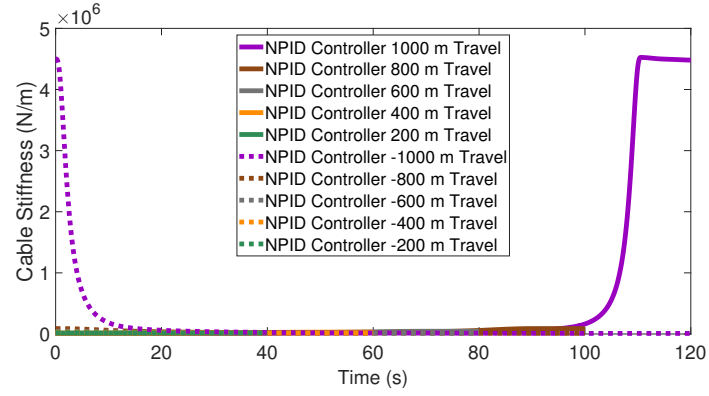


Figure 6.52: Change in the cabin-side cable stiffness (k_c) during NPID control of 3200 kg cabins travelling to different floors – Elevator C

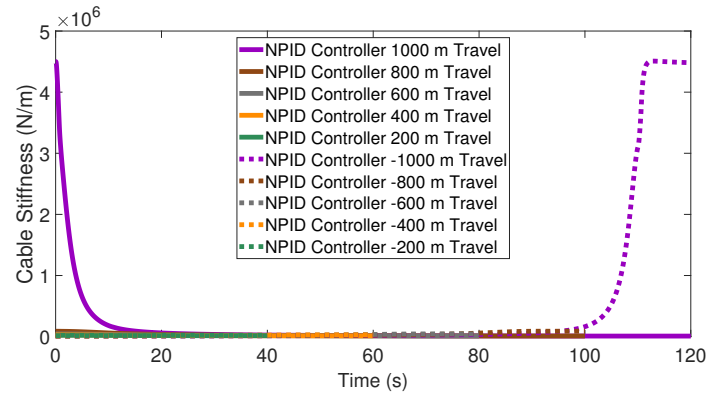


Figure 6.53: Change in the counterweight-side cable stiffness (k_w) during NPID control of 3200 kg cabins travelling to different floors – Elevator C

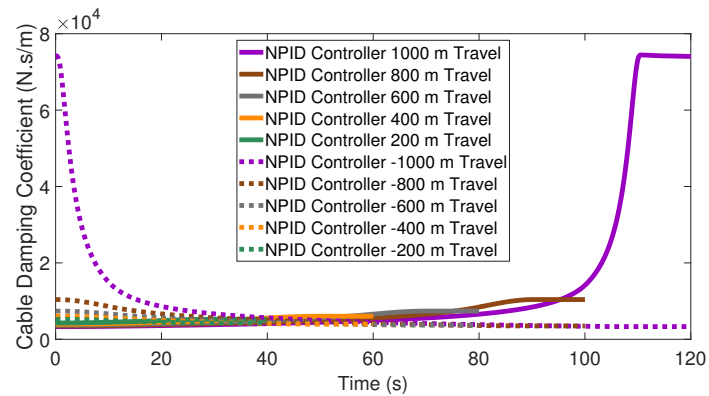


Figure 6.54: Change in the cabin-side cable damping coefficient (c_c) during NPID control of 3200 kg cabins travelling to different floors – Elevator C

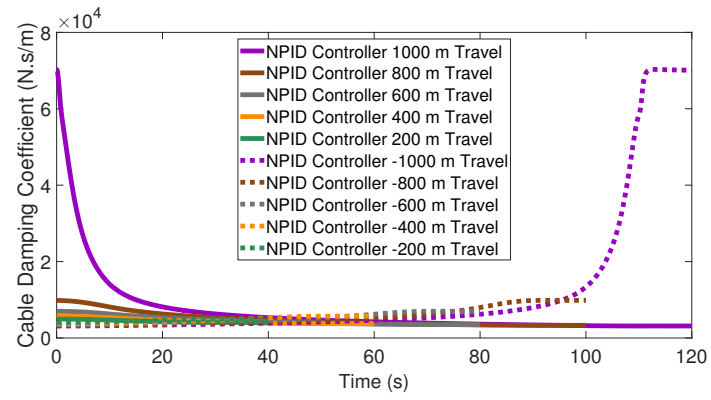


Figure 6.55: Change in the counterweight-side cable damping coefficient (c_w) during NPID control of 3200 kg cabins travelling to different floors – Elevator C

6.5.2 Robustness analysis – NPDF controller for Elevator C

Table 6.6: Robustness analysis – NPDF controller for control of Elevator C

Lifting Height	Mass of Elevator C Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	112.318	112.315	112.295	112.275	112.244
	Pass	Pass	Pass	Pass	Pass
400 m	8.85e-09	8.85e-09	8.85e-09	8.85e-09	8.85e-09
	D (+0.11m)	D (+0.11m)	D (+0.11m)	D (+0.11m)	D (+0.11m)
600 m	6.03e-09	6.03e-09	6.03e-09	6.03e-09	6.03e-09
	D (+0.24m)	D (+0.24m)	D (+0.24m)	D (+0.24m)	D (+0.24m)
800 m	8.82e-09	8.82e-09	8.82e-09	8.82e-09	8.82e-09
	D (+0.13m)	D (+0.13m)	D (+0.13m)	D (+0.13m)	D (+0.13m)
1000 m	102.074	102.075	102.070	102.061	102.048
	Pass	Pass	Pass	Pass	Pass
-1000 m	102.058	102.055	102.047	102.039	102.024
	Pass	Pass	Pass	Pass	Pass
-800 m	8.82e-09	8.82e-09	8.82e-09	8.82e-09	8.82e-09
	D (-0.13m)	D (-0.13m)	D (-0.13m)	D (-0.13m)	D (-0.13m)
-600 m	6.03e-09	6.03e-09	6.03e-09	6.03e-09	6.03e-09
	D (-0.24m)	D (-0.24m)	D (-0.24m)	D (-0.24m)	D (-0.24m)
-400 m	8.85e-09	8.85e-09	8.85e-09	8.85e-09	8.85e-09
	D (-0.11m)	D (-0.11m)	D (-0.11m)	D (-0.11m)	D (-0.11m)
-200 m	112.314	112.312	112.289	112.269	112.240
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

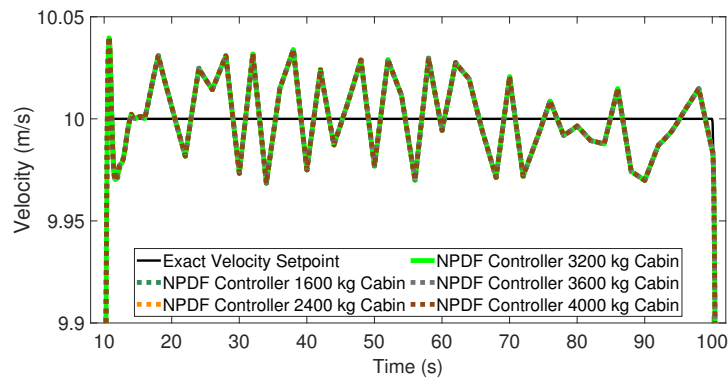


Figure 6.56: Velocity response of NPDF-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the period of steady-state travel) – Elevator C

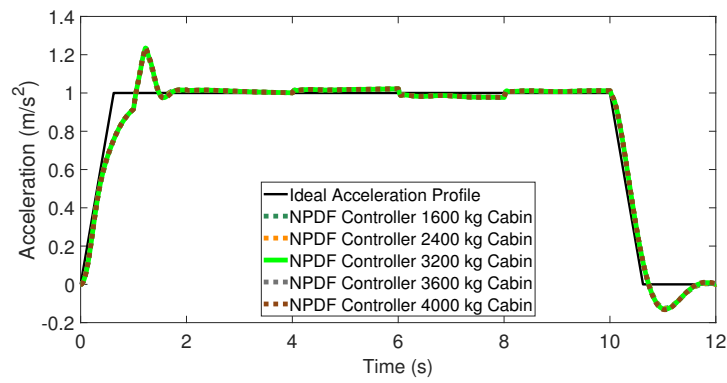


Figure 6.57: Acceleration response of NPDF-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the period of acceleration) – Elevator C

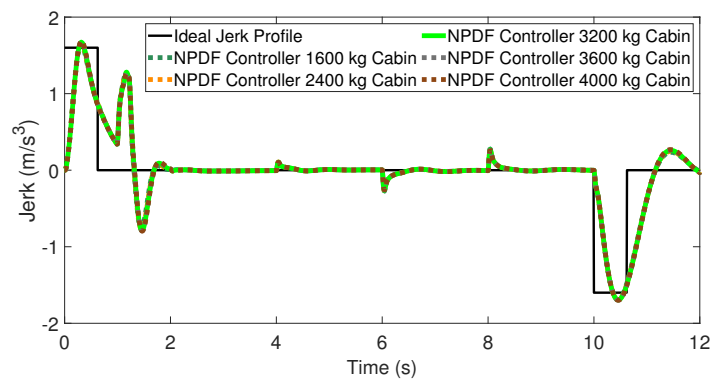


Figure 6.58: Jerk response of NPDF-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the period of acceleration) – Elevator C

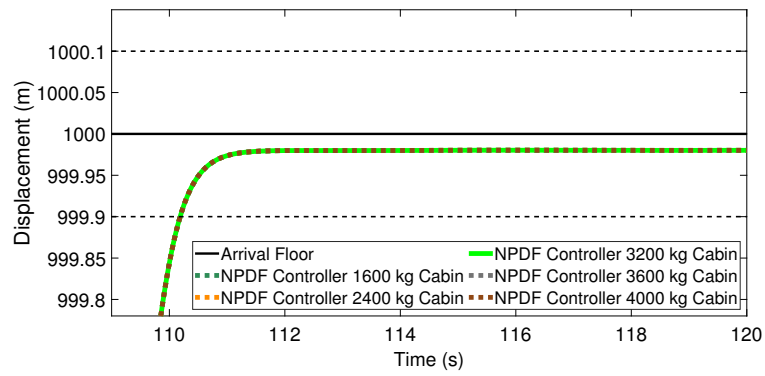


Figure 6.59: Displacement response of NPDF-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the moment of arrival) – Elevator C

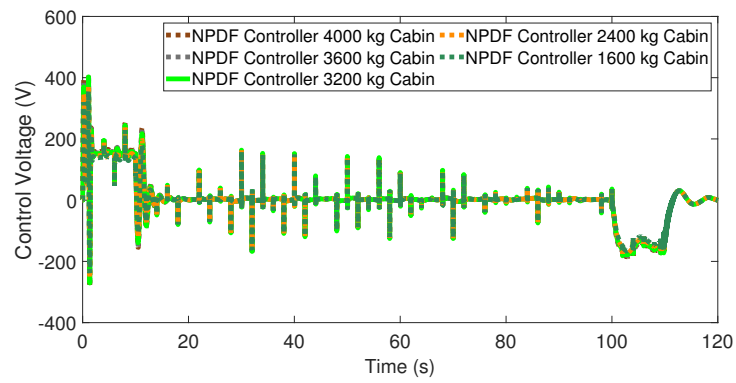


Figure 6.60: Control voltage output during NPDF control of cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

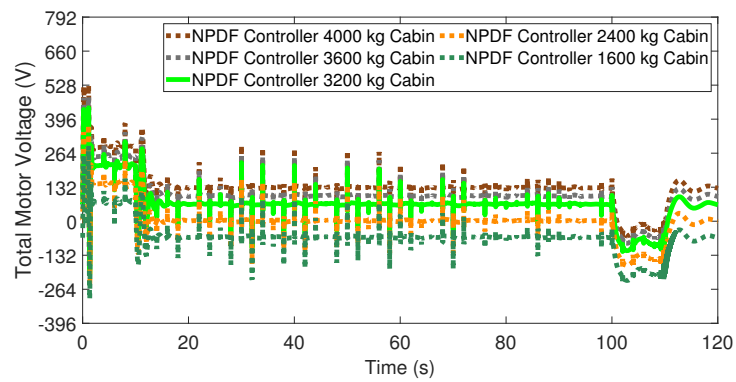


Figure 6.61: Total motor voltage during NPDF control of cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

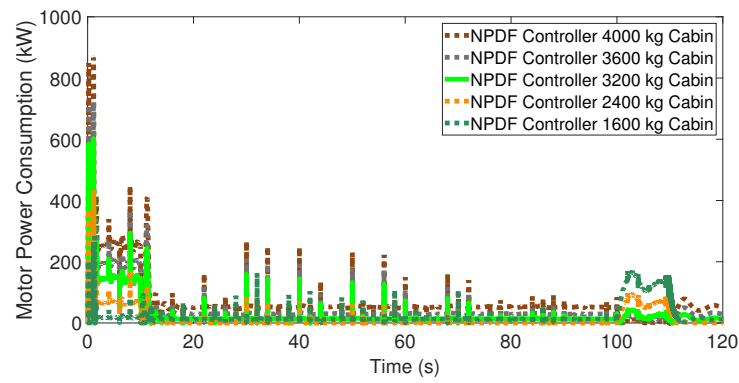


Figure 6.62: Total motor power consumption during NPDF control of cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

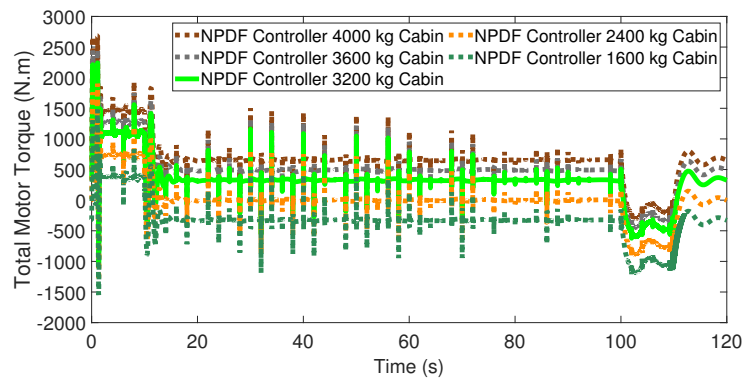


Figure 6.63: Total motor torque during actuation of NPDF-controlled cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

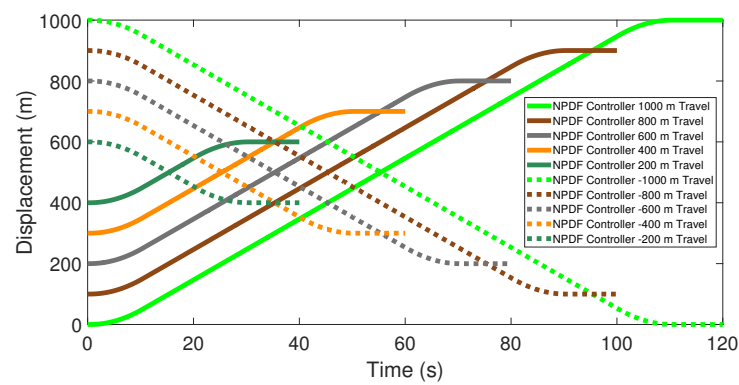


Figure 6.64: Displacement response of NPDF-controlled 3200 kg cabins travelling to different floors – Elevator C

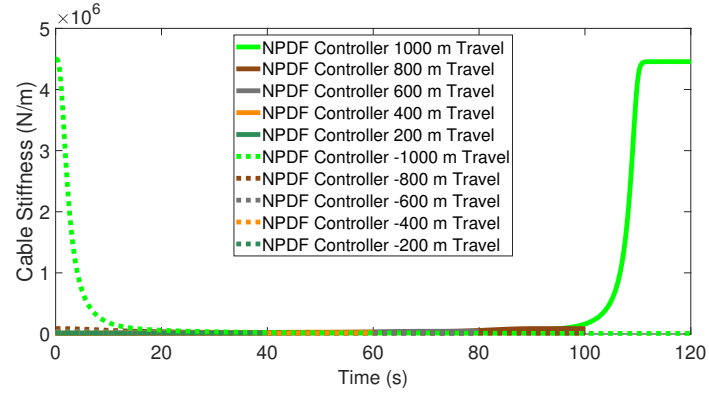


Figure 6.65: Change in the cabin-side cable stiffness (k_c) during NPDF control of 3200 kg cabins travelling to different floors – Elevator C

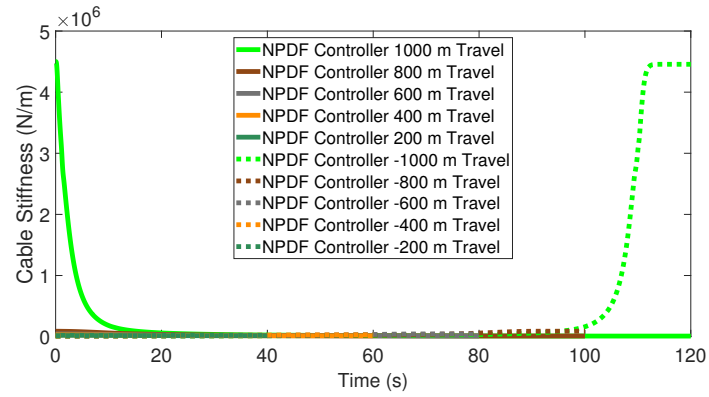


Figure 6.66: Change in the counterweight-side cable stiffness (k_w) during NPDF control of 3200 kg cabins travelling to different floors – Elevator C

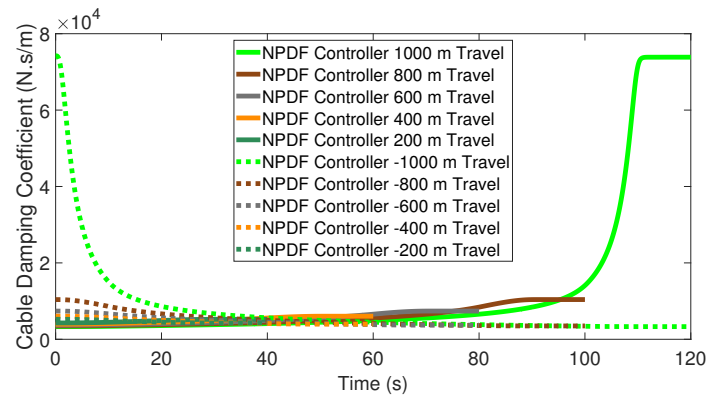


Figure 6.67: Change in the cabin-side cable damping coefficient (c_c) during NPDF control of 3200 kg cabins travelling to different floors – Elevator C

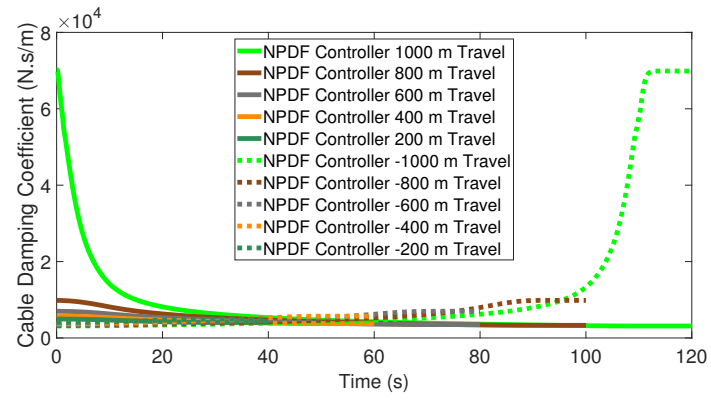


Figure 6.68: Change in the counterweight-side cable damping coefficient (c_w) during NPDP control of 3200 kg cabins travelling to different floors – Elevator C

6.5.3 Robustness analysis – FSMC for Elevator C

Table 6.7: Robustness analysis – FSMC for control of Elevator C

Lifting Height	Mass of Elevator C Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	129.960	129.857	129.640	129.596	129.557
	Pass	Pass	Pass	Pass	Pass
400 m	9.56e-09	9.50e-09	9.44e-09	9.41e-09	9.38e-09
	D (+0.11m)	D (+0.11m)	D (+0.12m)	D (+0.12m)	D (+0.13m)
600 m	5.91e-09	5.92e-09	5.90e-09	5.93e-09	5.95e-09
	D (+0.26m)	D (+0.26m)	D (+0.26m)	D (+0.26m)	D (+0.25m)
800 m	9.41e-09	9.36e-09	9.32e-09	9.28e-09	9.24e-09
	D (+0.12m)	D (+0.13m)	D (+0.13m)	D (+0.14m)	D (+0.14m)
1000 m	106.382	106.409	106.385	106.338	106.297
	Pass	Pass	Pass	Pass	Pass
-1000 m	106.254	106.326	106.316	106.306	106.284
	Pass	Pass	Pass	Pass	Pass
-800 m	9.29e-09	9.40e-09	9.51e-09	9.54e-09	9.55e-09
	D (-0.13m)	D (-0.12m)	D (-0.12m)	D (-0.12m)	D (-0.12m)
-600 m	5.95e-09	5.90e-09	5.86e-09	5.86e-09	5.85e-09
	D (-0.26m)	D (-0.26m)	D (-0.26m)	D (-0.27m)	D (-0.27m)
-400 m	9.36e-09	9.46e-09	9.55e-09	9.59e-09	9.62e-09
	D (-0.13m)	D (-0.12m)	D (-0.11m)	D (-0.11m)	D (-0.12m)
-200 m	129.789	129.887	129.957	129.975	129.963
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

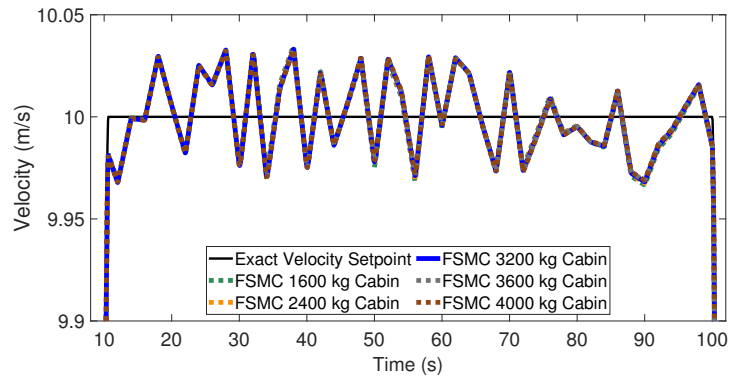


Figure 6.69: Velocity response of FSMC-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the period of steady-state travel) – Elevator C

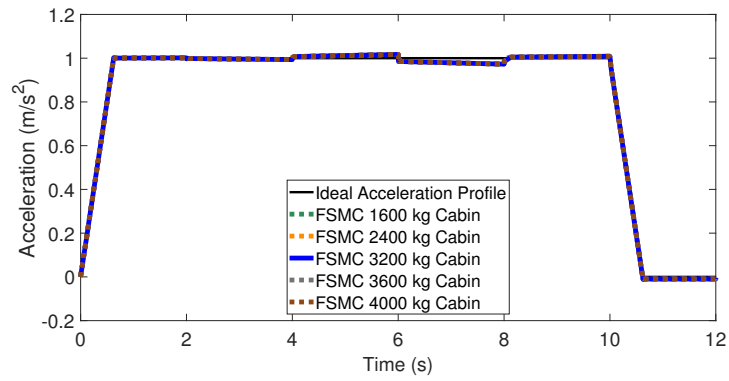


Figure 6.70: Acceleration response of FSMC-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the period of acceleration) – Elevator C

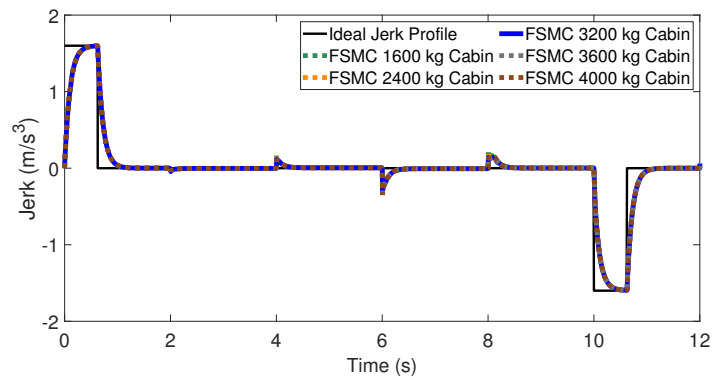


Figure 6.71: Jerk response of FSMC-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the period of acceleration) – Elevator C

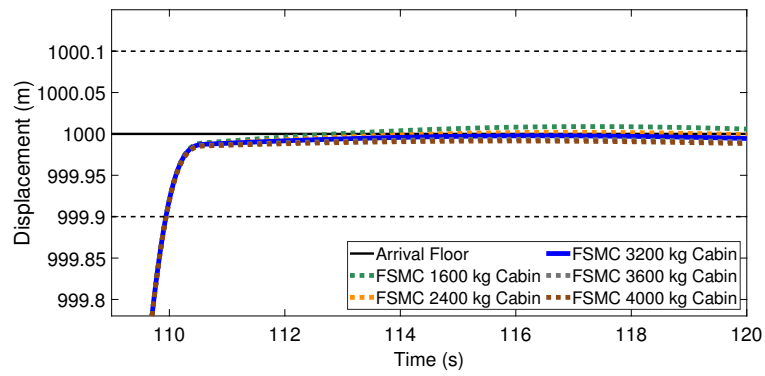


Figure 6.72: Displacement response of FSMC-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the moment of arrival) – Elevator C

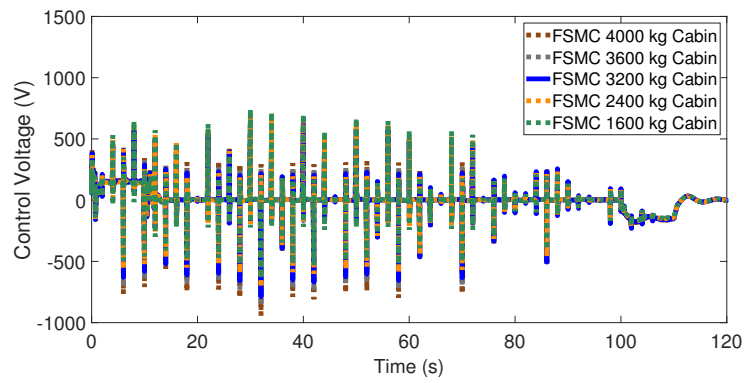


Figure 6.73: Control voltage output during FSMC control of cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

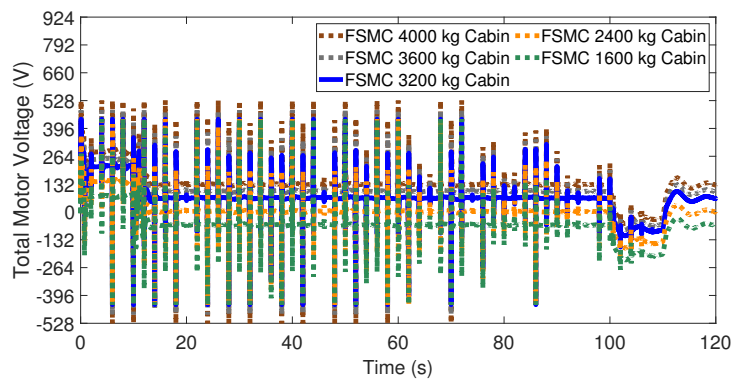


Figure 6.74: Total motor voltage during FSMC control of cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

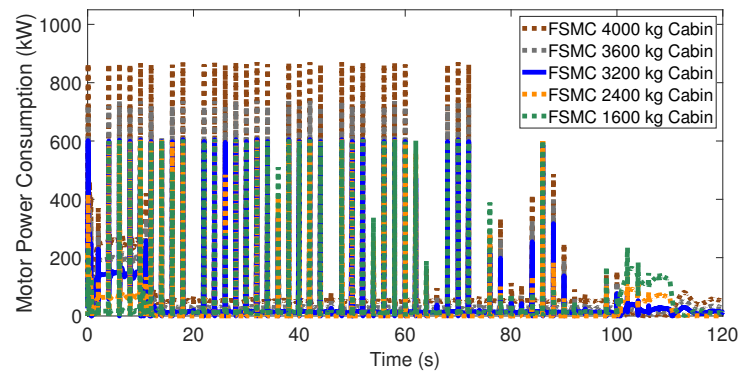


Figure 6.75: Total motor power consumption during FSMC control of cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

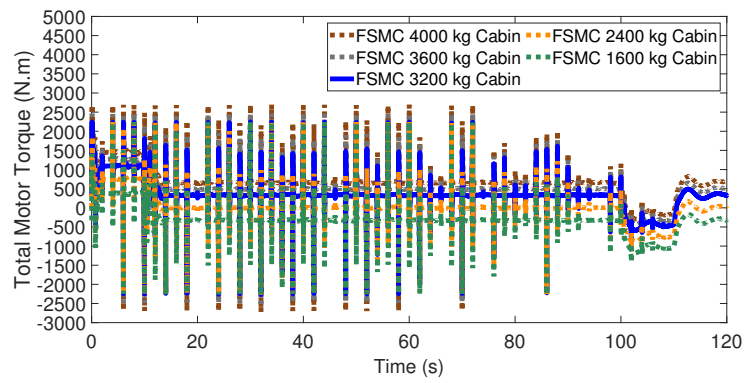


Figure 6.76: Total motor torque during actuation of FSMC-controlled cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

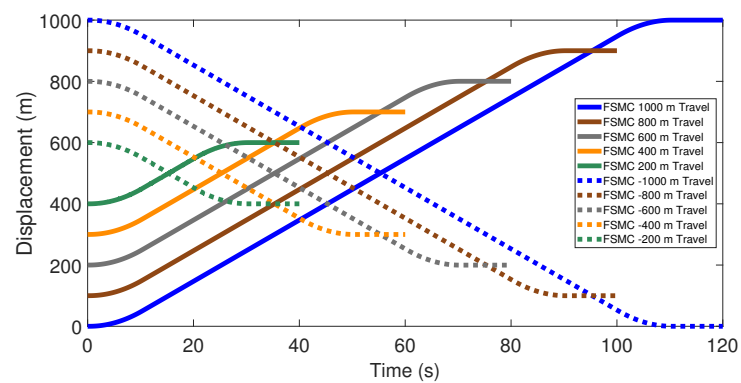


Figure 6.77: Displacement response of FSMC-controlled 3200 kg cabins travelling to different floors – Elevator C

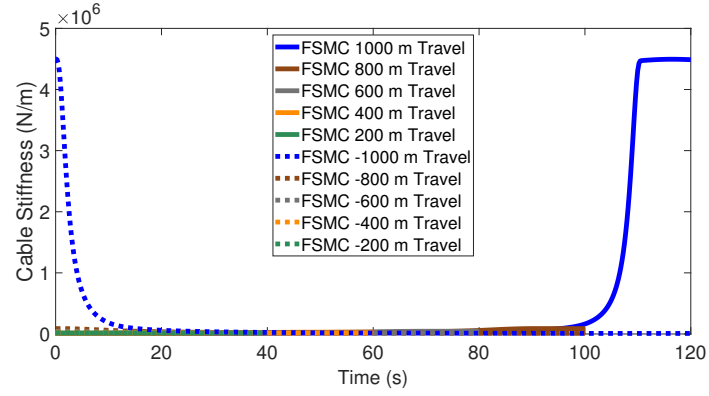


Figure 6.78: Change in the cabin-side cable stiffness (k_c) during FSMC control of 3200 kg cabins travelling to different floors – Elevator C

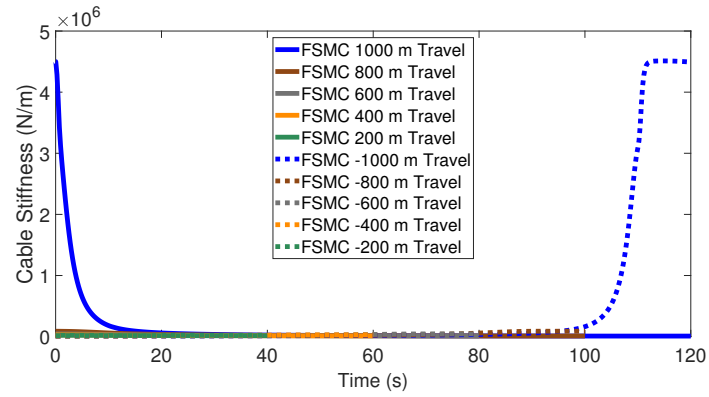


Figure 6.79: Change in the counterweight-side cable stiffness (k_w) during FSMC control of 3200 kg cabins travelling to different floors – Elevator C

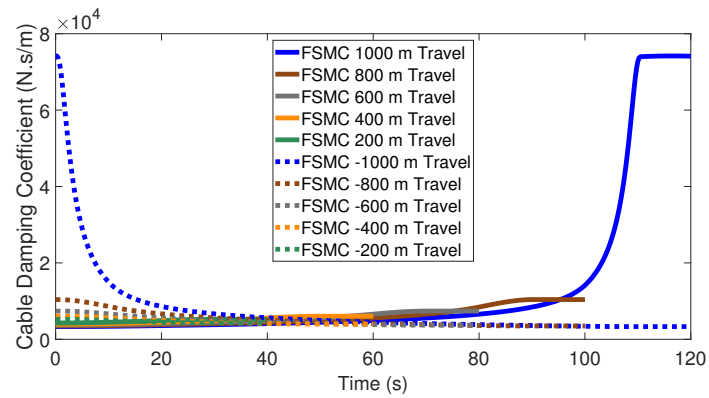


Figure 6.80: Change in the cabin-side cable damping coefficient (c_c) during FSMC control of 3200 kg cabins travelling to different floors – Elevator C

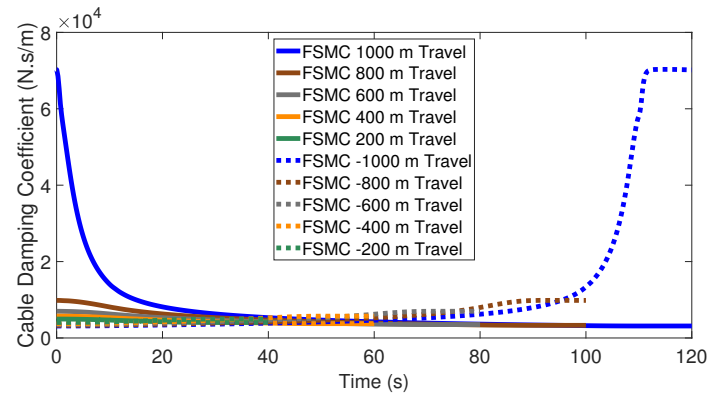


Figure 6.81: Change in the counterweight-side cable damping coefficient (c_w) during FSMC control of 3200 kg cabins travelling to different floors – Elevator C

6.5.4 Robustness analysis – SSMC for Elevator C

Table 6.8: Robustness analysis – SSMC for control of Elevator C

Lifting Height	Mass of Elevator C Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	130.195	130.186	130.141	130.121	130.088
	Pass	Pass	Pass	Pass	Pass
400 m	9.33e-09	9.34e-09	9.35e-09	9.35e-09	9.35e-09
	D (+0.12m)	D (+0.12m)	D (+0.12m)	D (+0.12m)	D (+0.12m)
600 m	6.10e-09	6.10e-09	6.11e-09	6.11e-09	6.11e-09
	D (+0.25m)	D (+0.25m)	D (+0.25m)	D (+0.25m)	D (+0.25m)
800 m	9.02e-09	9.03e-09	9.03e-09	9.03e-09	9.03e-09
	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)
1000 m	106.169	106.186	106.173	106.142	106.141
	Pass	Pass	Pass	Pass	Pass
-1000 m	106.193	106.209	106.212	106.213	106.204
	Pass	Pass	Pass	Pass	Pass
-800 m	9.03e-09	9.02e-09	9.02e-09	9.01e-09	9.01e-09
	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.14m)
-600 m	6.12e-09	6.12e-09	6.11e-09	6.11e-09	6.11e-09
	D (-0.25m)	D (-0.25m)	D (-0.25m)	D (-0.25m)	D (-0.25m)
-400 m	9.35e-09	9.34e-09	9.33e-09	9.32e-09	9.32e-09
	D (-0.12m)	D (-0.12m)	D (-0.12m)	D (-0.12m)	D (-0.12m)
-200 m	130.171	130.193	130.187	130.176	130.147
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

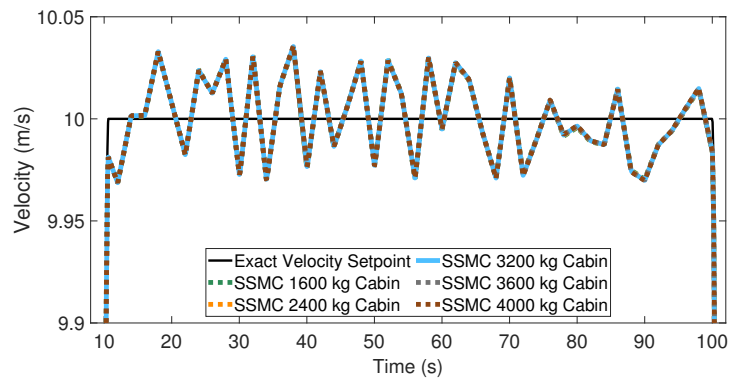


Figure 6.82: Velocity response of SSMC-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the period of steady-state travel) – Elevator C

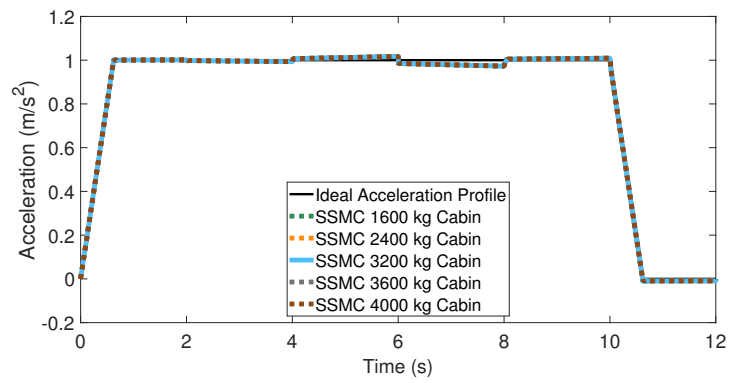


Figure 6.83: Acceleration response of SSMC-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the period of acceleration) – Elevator C

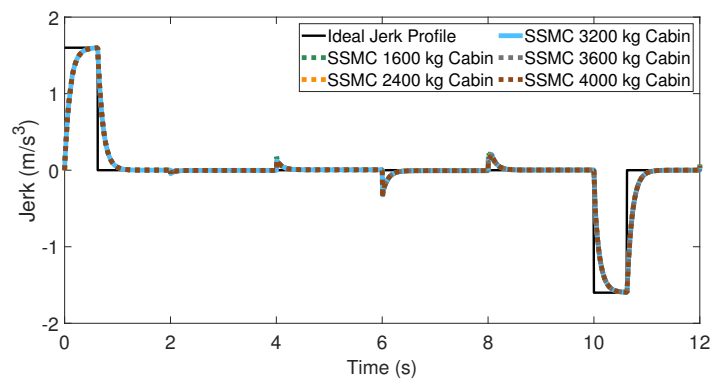


Figure 6.84: Jerk response of SSMC-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the period of acceleration) – Elevator C

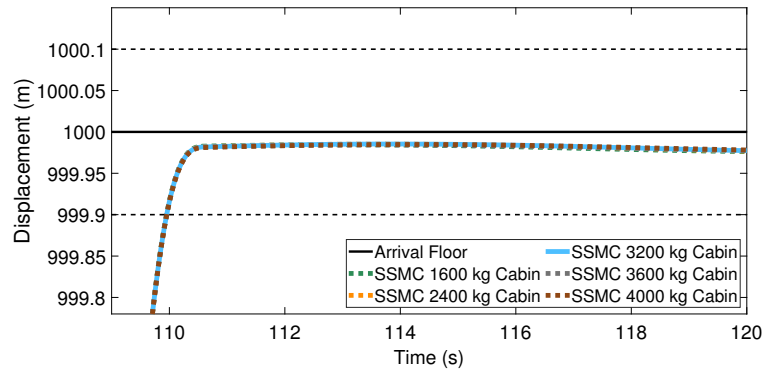


Figure 6.85: Displacement response of SSMC-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the moment of arrival) – Elevator C

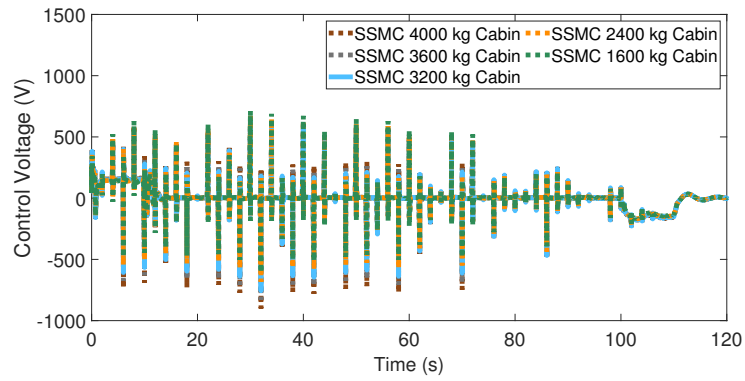


Figure 6.86: Control voltage output during SSMC control of cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

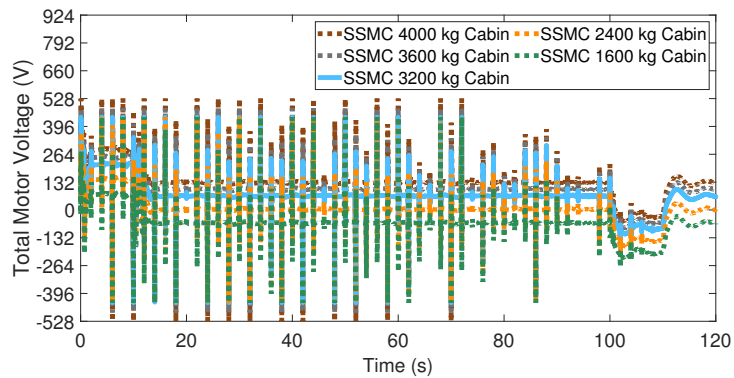


Figure 6.87: Total motor voltage during SSMC control of cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

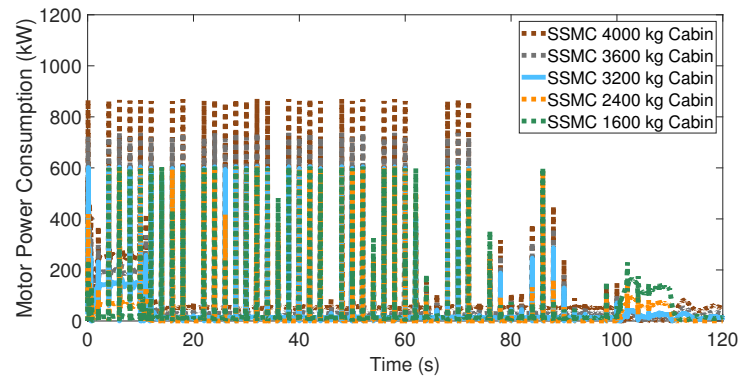


Figure 6.88: Total motor power consumption during SSMC control of cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

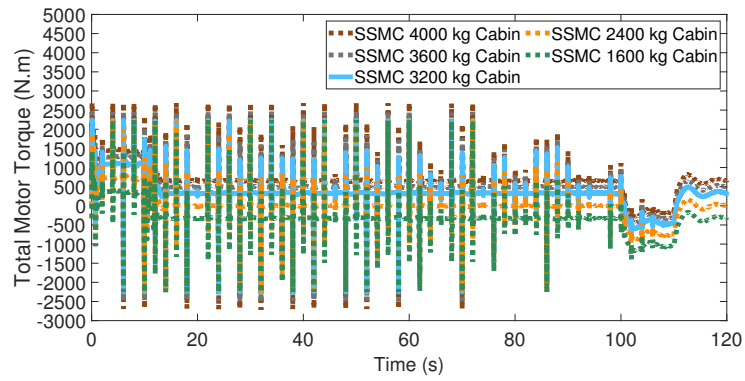


Figure 6.89: Total motor torque during actuation of SSMC-controlled cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

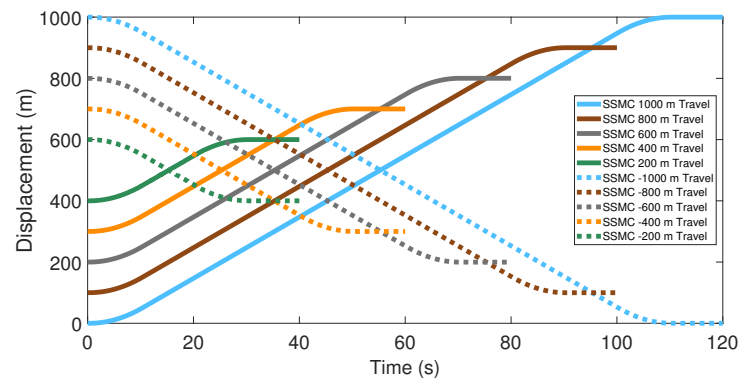


Figure 6.90: Displacement response of SSMC-controlled 3200 kg cabins travelling to different floors – Elevator C

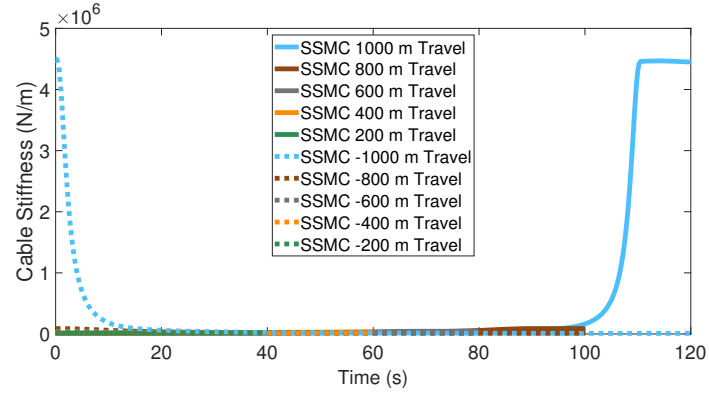


Figure 6.91: Change in the cabin-side cable stiffness (k_c) during SSMC control of 3200 kg cabins travelling to different floors – Elevator C

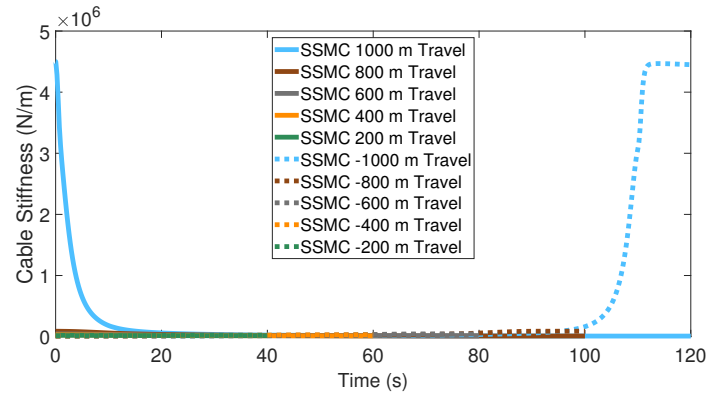


Figure 6.92: Change in the counterweight-side cable stiffness (k_w) during SSMC control of 3200 kg cabins travelling to different floors – Elevator C

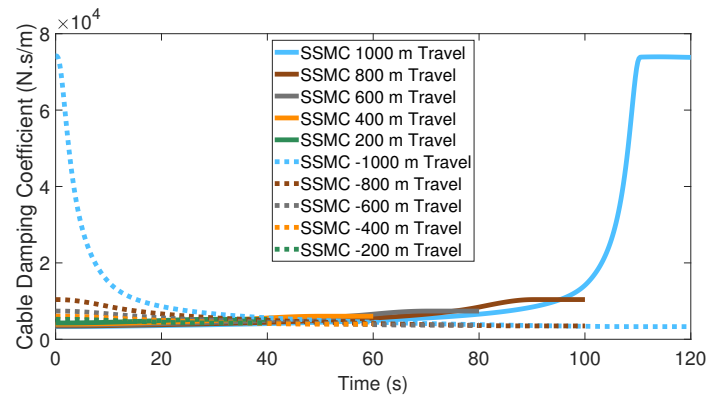


Figure 6.93: Change in the cabin-side cable damping coefficient (c_c) during SSMC control of 3200 kg cabins travelling to different floors – Elevator C

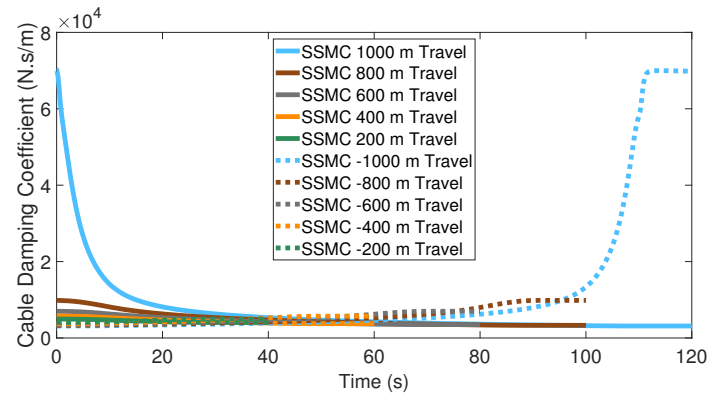


Figure 6.94: Change in the counterweight-side cable damping coefficient (c_w) during SSMC control of 3200 kg cabins travelling to different floors – Elevator C

6.5.5 Robustness analysis – RBFNN-SMC for Elevator C

Table 6.9: Robustness analysis – RBFNN-SMC for control of Elevator C

Lifting Height	Mass of Elevator C Cabin and Occupants				
	1600 kg	2400 kg	3200 kg	3600 kg	4000 kg
200 m	130.224	130.233	130.216	130.194	130.158
	Pass	Pass	Pass	Pass	Pass
400 m	9.34e-09	9.34e-09	9.34e-09	9.34e-09	9.33e-09
	D (+0.12m)	D (+0.12m)	D (+0.12m)	D (+0.12m)	D (+0.12m)
600 m	6.10e-09	6.10e-09	6.09e-09	6.09e-09	6.09e-09
	D (+0.25m)	D (+0.25m)	D (+0.25m)	D (+0.25m)	D (+0.25m)
800 m	9.03e-09	9.03e-09	9.03e-09	9.02e-09	9.02e-09
	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)	D (+0.14m)
1000 m	106.207	106.209	106.203	106.194	106.178
	Pass	Pass	Pass	Pass	Pass
-1000 m	106.221	106.223	106.216	106.207	106.191
	Pass	Pass	Pass	Pass	Pass
-800 m	9.02e-09	9.02e-09	9.02e-09	9.02e-09	9.02e-09
	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.14m)	D (-0.14m)
-600 m	6.09e-09	6.09e-09	6.09e-09	6.09e-09	6.09e-09
	D (-0.25m)	D (-0.25m)	D (-0.25m)	D (-0.25m)	D (-0.25m)
-400 m	9.34e-09	9.34e-09	9.34e-09	9.34e-09	9.34e-09
	D (-0.12m)	D (-0.12m)	D (-0.12m)	D (-0.12m)	D (-0.12m)
-200 m	130.224	130.234	130.219	130.198	130.164
	Pass	Pass	Pass	Pass	Pass

Refer to Tables 3.7, 3.8 and 3.9 for key

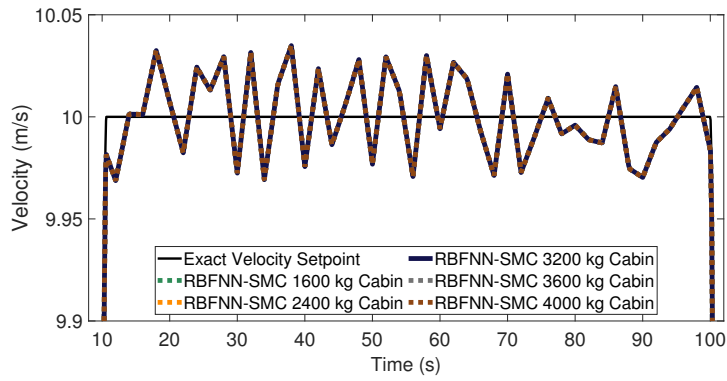


Figure 6.95: Velocity response of RBFNN-SMC-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the period of steady-state travel) – Elevator C

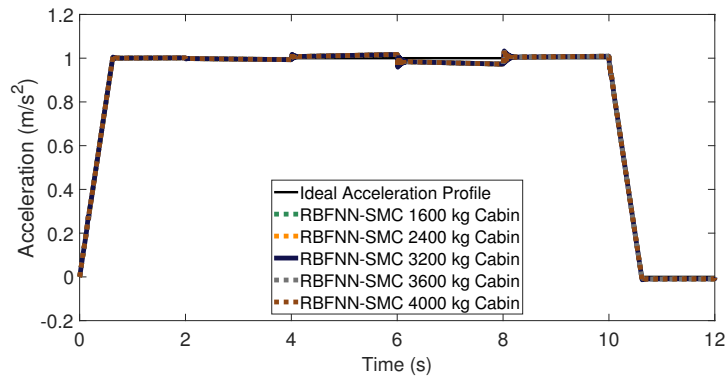


Figure 6.96: Acceleration response of RBFNN-SMC-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the period of acceleration) – Elevator C

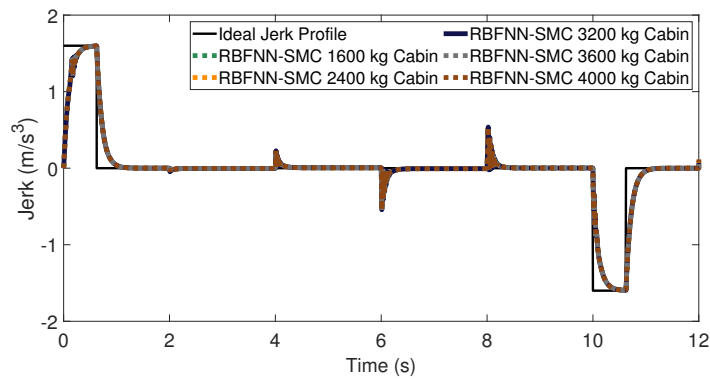


Figure 6.97: Jerk response of RBFNN-SMC-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the period of acceleration) – Elevator C

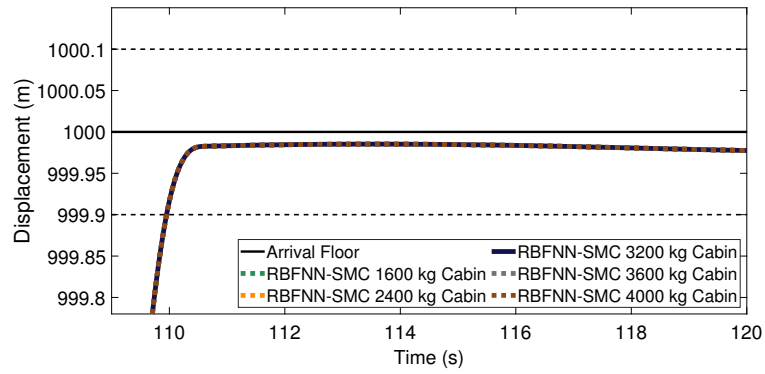


Figure 6.98: Displacement response of RBFNN-SMC-controlled cabins of various masses travelling upwards for a distance of 1000 m (zoomed into the moment of arrival) – Elevator C

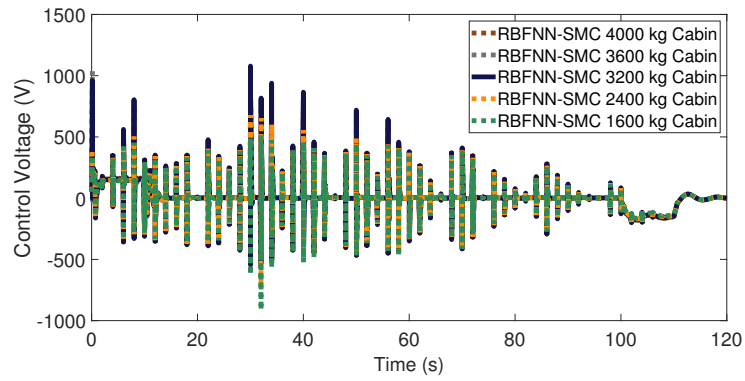


Figure 6.99: Control voltage output during RBFNN-SMC control of cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

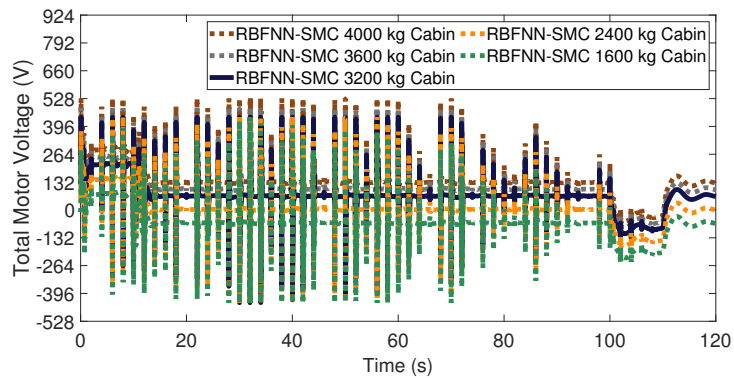


Figure 6.100: Total motor voltage during RBFNN-SMC control of cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

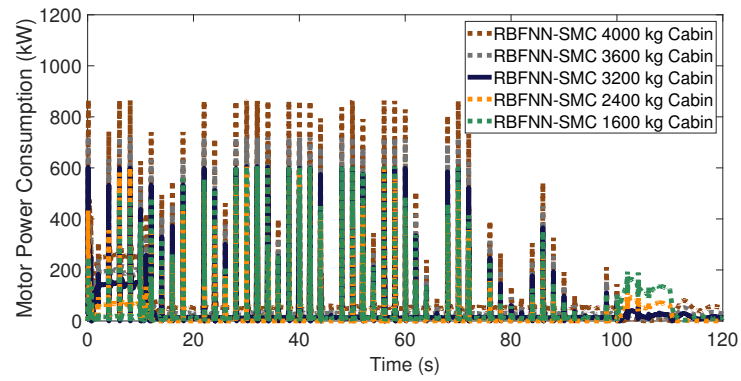


Figure 6.101: Total motor power consumption during RBFNN-SMC control of cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

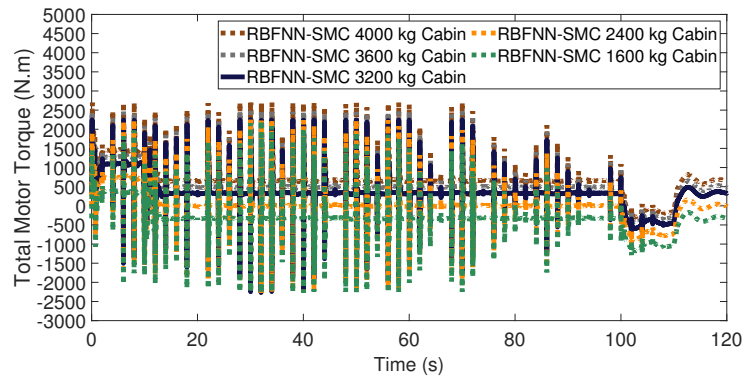


Figure 6.102: Total motor torque during actuation of RBFNN-SMC-controlled cabins of various masses travelling upwards for a distance of 1000 m – Elevator C

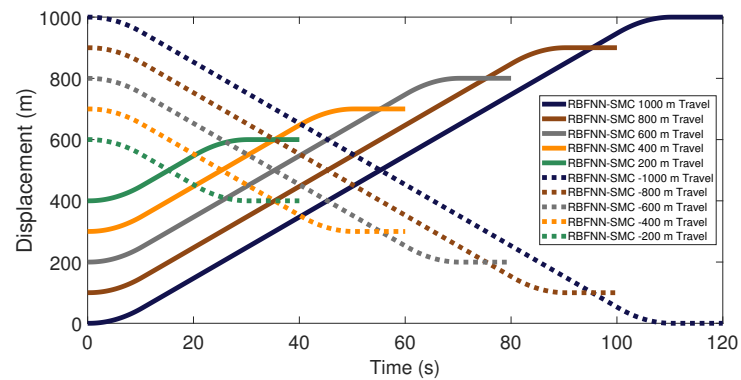


Figure 6.103: Displacement response of RBFNN-SMC-controlled 3200 kg cabins travelling to different floors – Elevator C

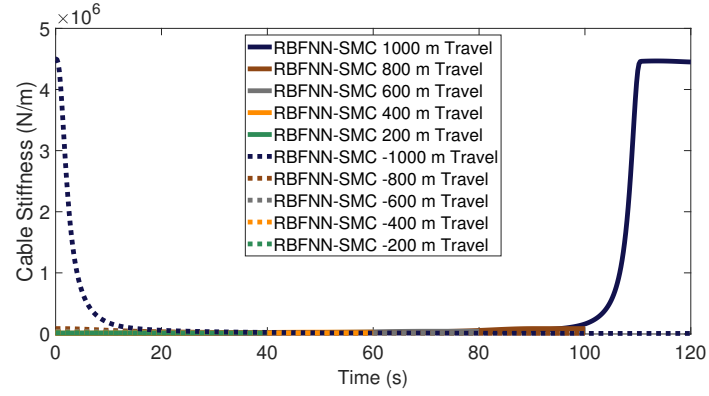


Figure 6.104: Change in the cabin-side cable stiffness (k_c) during RBFNN-SMC control of 3200 kg cabins travelling to different floors – Elevator C

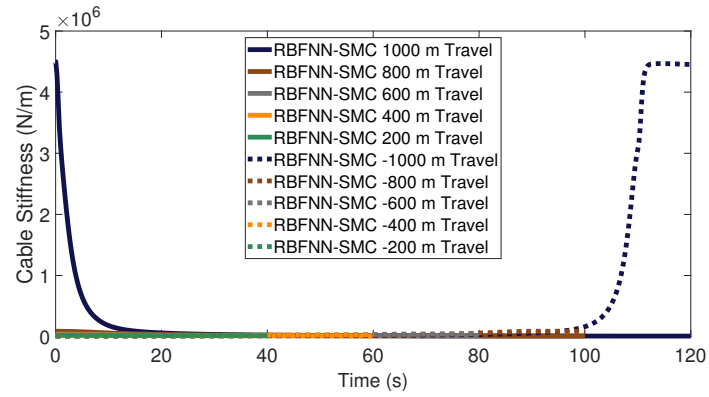


Figure 6.105: Change in the counterweight-side cable stiffness (k_w) during RBFNN-SMC control of 3200 kg cabins travelling to different floors – Elevator C

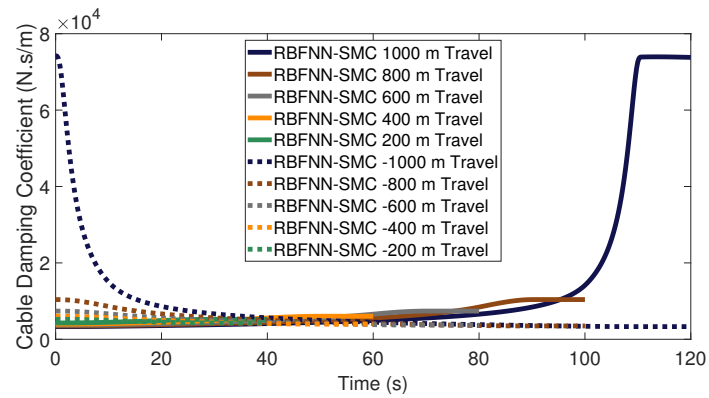


Figure 6.106: Change in the cabin-side cable damping coefficient (c_c) during RBFNN-SMC control of 3200 kg cabins travelling to different floors – Elevator C

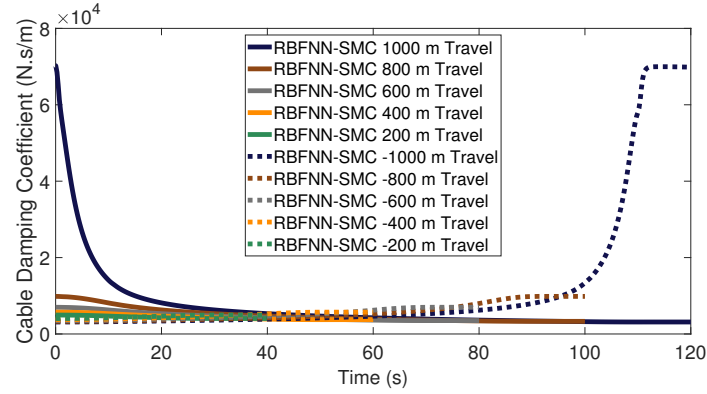


Figure 6.107: Change in the counterweight-side cable damping coefficient (c_w) during RBFNN-SMC control of 3200 kg cabins travelling to different floors – Elevator C

6.6 Implementation of Adaptive Re-levelling for Elevator C

6.6.1 3200 kg cabin travelling upwards for a distance of 1000 m – Elevator C

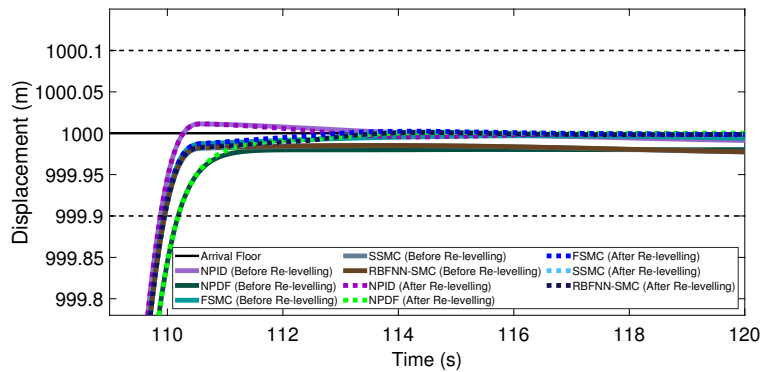


Figure 6.108: Displacement response of the 3200 kg cabins with and without re-levelling (zoomed into the moment of arrival after travelling upwards for 1000 m) – Elevator C

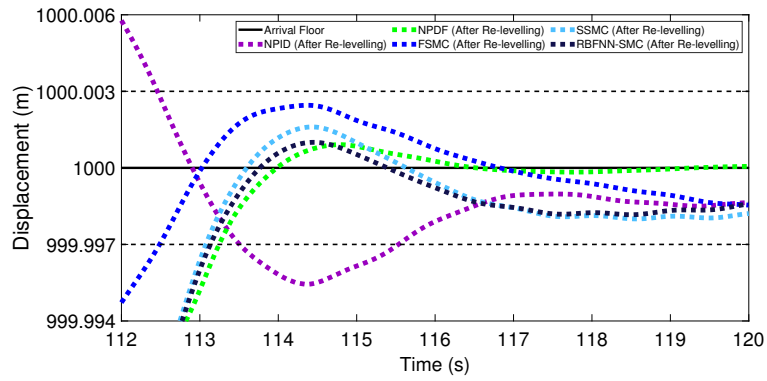


Figure 6.109: Displacement response of the 3200 kg cabins during re-levelling (zoomed into the moment that the elevator doors may open after travelling upwards for 1000 m) – Elevator C

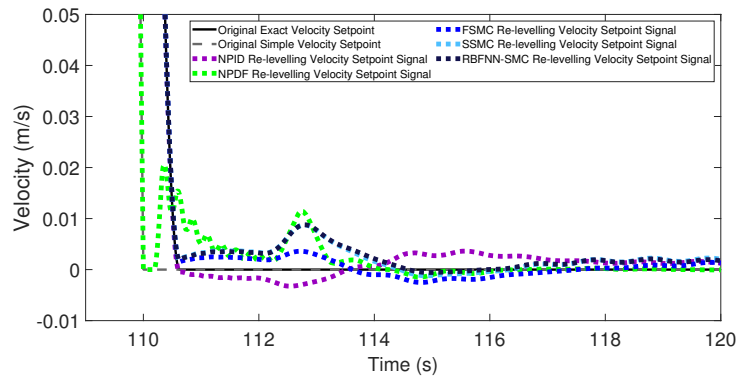


Figure 6.110: Adaptive re-levelling velocity setpoint signals (v_{d-r}) for re-levelling of the 3200 kg cabins travelling upwards for 1000 m – Elevator C

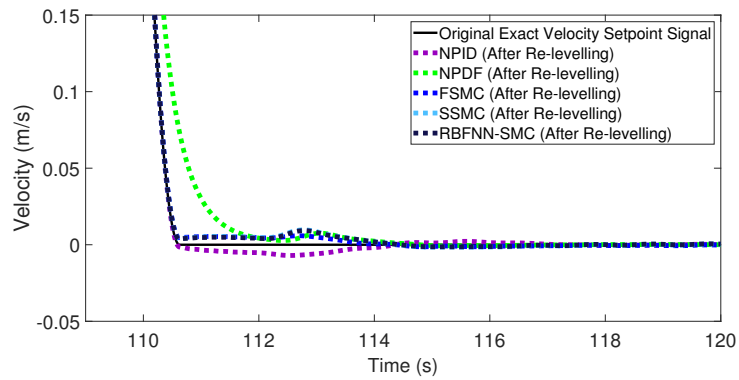


Figure 6.111: Velocity response of the 3200 kg cabins during re-levelling (zoomed into the moment of arrival after travelling upwards for 1000 m) – Elevator C

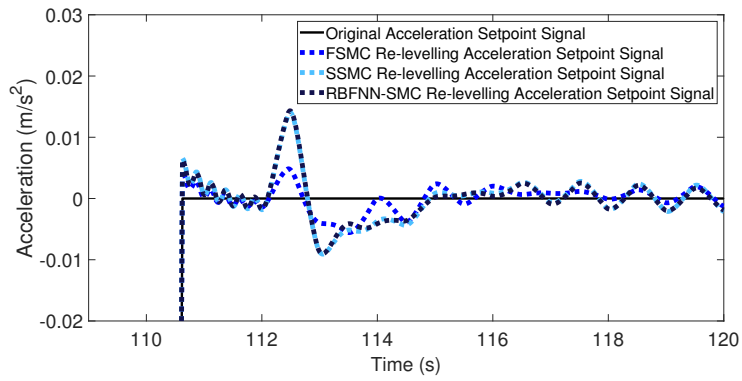


Figure 6.112: Adaptive re-levelling acceleration setpoint signals (a_{d-r}) for re-levelling of the SMC-controlled 3200 kg cabins travelling upwards for 1000 m – Elevator C

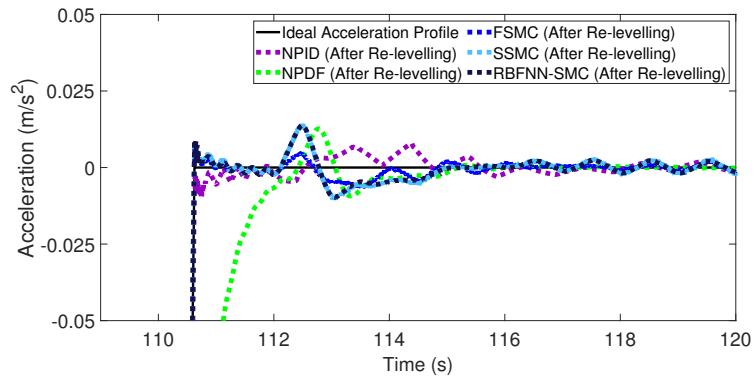


Figure 6.113: Acceleration response of the 3200 kg cabins during re-levelling (zoomed into the moment of arrival after travelling upwards for 1000 m) – Elevator C

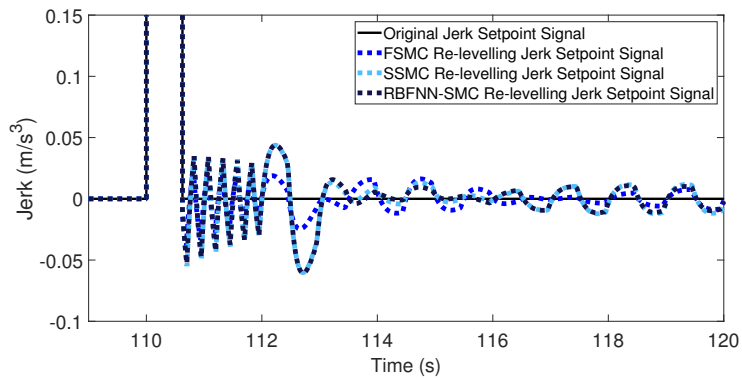


Figure 6.114: Adaptive re-levelling jerk setpoint signals (j_{d-r}) for re-levelling of the SMC-controlled 3200 kg cabins travelling upwards for 1000 m – Elevator C

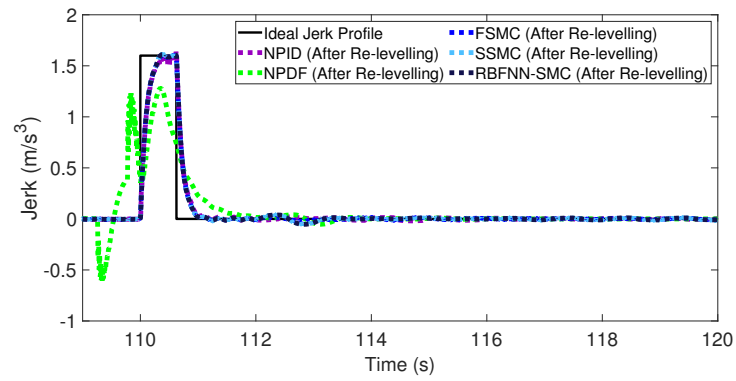


Figure 6.115: Jerk response of the 3200 kg cabins during re-levelling (zoomed into the moment of arrival after travelling upwards for 1000 m) – Elevator C

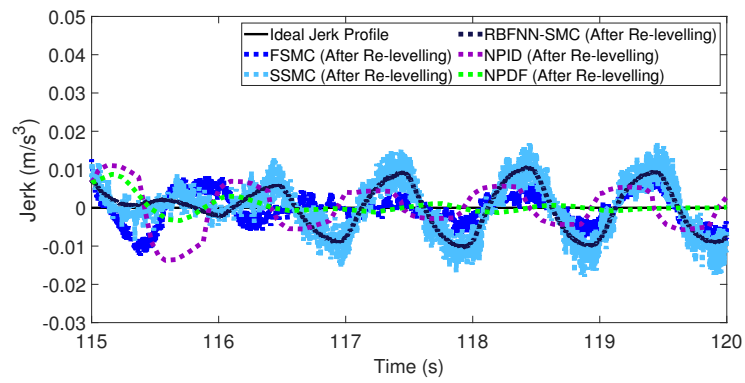


Figure 6.116: Jerk response of the 3200 kg cabins during re-levelling (zoomed into the period where end jerk is evaluated after travelling upwards for 1000 m) – Elevator C

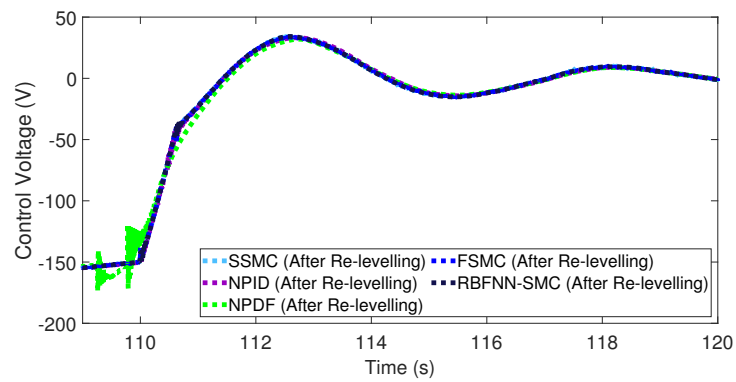


Figure 6.117: Control voltage output during re-levelling of the 3200 kg cabins (zoomed into the moment of arrival after travelling upwards for 1000 m) – Elevator C

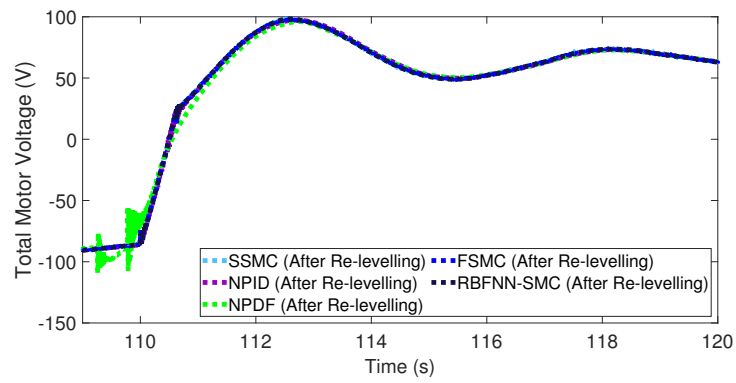


Figure 6.118: Total motor voltage during re-levelling of the 3200 kg cabins (zoomed into the moment of arrival after travelling upwards for 1000 m) – Elevator C

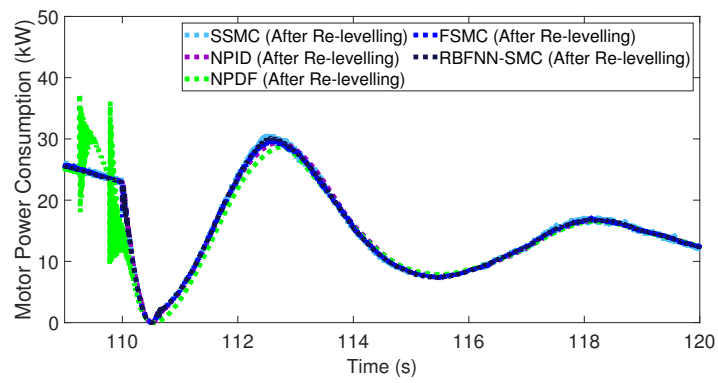


Figure 6.119: Total motor power consumption during re-levelling of the 3200 kg cabins (zoomed into the moment of arrival after travelling upwards for 1000 m) – Elevator C

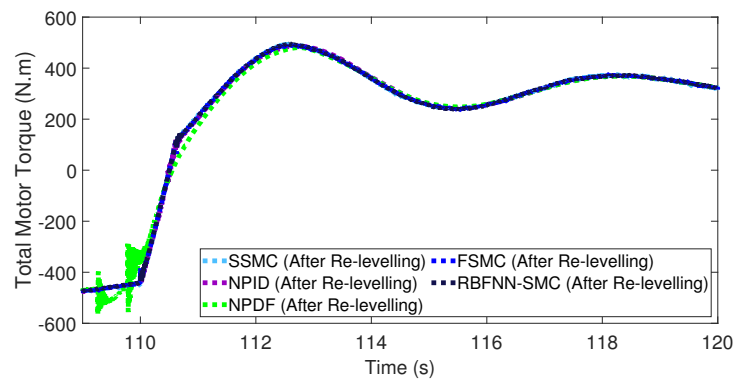


Figure 6.120: Total motor torque for re-levelling of the 3200 kg cabins (zoomed into the moment of arrival after travelling upwards for 1000 m) – Elevator C

6.6.2 3200 kg cabin travelling upwards for a distance of 600 m – Elevator C

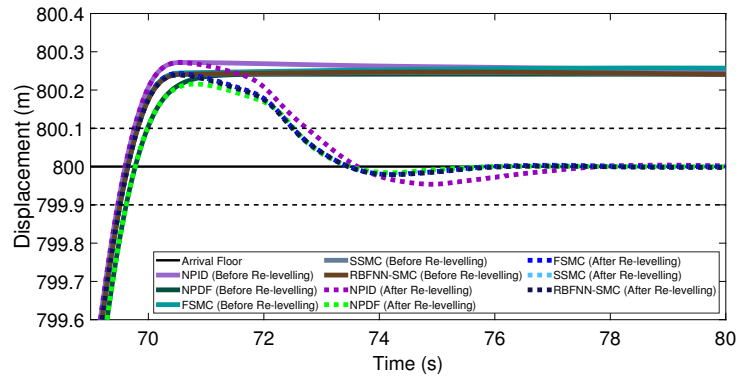


Figure 6.121: Displacement response of the 3200 kg cabins with and without re-levelling (zoomed into the moment of arrival after travelling upwards for 600 m) – Elevator C

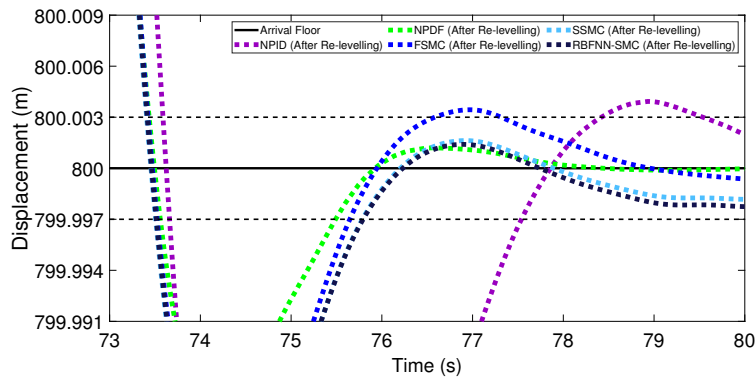


Figure 6.122: Displacement response of the 3200 kg cabins during re-levelling (zoomed into the moment that the elevator doors may open after travelling upwards for 600 m) – Elevator C

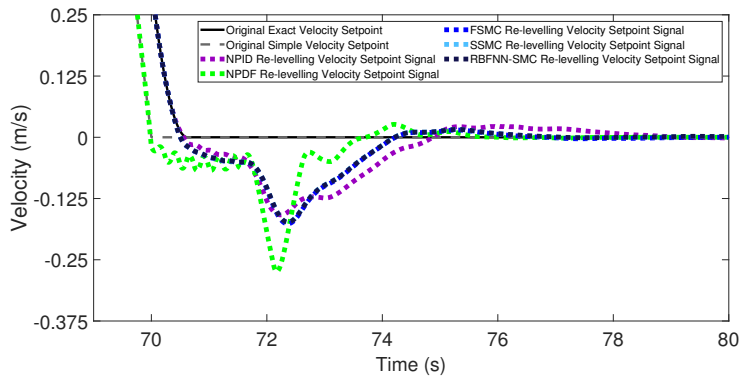


Figure 6.123: Adaptive re-levelling velocity setpoint signals (v_{d-r}) for re-levelling of the 3200 kg cabins travelling upwards for 600 m – Elevator C

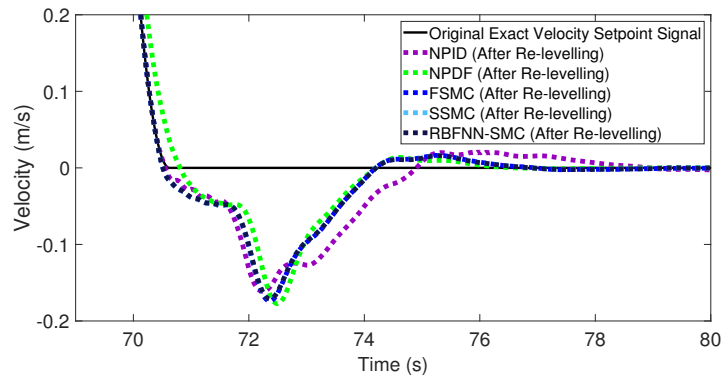


Figure 6.124: Velocity response of the 3200 kg cabins during re-levelling (zoomed into the moment of arrival after travelling upwards for 600 m) – Elevator C

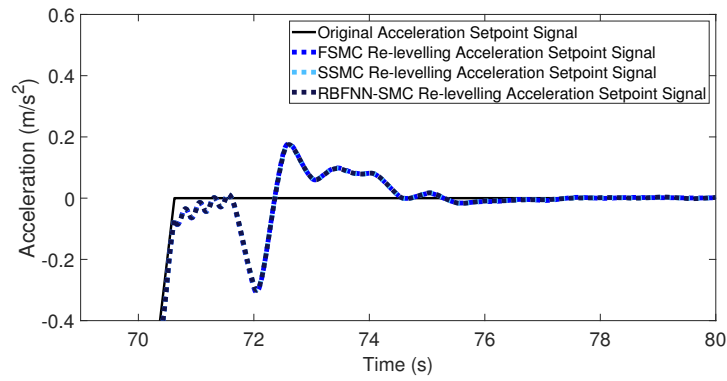


Figure 6.125: Adaptive re-levelling acceleration setpoint signals (a_{d-r}) for re-levelling of the SMC-controlled 3200 kg cabins travelling upwards for 600 m – Elevator C

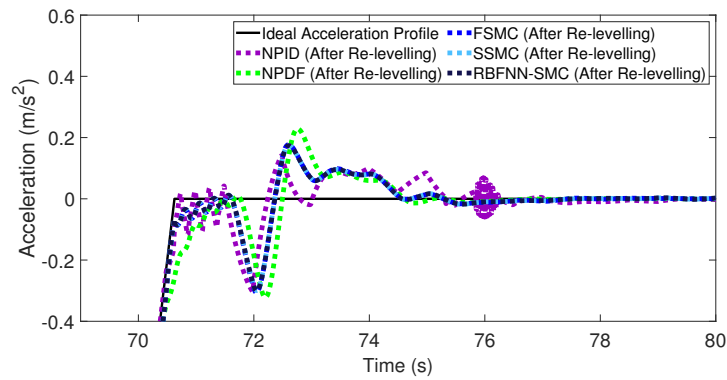


Figure 6.126: Acceleration response of the 3200 kg cabins during re-levelling (zoomed into the moment of arrival after travelling upwards for 600 m) – Elevator C

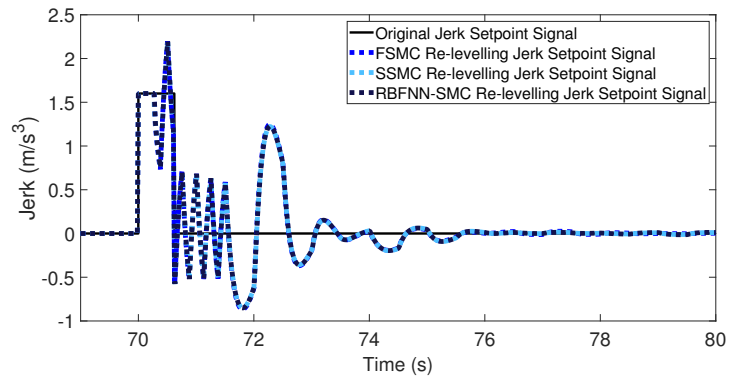


Figure 6.127: Adaptive re-levelling jerk setpoint signals (j_{d-r}) for re-levelling of the SMC-controlled 3200 kg cabins travelling upwards for 600 m – Elevator C

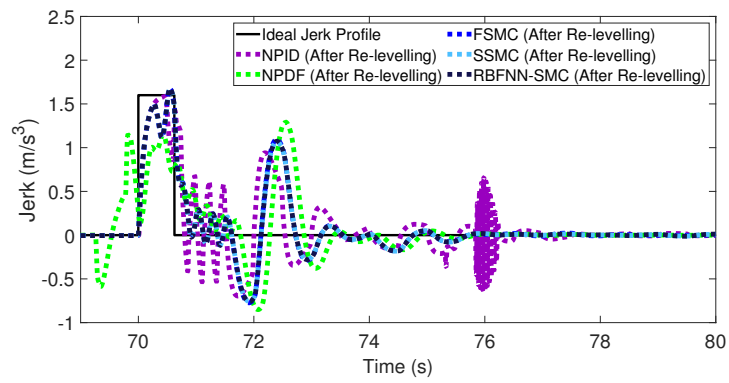


Figure 6.128: Jerk response of the 3200 kg cabins during re-levelling (zoomed into the moment of arrival after travelling upwards for 600 m) – Elevator C

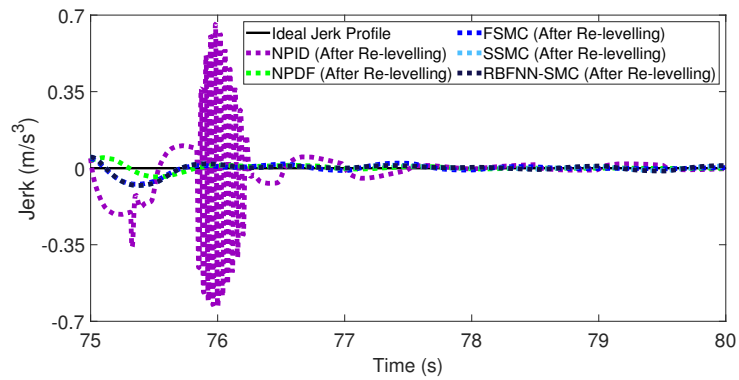


Figure 6.129: Jerk response of the 3200 kg cabins during re-levelling (zoomed into the period where end jerk is evaluated after travelling upwards for 600 m) – Elevator C

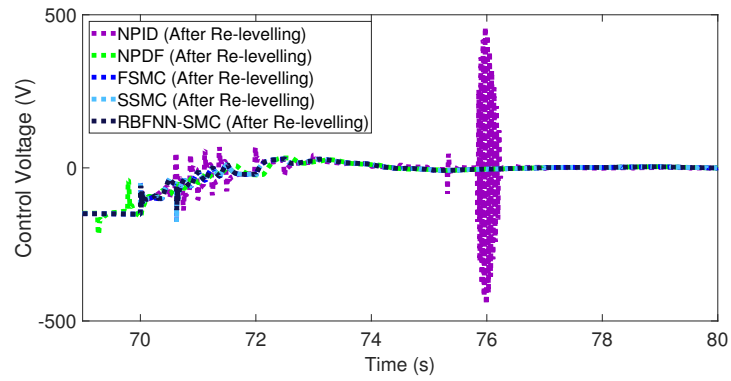


Figure 6.130: Control voltage output during re-levelling of the 3200 kg cabins (zoomed into the moment of arrival after travelling upwards for 600 m) – Elevator C

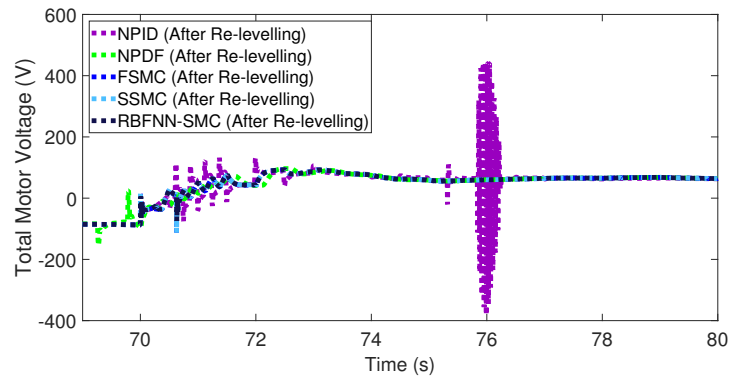


Figure 6.131: Total motor voltage during re-levelling of the 3200 kg cabins (zoomed into the moment of arrival after travelling upwards for 600 m) – Elevator C

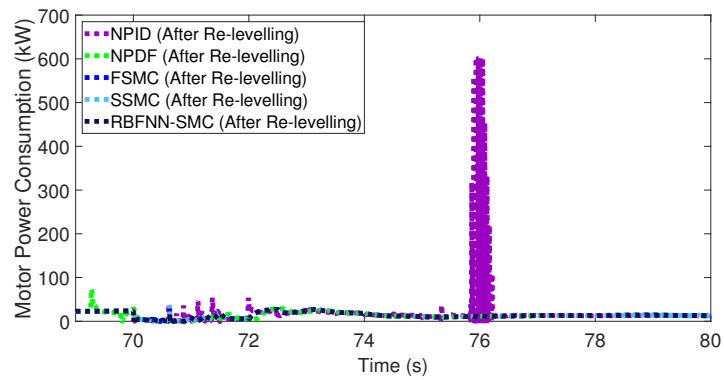


Figure 6.132: Total motor power consumption during re-levelling of the 3200 kg cabins (zoomed into the moment of arrival after travelling upwards for 600 m) – Elevator C

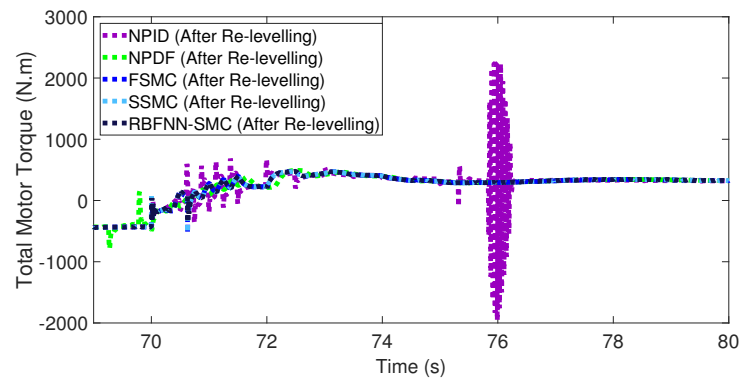


Figure 6.133: Total motor torque for re-levelling of the 3200 kg cabins (zoomed into the moment of arrival after travelling upwards for 600 m) – Elevator C

6.7 Chattering Analysis of Various SMC Structures During Control of Elevator C

Table 6.10: Controller performance summary – Elevator C (SMC chattering analysis)

Parameter	FSMC		SSMC		RBFNN-SMC	
	Saturation	Sign	Saturation	Sign	Saturation	Sign
	Function	Function	Function	Function	Function	Function
Saturation Function Coefficient (ρ)	0.4539*	0	0.4539*	0	0.4539*	0
Reaching Law Gain (K_R)	177.23*	177.23*	177.23*	177.23*	177.23*	177.23*
λ_0 Coefficient	80.42*	80.42*	80.42*	80.42*	80.42*	80.42*
λ_1 Coefficient	20.03*	20.03*	20.03*	20.03*	20.03*	20.03*
λ_2 Coefficient	662.75*	662.75*	662.75*	662.75*	662.75*	662.75*
Number of Hidden Layer Neurons (n_n)	-	-	-	-	8**	8**
Initial Hidden Layer Neuron Connection Weights (w_0)	-	-	-	-	-1.23**	-1.23**
First Hidden Layer Neuron Radial Centre (c_1)	-	-	-	-	-1417**	-1417**
Hidden Layer Neurons Radial Centre Spread (b)	-	-	-	-	1334.40**	1334.40**
RBFNN-SMC Adaptive Law Parameter (γ)	-	-	-	-	130000**	130000**
Fitness Value (F_C)	106.177	106.174	106.175	106.156	106.202	106.201
Rise Time [s] (3200 kg Cabin, 1000 m Upwards Travel)	8.99	8.89	8.99	8.99	8.99	8.99
Settling Time [s] (3200 kg Cabin, 1000 m Upwards Travel)	10.10	10.12	10.10	10.10	10.10	10.10
Velocity Overshoot [%] (3200 kg Cabin, 1000 m Upwards Travel)	0.64	0.70	0.65	0.66	0.64	0.64

*SMC parameters taken from GA-optimised SSMC defined in [Table 6.4](#)

**RBFNN parameters taken from GA-optimised RBFNN-SMC defined in [Table 6.4](#)

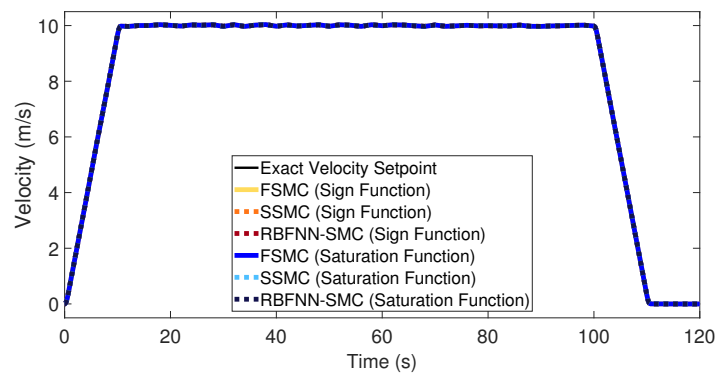


Figure 6.134: Velocity response of the 3200 kg cabins – Elevator C (SMC chattering analysis). Refer to Figures [10.33](#) and [10.34](#) for more detail.

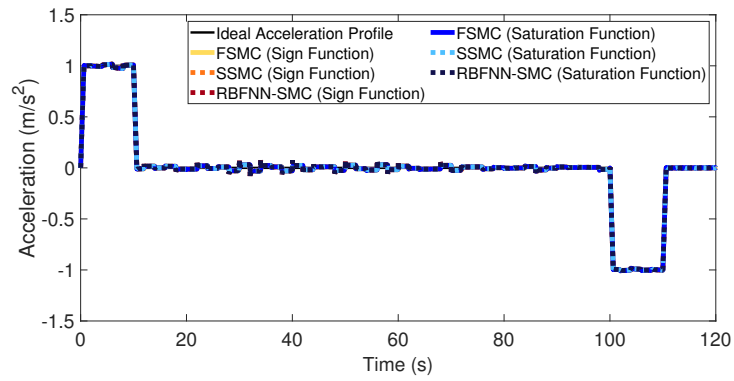


Figure 6.135: Acceleration response of the 3200 kg cabins – Elevator C (SMC chattering analysis). Refer to Figures 10.35 – 10.37 for more detail.

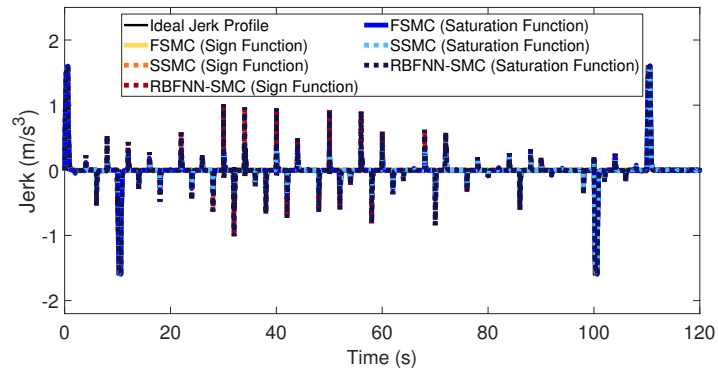


Figure 6.136: Jerk response of the 3200 kg cabins – Elevator C (SMC chattering analysis). Refer to Figures 10.38 – 10.40 for more detail.

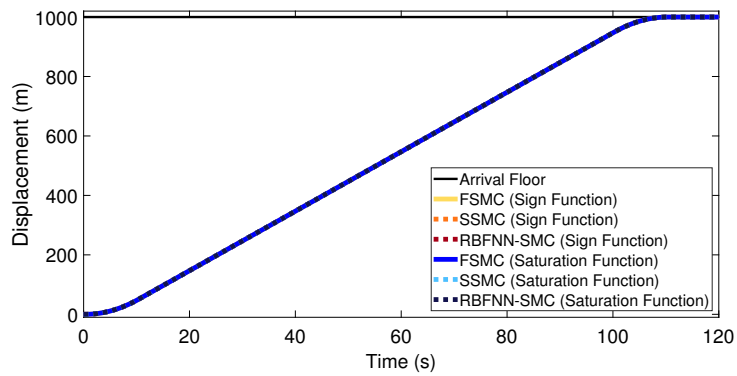


Figure 6.137: Displacement response of the 3200 kg cabins – Elevator C (SMC chattering analysis)

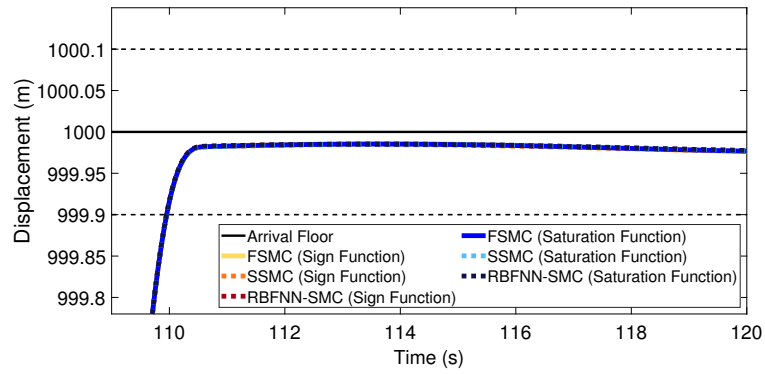


Figure 6.138: Displacement response of the 3200 kg cabins (zoomed into the moment of arrival) – Elevator C (SMC chattering analysis)

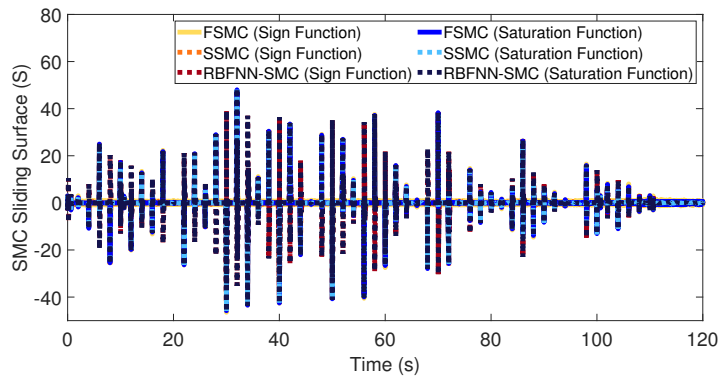


Figure 6.139: SMC sliding surface (S) during SMC control of the 3200 kg cabins – Elevator C (SMC chattering analysis)

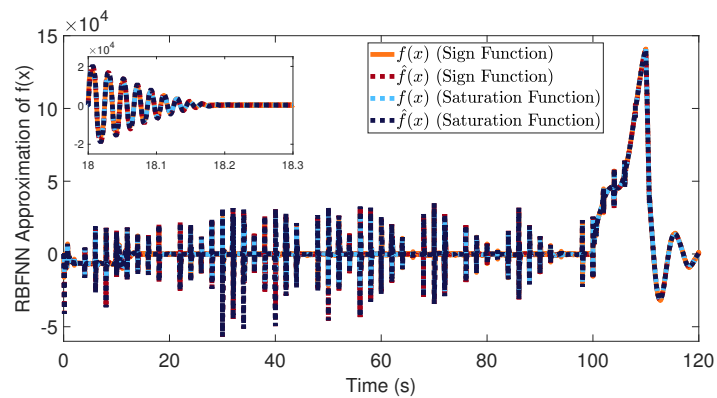


Figure 6.140: RBFNN approximation of $f(x)$ during RBFNN-SMC control of the 3200 kg cabins (featuring an inset zoomed into the period between $t = 18$ s and $t = 18.3$ s) – Elevator C (SMC chattering analysis)

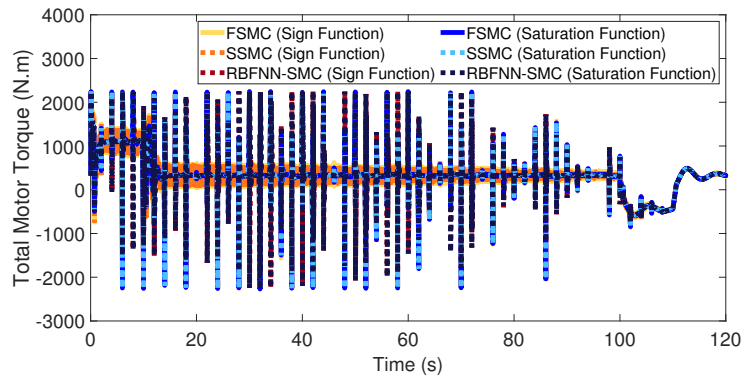


Figure 6.141: Total motor torque during actuation of the 3200 kg cabins – Elevator C (SMC chattering analysis)

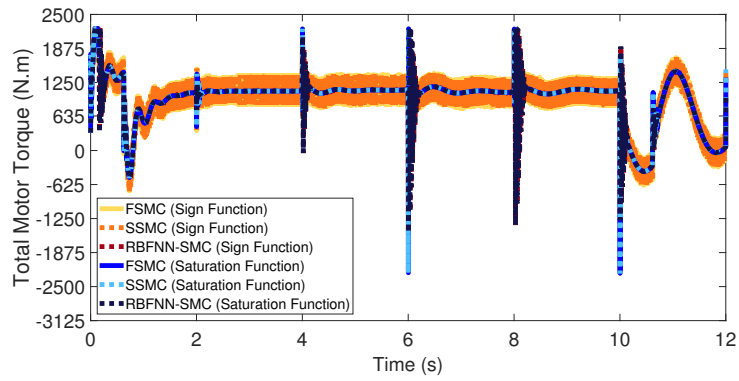


Figure 6.142: Total motor torque during actuation of the 3200 kg cabins (zoomed into the period of acceleration) – Elevator C (SMC chattering analysis)

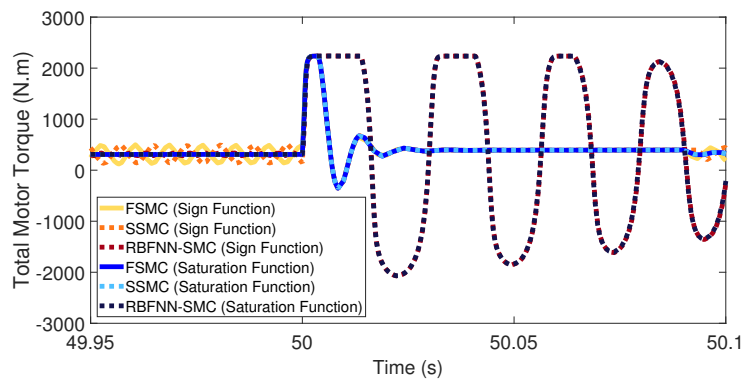


Figure 6.143: Total motor torque during actuation of the 3200 kg cabins (zoomed into a section during the period of steady-state travel) – Elevator C (SMC chattering analysis)

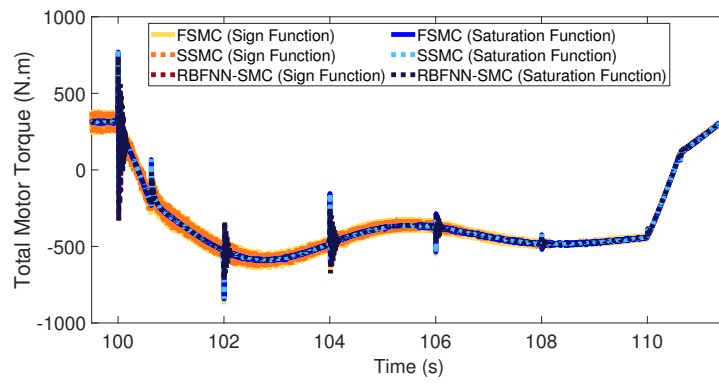


Figure 6.144: Total motor torque during actuation of the 3200 kg cabins (zoomed into the period of deceleration) – Elevator C (SMC chattering analysis)

7 Discussion

7.1 Control of Elevator A

Referring first to the summary of results provided in [Table 4.3](#), it can be seen that the NPDF controller achieved the highest solution fitness out of all four of the analysed control schemes, significantly outperforming both PID controller variants. Although improvements over its conventional equivalent were observed, notably in the rise and settling times of the responses; the repeatability results provided in [Table 4.2](#) indicate that the average solution fitness of the NPDF controller was lower than that of the CPDF controller. This was due to the addition of six extra parameters to be tuned having a drastic impact on the solution repeatability, evidenced by the high standard deviation of the NPDF controller fitness results. The reduced search spaces of the controller gains (K_P , K_I and K_D) for the CPID and NPID controllers ensured better solution convergence, with the standard deviation of the NPID controller fitness results being only marginally higher than that of the CPID controller. In general, predictably higher standard deviations were observed for control parameters having the largest search spaces in [Table 4.1](#). One exception was the relatively low standard deviations of the derivative gains for both PDF control architectures, despite having identical search spaces to the K_P and K_I gains. This demonstrates the importance of carefully tuning the derivative term of a PDF controller, with the parameter having a significant influence on the effectiveness of the control scheme.

A notable finding during the determination of the search spaces was the relatively low upper bounds of the CPID controller gains, particularly the integral gain. This limitation was largely due to the use of the simple velocity setpoint, which does not account for jerk. Essentially, the controller was instructed to track the setpoint as closely as possible without exceeding the jerk constraints, thereby inducing a large error between the setpoint and the process variable during acceleration. The subsequent integral windup constrains the maximum allowable K_I gain value, hindering the ability of the controller to control the system. The search spaces for the NPID controller gains were increased, with the mean value of the K_I gain across the ten repeatability simulations being recorded as 20.93 for the NPID controller, compared to just 0.0085 for its conventional equivalent. This suggests that the introduction of a negative α_I parameter is a successful anti-windup strategy, with the controller

increasing integral action for small errors and reducing it when the error is large; which achieved noticeably more effective control compared with the CPID controller.

Despite the improvements of the NPID controller over the CPID controller, the trend of PDF controller dominance recorded in previous work continued, with even the conventional PDF controller completely outperforming the nonlinear PID controller. This is clearly illustrated in the evolution of the solution fitnesses in [Figure 4.1](#), as well as in the velocity responses in [Figure 4.2](#). From [Figure 4.3](#), an additional improvement of the NPID controller over the CPID controller can be seen in the form of lower peaks during acceleration and deceleration of the system. This improvement in comfort (albeit a minor one) was achieved without compromising on performance. Both the CPDF and NPDF controllers recorded higher acceleration values than the CPID and NPID controllers, which is to be expected giving the superior setpoint tracking achieved by the PDF control architectures. A notable aspect of the CPDF controller response is the oscillations that were identified towards the end of the journey, a result similar to the findings of Vladić et al., [1] (refer to [Figure 1.4](#)). These fluctuations were likely a result of the high stiffness of the cabin-side lifting cable when approaching the top floor (refer to [Figure 4.11](#)), coupled with the relatively low end-of-travel damping coefficient value of 10000 N.s/m. The absence of compensation ropes could have also had an effect, due to the low mass on the cabin-side of the lifting pulley at the end of the travel operation (as shown in [Figure 4.13](#)). Similar oscillations are not observed in the NPDF controller response, with the introduction of the nonlinear functions ensuring that the controller was able to mitigate the vibrations.

The fluctuations in the CPDF controller response are more apparent in the jerk profile plotted in [Figure 4.4](#). Although technically within the acceptable jerk limitations stipulated in [Section 3.3.1](#), such a response at a time when passengers are set to transfer into and out of the cabin is potentially problematic. From [Figure 4.10](#), it can be seen that excessive chattering in the motor torque occurred during this time, a response that could cause serious damage to the actuator. This was not observed during NPDF control of the system, with the motor torque remaining stable throughout operation of the system. [Figure 4.5](#) indicates that the absence of chattering did not delay the arrival of the NPDF-controlled cabin, which reached the destination marginally earlier than its CPDF-controlled counterpart. In addition to reaching the arrival floor earlier than the PID-controlled cabins, both PDF controllers were able to secure a more stable arrival, effectively bringing the cabins to a complete stop. Despite the relatively poor performance of both PID controllers, all four control architectures ensured that the cabins arrived within 65 seconds and remained within 0.1 m of the target floor.

The superior performance of the NPID controller over its traditional equivalent is clearly illustrated in [Figure 4.14](#), which presents the responses of the CPID and NPID-controlled cabins following a $\pm 20\%$ variation in cabin mass. This was most obvious during the period of acceleration, with the NPID controller exhibiting slightly improved tracking capabilities. The higher robustness of the NPID controller is demonstrated in [Figure 4.17](#), with all three NPID controlled-cabins displaying a similar displacement response; whereas both the overloaded and underloaded CPID-controlled cabins

failed to meet the displacement constraint. [Figure 4.18](#) highlights the exceptionally high robustness of both PDF controller variants, with the three separate responses of each controller being almost completely identical. Additionally, the enhanced disturbance rejection capabilities of the control systems are evidenced by the sharper responses to external interference, compared with the more rounded responses of the PID control architectures.

From [Figure 4.20](#), it is clear that the oscillations in the jerk response of the CPDF-controlled cabin were exacerbated following the reduction in cabin mass, resulting in the jerk constraint being exceeded. This highly oscillatory behaviour, with peaks outside of the specified maximum allowable jerk, would pose a serious risk to both cabin occupants and components of the elevator system. Noting that both the CPID and NPID-controlled 2560 kg cabins also exceeded the maximum allowable jerk, albeit without experiencing similar oscillations (refer to [Figure 4.16](#)), this supports the hypothesis that the oscillations were partly caused by the low end-of-travel cabin-side moving mass due to the absence of compensation ropes. In spite of the difficulties induced by the high cable stiffness, low damping and fluctuating cable mass; the NPDF controller was able to meet all performance requirements and constraints for each of the cabin masses considered, being the only control system to do so.

7.2 Control of Elevator B

As detailed in [Section 3.4.2](#), significant changes to the optimisation process were implemented for tuning of the controllers for Elevator B. From the repeatability results for CPID, CPDF, NPID and NPDF controller optimisation using the balanced fitness function ([Table 5.3](#)), it is evident that the time to simulate ten individuals within a population rose significantly from the values detailed in [Table 4.2](#) from the previous chapter. This was not an unexpected result, due to a combination of the higher run time per simulation (resulting from the increased height of Elevator B), as well as the maximum number of simulations per individual increasing from one to five. Following these adaptations, it would have been possible for the run time per ten individuals to surge by over 700%, thereby rendering the optimisation procedure completely impractical. From the recorded values, it can be seen that the adaptation to the GA-code stopping conditions ([Table 3.12](#)), introduction of simulation stopping conditions ([Table 3.13](#)) and intricate structuring of the process ([Tables 3.14](#) and [3.15](#)) ensured that the run times remained acceptable.

A notable consequence of the introduction of simulation stopping conditions in particular was the subsequent reduction in run times per ten individuals of the nonlinear PID and PDF controllers, compared with their traditional equivalents. From [Tables 5.3](#), [5.13](#) and [5.22](#), it can be seen that lower run times per ten individuals were recorded for the NPDF controller compared with the CPDF controller,

regardless of the fitness function used for evaluation. This was due to the fact that the NPID controller experienced more early terminations, with unsuitable nonlinear α and/or δ terms often leading to solutions that either failed to meet one of the requirements or constraints, or were quickly identified as non-competitive individuals. This allowed for larger population sizes to be set in order to account for the higher number of control parameters, without incurring excessive total run times. A similar trend was observed regarding the CPID and NPID controllers, however this was not the case during optimisation using the balanced fitness function. This was caused by the CPID controller being unable to find a single solution to control the system during all five of the simulations, a problem that the NPID controller did not encounter. As the search space parameters were determined through simulations using only the standard cabin mass of 3200 kg, the issue was not initially identified. Although this was rectified for optimisation using the comfort and sustainability-oriented fitness functions, with the upper bounds of the K_P , K_I and K_D gain search spaces being increased, the success of the NPID controller is an interesting result. It corroborates the evidence obtained during control of Elevator A, that a NPID controller is able to account for parameter variations in a way that a CPID controller cannot, without the need to redefine the allowable gains.

Regarding the FSMC and SSMC repeatability results, notable improvements in the run time per ten individuals were recorded for the simplified variant of the controller, without any corresponding loss in control performance. As run time is heavily dependent on the controller parameters, which differ greatly during each optimisation procedure, an accurate run time analysis requires that identical SMC terms be applied to both versions of the controller. In order to achieve this, a set of 100 random SMC parameters (ρ , K_R , λ_0 , λ_1 and λ_2) was generated and applied to both the FSMC and SSMC, with each individual in the set being simulated sequentially. A second set of parameters was produced, differing from the original in that all saturation function values were set to $\rho = 0$ in order to analyse the run times of the SMCs when utilising a sign function. Both sets of terms were simulated ten times, with the run time results detailed in [Table 10.1](#). As shown, the average run times of the simplified SMC were considerably lower than that of the FSMC in both cases, with a greater discrepancy being observed when a sign function was used. The corresponding control results indicated a negligible reduction in the average performance of the SSMC compared with the FSMC, suggesting that there is merit to designing the control law using a simplified interpretation of the system.

From [Figures 5.1](#), [5.16](#) and [5.31](#), it is shown that the NPID controller achieved the best performance, irrespective of the fitness function structure used for evaluation. The velocity responses of the controllers optimised using the balanced, comfort-oriented and sustainability-oriented fitness functions may be found in [Figures 5.2](#), [5.17](#) and [5.32](#). It can be seen that all of the controllers exhibited similar tracking performance when optimised using the balanced fitness function, with the CPID and NPID controllers inducing a noticeably slower (and subsequently more comfortable) actuation of the cabin when comfort and power saving were prioritised. More detail to the balanced velocity response is provided in [Figures 10.1](#) and [10.2](#). The poor performance of the CPID controller is highlighted

in Figure 10.2, with the control system reacting more slowly to external disturbances than all other controllers. Although the NPID controller also struggled to regain control following the transition from acceleration to steady-state travel (refer to Figure 10.1), Figure 10.2 indicates that a high robustness to external disturbances was achieved over time. Following the adjustment of the CPID and NPID controller search spaces for optimisation using the comfort-oriented fitness function, an improvement in the disturbance rejection capabilities was observed in Figures 10.9 and 10.10. Although each of the CPID, NPID, FSMC and SSMC architectures achieved a slightly more gentle passage to steady-state travel, compared with controllers optimised using the balanced fitness function; the improvements were not on par with the CPDF and NPDF controllers – which were able to execute significantly more comfortable travel operations. The zoomed velocity responses of the controllers optimised using the sustainability-oriented fitness function can be found in Figures 10.17 and 10.18. As shown, the reduction in power consumption resulted in poor CPID and NPID controller responses following the transition from acceleration; particularly in comparison with the FSMC and SSMC. The CPDF and NPDF controller responses were almost identical to those returned when comfort was prioritised, indicating that the reduction in acceleration and jerk are added bonuses that accompany the prioritisation of power saving.

The acceleration responses corresponding to the three fitness function structures are provided in Figures 5.3, 5.18 and 5.33, with the jerk responses given in Figures 5.4, 5.19 and 5.34. Notably, the oscillations that were observed in the acceleration and jerk plots of the CPDF controller for Elevator A did not reoccur. This is likely due to the increased cabin-side lifting cable damping recorded towards the end of travel (refer to Figures 5.14, 5.29 and 5.44), in addition to the inclusion of compensation ropes. There is also a possibility that solutions where such oscillations transpired were rejected, as a result of the updated requirement that occupants may not experience a jerk in excess of 0.17 m/s^3 starting 5 seconds after the scheduled arrival. The improved ride comfort achieved by the CPDF and NPDF controllers is most visible in Figure 5.19, peaking at far lower jerk values than the CPID, NPID, FSMC and SSMC-controlled cabins. The displacement profiles are provided in Figures 5.5, 5.20 and 5.35, with more detail relating to the arrival of the cabins given in Figures 5.6, 5.21 and 5.36. Referring firstly to the responses of the controllers optimised using the balanced fitness function in Figure 5.6, it is shown that the ill-suited CPID and NPID controller gain search spaces manifested in an unstable arrivals. The CPDF, NPDF, FSMC and SSMC architectures settled to almost identical final positions, with both SMC variants doing so with negligible overshoot. Although the CPDF controller arrived fractionally earlier than the NPDF controller; the increased overshoot, coupled with a generally less comfortable ride, ensured that the NPDF controller produced the fittest solution. From Figure 5.21, it can be seen that the more gentle responses initiated by the comfort-prioritising CPDF and NPDF controllers resulted in arrival times that were approximately 3 – 3.5 seconds later than the other control architectures. This is an unavoidable consequence of the prioritisation of ride comfort, however, both the CPDF and NPDF-controlled cabins were still able to arrive within the required time of 115 seconds. A significant result observed in the displacement responses of the controllers

that were designed to prioritise power consumption (Figure 5.36) was the earlier arrival of the NPID controller, compared with the CPID controller. Although the power consumption of both systems in actuating a 3200 kg cabin to travel upwards for 1000 m (illustrated in Figure 5.40) was calculated to be 1.35 kWh, the NPID controller ensured an arrival time over 1 second earlier than the CPID-controlled elevator car. This implies that the NPID controller was more efficient, obtaining better performance despite the motor consuming the same amount of power. This was less significant when comparing the NPID and CPID controllers, with both systems consuming 1.47 kWh and arriving almost concurrently. Both SMC-controlled elevators consumed 1.46 kWh, marginally better than the PID-controlled systems.

In terms of the sensitivity of the controllers to parameter variations detailed in Sections 5.2.4, 5.3.4 and 5.4.4; the tables indicate that both the CPID and NPID controllers were able to achieve at least acceptable performance regardless of cabin mass, travel distance, travel direction or fitness function orientation. The robustness of the CPID and NPID controllers was superior to that of both SMC variants, with the FSMC and SSMC being unable to meet the jerk constraint during control of the up-moving 2400 kg cabin in each of the three cases. This is a noteworthy finding, as literature on the subject states that the SMC architecture is highly robust to external disturbances and parameter changes [95]. Both the CPID and NPID controllers produced similar responses to the SMCs, albeit exceeding the jerk constraint by a greater value. The failure of the control systems was due to the cabin mass being identical to the counterweight mass of 2400 kg. As a result of balanced masses on either side of the lifting pulley, minor actuations of the system induced drastic movements that caused the jerk constraint to be exceeded during the transitions from different states of motion. From these results, it can be concluded that the hypothesis that optimising the controllers using the four extreme cabin mass-travel direction cases will return a global solution is true only for the CPID and NPID controllers. For the CPID, NPID, FSMC and SSMC architectures, the optimisation procedure must include a 2400 kg cabin travelling upwards for a distance of 1000 m.

The robustness results of the controllers optimised using the balanced fitness function illustrates a further improvement of the NPID controller over the CPID controller. In Table 5.5, it can be seen that the poorly chosen CPID controller search space parameters resulted in six poor performances and seven unacceptable performances. By comparison, the NPID controller, optimised using the same K_P , K_I and K_D search spaces, induced an unacceptable performance in only three simulations (refer to Table 5.7). Considering this result, in addition to the numerous enhancements in control performance achieved by the NPID and NPID controllers during control of Elevators A and B; it can be said that the nonlinear PID and PDF variants will almost always outperform their traditional equivalents, assuming that the controllers are properly tuned. Should there be a highly-specific scenario where conventional control is the best option, a suitable optimisation procedure would ensure that the nonlinear α terms converge to values of 1, thereby causing the NPID and NPID controllers to behave

as their traditional counterparts. Considering the increased computational power and design complexities that would be introduced, each industrial system requiring control should be independently examined using a cost-benefit analysis to determine whether or not upgrading to NPID/NPDF control would be worthwhile.

With regards to the three fitness function structures used for optimisation of the controllers for Elevator B, there is a unique benefit associated with the sustainability-oriented function. As opposed to factors such as setpoint tracking and ride comfort, which are relevant to passengers only during the specific journey that they are taking; the reduction in power consumption is cumulative. For the hypothetical case of an elevator making 80 round trips to the top floor per day, everyday during a calendar year; a NPDF-controlled elevator (tuned to prioritise power saving) would consume approximately 77.48 MWh. For the case of a NPDF controller tuned using the balanced fitness function, the annual power consumption of the system would be approximately 82.00 MWh. This would translate to a yearly saving of roughly 4520 kWh simply by adjusting the fitness function used for optimisation, a value higher than the electricity consumption of the average British home (in 2018) over the same period of time [96]. Further sustainability improvements could be achieved by replacing counter-current braking with a regenerative braking system, whereby the motor acts as a generator during the descent of a cabin having a mass greater than the counterweight and the ascent of a cabin having a lower mass than the counterweight. Such systems already exist in modern elevators, with energy savings of up to 30% being reported [97].

7.3 Control of Elevator C

The GA parameters for optimisation of the controllers for Elevator C are detailed in Table 6.1, with minor adaptations to the search spaces given in Table 5.12 being implemented. As opposed to previous chapters, different search spaces were applied for the NPDF and NPID controller δ terms, with upper bounds for the NPDF controller being increased to 10. The reasoning behind this change is the fact that the nonlinear functions of the NPID controller adapt the error signal (U_e), integral of the error signal ($\int U_e dt$) and error signal rate ($\dot{U}_e$); which are all likely to be of relatively low value due to the use of the exact setpoint signal. The nonlinear functions of the NPDF controller, on the other hand, act on the sensor signal (U_s), sensor signal rate ($\dot{U}_s$) and integral of the error signal ($\int U_e dt$) calculated using the simple velocity setpoint; all of which are likely to have higher values. An additional difference to previous chapters is the introduction of highly-fit initial guesses inserted into the original populations. Comparing the standard deviations of the solution fitnesses during control of Elevator C in Table 6.3 with those recorded during control of Elevator B, it can be seen that only minor improvements were recorded. This implies that the GA-code, as designed in Section 3.4.2, is able to effectively converge to the global maxima whether or not an initial guess is provided.

The main consequence of the reduction in the override height of Elevator C to 2 m was the resulting effect on the cable dynamics during travel to and from the top floor, as illustrated in Figures 6.39 – 6.42. Noting an initial cabin-side cable length of 1002 m and a final cabin-side cable length of 2 m, the increase in the cabin-side cable stiffness of Elevator C can be calculated using Equation 2.2 to be 50000% for an elevator travelling from the bottom to the top floor. By comparison, Elevator B experienced a 10000% increase during the same operation. As expected, this increase introduced a serious control challenge to be overcome, evidenced by the average run time per ten individuals of the NPID and NPDF controllers in Table 6.3. The notable drop in the run times, compared with those recorded during control of Elevator B, suggests that a significantly higher number of simulations experienced premature termination. Although the alterations to the search spaces could have influenced the efficacy of the controllers, it is unlikely that such a drastic reduction could be solely caused by such minor adjustments. This was confirmed by briefly increasing the override height to 10 m, which greatly improved the controllability of Elevator C using NPID and NPDF control. In contrast to the NPID and NPDF controllers, the FSMC and SSMC architectures returned similar run times as recorded in the previous chapter, with the controllers being seemingly undeterred by the reduction in override height. The aforementioned robustness of the SMC architecture ensured that the majority of solutions within each population were successful, despite the more severe changes in the nonlinear cable dynamics.

The initial RBFNN parameters (n_n , w_0 , c_1 , b and γ) of the RBFNN-SMC were determined through a brief GA-optimisation procedure, with the SMC parameters (ρ , K_R , λ_0 , λ_1 and λ_2) being inherited from the SSMC. As detailed in Table 6.3, excessive run times to simulate ten individuals were recorded, without any noticeable improvements to the fitness of the initial guess being observed. This can be seen in the evolution of the fitness function for each of the controllers, which is illustrated in Figure 6.1. As shown, the NPID controller attained the highest fitness function, closely followed by each of the three SMC variants. The NPDF controller returned the lowest fitness value, due to a combination of the relatively high velocity overshoot (refer to Figure 10.25) and the later arrival (refer to Figure 6.25). It should be noted, however, that the NPDF-controlled Elevator C cabin arrived less than half a second after its NPID-controlled equivalent; with the high stability of the arrival actually hindering the recorded fitness. As is visible in the displacement response plot, the gradual drop of the NPID-controlled cabin across the arrival floor resulted in a high arrival accuracy being recorded. The FSMC, which obtained the second highest solution fitness, benefited from a similar instability. It can be concluded that an additional term should be added to the cost function for a more accurate evaluation in future, whereby the controllers are greatly rewarded for minimising velocity once the cabin has arrived.

An additional observation from the velocity and displacement results is the essentially identical responses of the SSMC and RBFNN-SMC, with the SSMC plot being almost completely hidden behind that of the RBFNN-SMC. Although similar performance was to be expected, given that the RBFNN-SMC inherited the SMC parameters directly from the SSMC; the fact that the responses are virtually

indistinguishable whether $f(x)$ was approximated or explicitly defined is a significant result. It suggests that for a real-world system, where the system dynamics and uncertainties would likely be nearly impossible to model with complete accuracy, RBFNN approximation could allow effective control of the system to be achieved without the need to develop a complex control law. Differences between the SSMC and RBFNN-SMC are most clearly visible in the acceleration and jerk responses, particularly in the zoomed Figures 10.28 and 10.31. As shown, oscillations in the RBFNN-SMC responses were observed following sharp changes in the feedback signals caused by sensor noise. Similar fluctuations following a change in the system states is reported in literature, with control being regained after a short period of time [42]. Although such reactions reduced the experienced ride comfort, the resulting vibrations remained well within the maximum allowable acceleration and jerk constraints. The approximation of the system dynamics is illustrated in Figure 6.33, which includes a magnification of the response to a noise-induced spike occurring at 18 seconds. As shown, a marginal reduction in the approximation accuracy was observed as $f(x)$ began to fluctuate, with $\hat{f}(x)$ peaking at noticeably higher values. Control was regained within 0.2 seconds, as the connection weights of the hidden layer neurons were adapted in real-time to account for the disturbance, as shown in Figure 6.34.

The transformations of the respective signals within the nonlinear functions of the NPID and NPDF controllers are illustrated in Figures 6.26 – 6.30. The existence of two terms defining each of the three nonlinear functions greatly increases the flexibility of the control architectures, at the expense of a more complex design process. The magnitudes of the six terms can each have a significant effect on the control performance, with different combinations of α and δ terms having notable effects on the final response. The reason that all of the optimal NPDF controller α terms throughout this dissertation converged to values between 0.7 and 1.3 (which was not the case for NPID control) can be explained by understanding the effects of the parameters, coupled with the sizes of the signals that were adapted. As shown in the responses, each of the NPDF controller signals were of significantly higher values than the three signals adapted by the NPID controller. α terms lower than 0.7 would result in a NPDF control response too weak for larger signals, with the opposite effect occurring for α terms in excess of 1.3. As the nonlinear function of the NPID controller acts on U_e , $\int U_e dt$ and $\dot{U}_e$ calculated using the exact setpoint, parameters that all remained well below values of 1, similar issues did not occur. This allowed for the NPID controller to converge to α terms of $\alpha_P = 0.0810$, $\alpha_I = 1.7802$ and $\alpha_D = 1.5334$. The influence of the nonlinear functions on control performance is made clear when analysing the evolution of the NPDF controller fitness function and control parameters in Figures 6.1 – 6.10. As shown, the improved control performance was achieved solely by the modification of the δ_P and δ_I terms, with the seven other parameters remaining unchanged from the initial guesses. The evolution of δ_P from 3.05 to 3.55 resulted in a marginal decrease in proportional action for lower feedback sensor signals, while δ_I being lowered from 4.51 to 2.51 led to a more noticeable increase in integral action for smaller values of $\int U_e dt$.

In terms of the robustness to parameter variations, Tables 6.5 – 6.9 indicate that all control systems achieved at least acceptable performance for each of the cabin masses, travel distances and travel directions considered. This improvement over the robustness results returned during control of Elevator B is likely due to a combination of the performance-oriented fitness function prioritising setpoint tracking, as well as the implementation of a more powerful motor. This further exemplifies the importance of motor selection in the control process, with the upgraded motor also being required to enable effective RBFNN-SMC control of the system, something that was not possible with the actuator used to drive Elevator B. The high robustness achieved by each of the controllers is clearly illustrated in the respective velocity, acceleration, jerk and displacement responses. Figures 6.49, 6.62, 6.75, 6.88 and 6.101 highlight the power consumption for actuation of each of the cabin masses. As would be expected, actuation of the 4000 kg cabin consumed the most power, whereas the 2400 kg cabin (not the 1600 kg cabin) consumed the least, due to being perfectly in-balance with the counterweight. The displacement responses of each of the 3200 kg cabins travelling to and from different floors are given in Figures 6.51, 6.64, 6.77, 6.90 and 6.103. As indicated in the robustness analysis tables, the 600 m travel operations (displayed by the solid grey plots) experienced the most severe displacement overshoots/undershoots - the lowest being 0.24 m for the NPID controller, with the highest being 0.27 m recorded during NPID control. Figures 6.52, 6.65, 6.78, 6.91 and 6.104 highlight the substantial increase in cabin-side cable stiffness caused by travelling to the top floor, in comparison to the other travel operations. Despite the 800 m travel operation arriving at a floor 900 m above ground (having started 100 m above ground), the corresponding cable stiffness response was dwarfed by that of the elevator arriving a mere 100 m higher. Although similar behaviour is observed in the damping coefficient, as shown in Figures 6.54, 6.67, 6.80, 6.93 and 6.106, the increase is not directly proportional. As such, the controllability of the system was greatly reduced, leaving open the possibility of oscillations being induced due to relatively low cable damping (as was observed during CPID control of Elevator A) should the override height be shortened any further.

Although each of the controllers successfully attained acceptable performance, arriving within 0.3 m of the target floors in every scenario, passengers would not be able to safely transfer into and out of the cabin with such a gap being present. An adaptive re-levelling operation was applied to each control system in an attempt to reduce the separation to no more than 3 mm. The displacement responses before and after application of the operation to the 3200 kg cabins that travelled to the top floor are illustrated in Figure 6.108, indicating that improved arrival accuracy was achieved for each of the control systems. More detail relating to the re-levelling responses is given in Figure 6.109, highlighting that all of the controllers were able to re-level to the required accuracy within 7 seconds of the scheduled arrival. Although the FSMC ensured the quickest time to door-open, the NPID controller greatly outperformed the competition in terms of precision, doing so with a door-open time of less than a second later. The adaptations to the various velocity setpoint signals to achieve re-levelling are shown in Figure 6.110, while the acceleration and jerk setpoints required for SMC re-levelling are provided in Figures 6.112 and 6.114, respectively. As seen in Figure 6.116, re-levelling was achieved

without exceeding the end jerk constraint of 0.17 m/s^3 , irrespective of the control architecture used. The re-levelling procedure was also applied to the responses that arrived furthest away from the target destination – the 3200 kg cabins travelling upwards for a distance of 600 m. From [Figure 6.108](#), it can be seen that the re-levelling process significantly reduced the distance between the cabin positions and the target floor. [Figure 6.122](#) illustrates that the NPID, FSMC, SSMC and RBFNN-SMC all met the time to door-open requirements, with the NPID controller enabling the quickest and most accurate re-levelling procedure. The NPID controller was unable to re-level the cabin within 77 seconds, in addition to the fact that the simulation was stopped before it could be confirmed that the cabin would remain within 3 mm of the arrival floor. It should be noted that the y-axis indicating a displacement of 800 m is not erroneous, with the axis displaying the height above ground. The cabins travelled a distance of 600 m, starting 200 m above ground and arriving 800 m above ground (refer to [Figures 6.51, 6.64, 6.77, 6.90 and 6.103](#)). From [Figure 6.129](#), it can be seen that the NPID controller also failed to limit the experienced end jerk to 0.17 m/s^3 , with high-frequency oscillations being induced for a short period of time. Although such a response is not necessarily a safety issue, the chattering observed in [Figure 6.133](#) could potentially damage the actuator.

Considering the overall re-levelling performance of the controllers, it can be said that the NPID controller was clearly the most effective architecture. While noticeable oscillations could be observed in the displacement responses of the NPID, FSMC, SSMC and RBFNN-SMC architectures; the NPID controller was able to adjust the position of the cabins to well within 1 mm of the arrival floor in both scenarios. In addition to the effectiveness of the control system, the implementation of adaptive re-levelling was significantly easier to achieve in comparison with the remaining control schemes. As NPID control was enabled using the simple velocity setpoint, re-levelling was performed without the need for any alterations to the adaptive re-levelling equation given in [Equation 2.143](#). Given the fact that the exact velocity setpoint was used for NPID control, with the signal being derived from the acceleration setpoint, the re-levelling equation had to be converted by applying a filtered derivative to ensure that the jerk constraints were not exceeded. The same is true for the three SMC architectures, with the additional need to adapt the setpoints for the higher derivatives. Beyond these considerations for the NPID, FSMC, SSMC and RBFNN-SMC architectures, additional restrictions were required in order to meet the comfort and safety constraints. Rather than initiating at the moment of arrival, re-levelling using the three SMC architectures had to be delayed until the cabin decelerated to a velocity of 0.1 m/s ; while the threshold for NPID controller re-levelling was set at 0.02 m/s .

Bearing in mind the effective attenuation of any vibrations during NPID control of Elevator A; the superior performance recorded in control of Elevator B for each of the three fitness function structures; the fact that the system remained relatively competitive during control of Elevator C, before subsequently exhibiting the best re-levelling capabilities; and the generally high robustness recorded throughout this dissertation – the NPID controller can be said to have outmatched its competition in terms of elevator control. A significant reason for the success of the architecture is the "Principle of

One Master," whereby only the integral mode is implemented in the forward path (refer to Section 3.2.2). The subsequent absence of numerator dynamics (coupled with the aid of the nonlinear functions) ensured that the control system was well adept at rejecting external disturbances, as well as ensuring highly stable and accurate cabin arrivals. The superiority of the architecture in comparison with NPID control in particular is a significant result, given the popularity of the PID system in industry [32], which includes its use in modern elevator VVVF drives [11] [12] [13] [14]. Given the similarity of the architectures, the results suggest that there would be merit in investigating the effects of replacing PI control with PDF control in real-world elevator applications.

Generally speaking, the NPID, FSMC and SSMC systems exhibited comparable performance throughout; converging to similar fitness values regardless of whether a performance-oriented, comfort-oriented, sustainability-oriented or balanced fitness function was used for optimisation. The three controllers displayed a notable lack of flexibility in comparison with the NPID controller, struggling to effectively prioritise comfort and energy efficiency. The SMC architecture, widely noted for being highly robust, was outperformed by the NPID controller in accounting for parameter changes; with the system being unable to limit the jerk (albeit marginally) when the mass of the Elevator B cabin was equal to that of the counterweight. An additional drawback to SMC is the realisability of the system in its current state, as it requires jerk to be measured and fed-back to the controller. While displacement, velocity and acceleration can all be recorded directly; no commercially available device exists to precisely measure jerk. In general, jerk is calculated using the parameters that can be measured, such as displacement [98] or acceleration [99]. As such, the NPID and NPID controller architectures can be said to be markedly simpler in structure, each requiring only a single velocity feedback signal. An added difficulty in achieving effective SMC control of a system is the requirement that the model dynamics be explicitly defined within the control law. Although results in this dissertation have suggested that utilising a simplified version of $f(x)$ can achieve effective control (with the major bonus of reduced computational expense), the fact remains that uncertainties are likely to exist and would not be accounted for in a mathematical model. This issue can be avoided through the implementation of RBFNN-SMC, with equivalent control being recorded despite $f(x)$ simply being approximated.

An additional benefit associated with utilising RBFNN approximation in SMC is the subsequent reduction in chattering, as is reported in literature on the subject [42] [100]. In order to fully evaluate the chattering behaviour of the FSMC, SSMC and RBFNN-SMC systems developed in this dissertation; the controllers must be identical in structure. Six SMC architectures were developed – an FSMC (saturation function), FSMC (sign function), SSMC (saturation function), SSMC (sign function), RBFNN-SMC (saturation function) and RBFNN-SMC (sign function). The parameters K_R , λ_0 , λ_1 and λ_2 of all six controllers were taken from the GA-optimised SSMC defined in Table 6.4, while the RBFNN parameters of the two RBFNN-SMC systems were inherited from the GA-optimised RBFNN-SMC. The saturation function parameter ($\rho = 0.4539$) was applied to the three systems using a saturation function, with the three remaining architectures achieving control using a sign function.

A summary of the control parameters is given in [Table 6.10](#). As shown in the subsequent velocity, acceleration, jerk and displacement responses; each of the control systems ensured effectively indistinguishable performance. From the enlarged torque responses given in [Figures 6.142, 6.143 and 6.144](#), it can be seen that both RBFNN-SMC architectures initiated similar torque responses, despite the differences between the sign and saturation functions. Referring to the controllers utilising a sign function, a complete reduction in chattering was seen in the RBFNN-SMC response during the majority of the travel procedure, compared with the FSMC and SSMC architectures. However, following sharp changes in the feedback signals incited by sensor noise, considerable fluctuations in motor torque were observed for a short period of time (as illustrated in [Figure 6.143](#)). These oscillations could potentially damage the motor, suggesting that significant filtering of sensor noise is required for RBFNN-SMC control of such a system to be feasible in practice. Therefore, future work relating to RBFNN-SMC should couple the system with a noise attenuating filter such as a Kalman filter, which has been shown to have highly efficient noise-reducing capabilities [\[101\]](#) [\[102\]](#). If sensor noise-incited chattering could be eliminated, it is possible that highly effective elevator control could be achieved with an RBFNN-SMC that employs a sign function. An initial analysis of Elevator B (to determine GA-code search space sizes) indicated that an FSMC and SSMC utilising a sign function greatly outperformed the PID and PDF control architectures, at the expense of unacceptable chattering being induced. While it may be possible to tune an SSMC separately before briefly optimising the RBFNN parameters, as was successfully accomplished in this dissertation, an improved response would likely be obtained by optimising all of the RBFNN and SMC parameters simultaneously. Due to the excessive run times recorded during GA-tuning of the initial RBFNN-SMC parameters without any major improvements to the fittest solution to show for it, a different optimisation method would likely be required. Alternative global optimisation techniques that have been suggested for selection of RBFNN-SMC parameters include differential evolution (DE) and particle swarm optimisation (PSO) [\[103\]](#). Additionally, RBFNN-SMC design utilising the minimum parameter learning (MPL) method could be implemented to reduce run time by decreasing the number of adaptive parameters, thereby easing the computational load [\[42\]](#).

8 Conclusions and Recommendations for Future Work

8.1 Conclusions

- The NPDF controller consistently exhibited the best performance throughout this dissertation, achieving the highest solution fitnesses during control of Elevators A and B. Although initially determined to be less effective during control of Elevator C, with performance being the prioritised aspect of control, the NPDF controller outperformed the competition once re-levelling was applied – swiftly adjusting the position of the cabin to within 1 mm of the arrival floor. This was achieved through a combination of the nonlinear functions and the "Principle of One Master," with the control architecture having only the integral mode in the forward path and, therefore, not being susceptible to numerator dynamics.
- Due to its structure, the NPDF control system demonstrated a particularly low sensitivity to parameter variations, superior even to the SMC architecture. The NPDF controller was the only control system to achieve at least acceptable performance for each of the cabin masses, travel distances and travel directions considered in this research. The noise and disturbance rejection capabilities of the architecture, which allowed for highly stable arrivals, suggests that the control system would be ideal for an elevator application.
- In addition to the high robustness in performance, the NPDF controller displayed notable flexibility in design. While the PID and SMC architectures struggled to give precedence to anything other than setpoint tracking, the PDF controllers were able to effectively prioritise aspects such as ride comfort and energy efficiency.
- Although similar results were recorded in many cases, the NPDF controller outperformed the CPDF controller in two notable situations. During CPDF control of Elevator A, significant oscillations were observed in the acceleration and jerk responses. These fluctuations, caused by a combination of the high cable stiffness, relatively low cable damping and absence of compensation ropes, were intensified following a 20% reduction in cabin mass. Similar responses were

not observed in the NPDF-controlled cabins, with the vibrations being completely attenuated for all three cabin masses. The second case was observed following optimisation of the controllers using the sustainability-oriented fitness function. Although both PDF-controlled elevators consumed 1.35 kWh during lifting of a 3200 kg cabin from the ground to the top floor, the NPDF-controlled cabin arrived over a second earlier. This indicates that the NPDF controller is considerably more efficient than its traditional equivalent.

- The NPID controller also exhibited improved performance over its conventional counterpart. During control of Elevator A, it was observed that the NPID controller was able to meet the displacement constraints for the overloaded and underloaded cabins, a feat that the CPID controller was unable to achieve. The introduction of a negative nonlinear α_I term played a key role in the improvement by helping to avoid integral windup, allowing for a higher K_I gain to be set. During control of Elevator B, similar improvements in robustness were observed. As a consequence of the search spaces of the CPID and NPID controller gains (K_P , K_I and K_D) being poorly chosen initially, the CPID controller recorded six poor performances and seven unacceptable performances during the robustness analysis. The NPID control results indicated no poor performances and only three unacceptable performances were recorded, an improvement achieved without any adjustments being made to the search space bounds. These results, coupled with those observed when comparing the CPDF and NPDF controllers, indicate that implementation of the nonlinear functions effectively expanded the range of operation of the PID and PDF architectures for control of a nonlinear system.
- The regularity of improved control performance obtained by the PDF architectures over both variants of PID control is a particularly noteworthy finding. Given the prevalence of PID control in industry (including its use in modern elevator drives) and considering the minor differences in structure between PDF and PID controllers; the results suggest that replacing existing PI or PID systems with equivalent PDF controllers could prove beneficial in certain cases.
- The FSMC and SSMC architectures were implemented for control of Elevators B and C, achieving effective control for the most part, with the exception of Elevator B cabins having a mass of 2400 kg. As was the case with the CPID and NPID controllers, both SMC variants were unable to limit the experienced jerk when the cabin and counterweight were in perfect balance; an issue not experienced by either PDF controller. While this result is at odds with the low sensitivity to parameter variations reported in literature, the robustness of the SMC architecture was evident during control of Elevator C. Following the reduction in override height to 2 m, the change in cable stiffness during travel to/from the top floor increased dramatically. While the NPID and NPDF controllers struggled to find solutions to account for the drastic nonlinearities, the majority of FSMC and SSMC individuals generated during GA-optimisation were suitable solutions. Both SMC architectures ensured acceptable re-levelling of the Elevator C cabin, surpassing the re-levelling capabilities of the NPID controller, which was unable to meet all of the

requirements and constraints during adjustment of the final position of the 3200 kg cabin that had travelled upwards for 600 m.

- In terms of comparing the FSMC and SSMC, substantial run time improvements were observed when utilising a simplified mathematical model of the system within the control law. The reductions in run time were not accomplished at the expense of performance, with virtually indistinguishable responses being observed when identical SMC parameters were applied to both variants. In terms of the practicality of FSMC or SSMC being applied to such a system, the difficulty in measuring experienced jerk and the inability to perfectly model all of the uncertainties and nonlinearities in the control law would severely hinder the performance of the controllers in reality. There would be little reason to apply FSMC or SSMC rather than NPDF control, considering that the latter requires only one feedback signal.
- Following the introduction of RBFNN to the SMC architecture, it was observed that effective control was achieved, despite the fact that the system dynamics were approximated in the control law (as opposed to being explicitly modelled). The performance of the RBFNN-SMC was almost identical to that of the SSMC, with both architectures sharing the same SMC parameters (ρ , K_R , λ_0 , λ_1 and λ_2). The most obvious difference between the SSMC and RBFNN-SMC systems was observed in the responses following sensor noise-induced spikes. Although the RBFNN-SMC was able to rapidly regain control, with the connection weights of the eight hidden layer neurons being adapted online to attenuate the oscillations, problematic chattering was identified in the torque response for short periods of time. While the RBFNN-SMC architecture was seen to greatly reduce chattering for the most part, the brief fluctuations following sharp changes in the sensor noise suggest that the control system is not viable without the aid of noise-reducing filters.
- Regarding GA-optimisation of the controllers, the developed GA-code was able to effectively identify highly-fit solutions for the majority of the control systems. From the standard deviation results recorded for Elevators B and C, only minor improvements in solution convergence were observed following the introduction of initial guesses, indicating that the GA-code is able to converge on the global maxima without the need for prior manual tuning. Run time was maintained at practical levels for most of the optimisation procedures, with careful structuring of the updated process being implemented in order to avoid the issue of excessive run times during controller tuning for Elevators B and C. Unacceptable run times were returned during GA-tuning of the initial RBFNN parameters, without any noticeable improvements to the solution fitness to show for it, suggesting that an alternative method for identification of optimal RBFNN parameters is required.

8.2 Recommendations for Future Work

- In continuing on from the current research and related publications, real-world investigations to compare PDF and PID control should be undertaken.
- The performance of the controllers designed in this dissertation should be compared with other architectures, such as fuzzy logic and adaptive backstepping control.
- Given the flexibility of the NPDF controller, the influence of the nonlinear δ terms and the fact that the nonlinear functions act on relatively large signals; the search space bounds of the δ term should be significantly increased in future investigations to determine the effects on solution fitness.
- Further investigations into the reduction of RBFNN-SMC run time should include an analysis of minimum parameter learning (MPL) and the subsequent trade-offs between control performance and computational burden. Additionally, such research should focus on these issues from a real-world standpoint, such as any potential hardware difficulties that may arise during implementation.
- In future, the effectiveness of the GA-code should be compared with that of other evolutionary algorithms such as ant colony optimisation (ACO), PSO and DE. In particular, the algorithms should be compared on the ability to reduce the computational time of the RBFNN-SMC optimisation procedure without compromising on solution convergence.
- As a result of the ongoing COVID-19 pandemic, the majority of the simulations performed in this dissertation were done so remotely. While this did not affect the accuracy of the results, it is possible that the recorded run times may have been influenced by external factors such as server load. Future work should compare simulation times on a controlled, local machine; particularly in terms of comparing the FSMC and SSMC architectures.
- Further research should be undertaken into the possibility of reducing the power consumption of the elevator systems designed in this investigation, such as the implementation of regenerative braking.

9 References

- [1] J. Vladić, R. Đokić, M. Kljajin and M. Karakasić, "Modelling and simulations of elevator dynamic behaviour," *Tehnicki vjesnik*, vol. 18, no. 3, pp. 423–434, 2011.
- [2] W. E. Dixon, A. Behal, D. M. Dawson and S. P. Nagarkatti, "Nonlinear Control of Engineering Systems: A Lyapunov-Based Approach," Boston: Birkhäuser, 2003.
- [3] J. J. E. Slotine and W. Li, "Applied Nonlinear Control," New Jersey: Prentice-Hall, 1991.
- [4] J. Vladić, P. Malesev, R. Sostakov and N. Brkljac, "Dynamic analysis of the load lifting mechanisms," *Strojniski vestnik*, vol. 54, no. 10, pp. 655–661, 2008.
- [5] J. Vladić, R. Đokić, V. Jovanović and D. Živanić, "Simulations of elevator cabins lifting and dynamic models," *The Fifth International Conference Transport and Logistics*, Bangkok, pp. 69–73, 2014.
- [6] J. Aldred, "Burj Khalifa—A new high for high-performance concrete," *Proceedings of the Institution of Civil Engineers-Civil Engineering*, vol. 163, no. 2, Thomas Telford Ltd, pp. 66–73, 2010.
- [7] N. Hollister and A. Wood, "Tallest 20 in 2020: Era of the Megatall: The Projected World's Tallest 20 Skyscrapers in the Year 2020," *CTBUH Journal*, pp. 44–47, 2012.
- [8] T. Catts, "Otis Elevator Vies for the Ultratall Skyscraper Market" Bloomberg L.P., 2013 [Online]. Available: <https://www.bloomberg.com/news/articles/2013-01-31/otis-elevator-vies-for-the-ultratall-skyscraper-market>. [Accessed 02 December 2020].
- [9] S. Mitric, "Elevator Systems for Tall Buildings Part II: Single-Mode Elevator Systems," *Transportation Science*, vol. 9, no. 1, pp. 74–85, 1975.
- [10] Otis Elevator Company, "Otis4000," Otis Elevator Company, 2014 [Online]. Available: http://www.otisworldwide.com/site/hk-chi/OT_DL_Documents/OT_DL_DownloadCenter/OTIS%204000/OTIS%204000.PDF. [Accessed 27 April 2018].

- [11] R. S. Colby, A. Vecchiotti, N. A. Greiner, L. M. Lamontagne and R. E. Thebeau, "Self commissioning controller for field-oriented elevator motor/drive system". The United States of America Patent 5929400, 07 July 1999.
- [12] R. Prakash, R. K. Singh and R. R. Kumar, "Variable voltage variable frequency speed control of induction motor using FPGA-Xilinx," *International Research Journal of Engineering and Technology*, vol. 2, no. 3, pp. 1268–1273, 2015.
- [13] J. S. Park, B. J. Hyon, J. H. Kim and J. H. Choi, "Implementation of VVVF drive for a three phase induction machine," *International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, Anacapri, IEEE, pp. 535–540, 2016.
- [14] S. Dang, B. Peng, D. Matthews and A. Gholamzadeh, "Modeling and simulation of the VVVF control of the three-phase AC asynchronous electromotor based on Matlab/Simulink," *Information Science, Electronics and Electrical Engineering*, vol. 2, Sapporo, IEEE, pp. 746–749, 2014.
- [15] J. Guo and J. Fan, "Study on automatic diagnostic of elevator brake coil wearing," *Control and Decision Conference*, Changsha, IEEE, pp. 1386–1389, 2014.
- [16] J. Vladić, M. Jovanović, R. Đokić, M. Kljajin and M. Karakasić, "Theoretical and experimental analysis of mine elevator dynamic characteristics," *Tehnicki vjesnik*, vol. 22, no. 4, pp. 1011–1020, 2015.
- [17] Danaher Motion, "Resolution, Disturbance Response and Noise During Constant-Speed Operation," Kollmorgen, 2003.
- [18] Q. Wang, H. Yu, M. Wang and X. Qi, "An Improved Sliding Mode Control Using Disturbance Torque Observer for Permanent Magnet Synchronous Motor," *IEEE Access*, vol. 7, pp. 36691–36701, 2019.
- [19] L. Janovský, "Elevator mechanical design," Mobile: Elevator World Inc., 1999.
- [20] J. A. L. Barreiro, H. Z. Huang and C. Moon, "Determining elevator brake, traction and related performance parameters". The United States of America Patent 6325179, 4 December 2001.
- [21] A. Kattainen, "Brake control apparatus and a method of controlling an elevator brake". The United States of America Patent Application 15/709104, 4 January 2018.
- [22] M. Rakesh and P. V. R. L. Narasimham, "Different braking techniques employed to a brushless DC motor drive used in locomotives," *International Electrical Engineering Journal*, vol. 3, no. 2, pp. 784–790, 2012.
- [23] S. M. Asyraf, P. M. Heerwan, I. M. Zulhilmi and I. M. Izhar, "Plugging Brake System as a Hill Descend Control for Electric Powered Wheelchair: Experimental Analysis," *4th International Conference on Advanced Robotics and Mechatronics*, Osaka, IEEE, pp. 319–324, 2019.

- [24] L. Al-Sharif, "Variable speed drives in lift systems," *Elevator World*, vol. 49, no. 9, pp. 96–106, 2001.
- [25] Dynatech, "OVERSPEED GOVERNOR," Dynatech, 2017 [Online]. Available: http://www.dynatech-elevation.com/documentos/articulos/Reducido_VEGA-ING.PDF. [Accessed 2 May 2018].
- [26] H. Matsuoka, Y. Higashida, N. Ohnuma, T. Abe, T. Nakayama, Y. Kawamura, Y. Z. Guan, K. Nakamura, C. S. Xin, X. Y. Xin and A. Arakawa, "Development of ultra-high-speed elevator that achieved the world's fastest elevator with a speed of 1,200 m/min," 2017 [Online]. Available: http://www.hitachi.com/rev/archive/2017/r2017_03/06/index.html. [Accessed 3 May 2018].
- [27] thyssenkrupp Elevator AG, "MULTI," thyssenkrupp Elevator AG, 2017 [Online]. Available: <https://multi.thyssenkrupp-elevator.com/en/>. [Accessed 2 July 2018].
- [28] KONE Corporation, "Discover the revolutionary KONE UltraRope," KONE Corporation, 2013 [Online]. Available: <http://download.kone.com/ultrarope/index.htm>. [Accessed 27 April 2018].
- [29] L. I. H. Llins, E. Assunção, M. Teixeira, R. Cardim, M. R. R. Cadalso, D. R. de Oliveira and E. R. P. da Silva, "Design of gain scheduling control using state derivative feedback," *Mathematical Problems in Engineering*, pp. pp. 1–11, 2017.
- [30] D. Rotondo, "Advances in gain-scheduling and fault tolerant control techniques," Cham: Springer, 2017.
- [31] J. Qiao, Z. Liu and Y. Zhang, "Gain scheduling PID control of the quad-rotor helicopter," *IEEE International Conference on Unmanned Systems*, Beijing, IEEE, pp. 1594–1601, 2017.
- [32] M. Mangera, D. S. Parshotam and I-L. R. Hill, A. Panday, J. O. Pedro, "Velocity tracking of a high-rise building elevator using PDF control," *11th Asian Control Conference*, Gold Coast, IEEE, pp. 2310–2315, 2017.
- [33] I-L. R. Hill, M. Mangera, D. S. Parshotam, A. Panday and J. O. Pedro, "Genetic algorithm based design of PID and PDF controllers for velocity tracking of a high-rise building elevator," *SICE International Symposium on Control Systems*, Tokyo, IEEE, pp. 136–143, 2018.
- [34] M. Y. Santoso, S. F. Su and A. S. Aisjah, "Nonlinear rudder roll stabilization using Fuzzy Gain Scheduling-PID controller for naval vessel," *International Conference on Fuzzy Theory and Its Applications*, Taipei, IEEE, pp. 94–99, 2013.
- [35] P. Shao, Z. Zhou, S. Ma and L. Bin, "Structural robust gain-scheduled PID control and application on a morphing wing UAV," *Chinese Control Conference*, Dalian, IEEE, pp. 3236–3241, 2017.
- [36] J. S. Shamma and M. Athans, "Gain scheduling: Potential hazards and possible remedies," *IEEE Control Systems*, vol. 12, no. 3, pp. pp. 101–107, 1992.

- [37] F. Jiang and Z. Gao, "An application of nonlinear PID control to a class of truck ABS problems," *Conference on Decision and Control*, Orlando, IEEE, pp. 516–521, 2001.
- [38] G. Zaidner, S. Korotkin, E. Shteimberg, A. Ellenbogen, M. Arad and Y. Cohen, "Non Linear PID and its application in Process Control," *Convention of Electrical and Electronics Engineers in Israel*, Eilat, IEEE, pp. 574–577, 2010.
- [39] S. Rudra, R. K. Barai and M. Maitra, "Block backstepping design of nonlinear state feedback control law for underactuated mechanical systems," Singapore: Springer, 2017.
- [40] M. Hamouda, K. Al-Haddad, F. Fnaiech and H. Blanchette, "Input-state feedback linearization control of two-stage matrix converters interfaced with high-speed microturbine generators," *Canada Electrical Power Conference*, Montreal, IEEE, pp. 302–307, 2007.
- [41] H. Li, X. Pan and C. Guo, "SMC for rudder/fin joint roll stabilization based on input-output feedback linearization," *Chinese Control Conference*, Dalian, IEEE, pp. 850–855, 2017.
- [42] J. Liu, "Sliding Mode Control Using MATLAB," Beijing: Academic Press, 2017.
- [43] F. R. Garces, V. M. Becerra, C. Kambhampati and K. Warwick, "Strategies for feedback linearisation: A dynamic neural network approach," London: Springer Science & Business Media, 2012.
- [44] S. Siegmund, C. Nowak and J. Diblík, "A generalized Picard-Lindelöf theorem," *Electronic Journal of Qualitative Theory of Differential Equations*, vol. 2016, no. 28, University of Szeged, p. 1–8, 2016.
- [45] H. B. Hassrizal, J. A. Rossiter, and A. R. Firdaus, "Feasibility Study of Sign Function Approaches in Sliding Mode Control for a Spacecraft's Attitude Control System," *2018 5th International Conference on Control, Decision and Information Technologies*, Thessaloniki, IEEE, pp. 289–294, 2018.
- [46] J. Taghia and J. Katupitiya, "Applied Guidance Methodologies for Off-road Vehicles, Cham: Springer," 2020.
- [47] H. Alipour, M. B. B. Sharifian and H. Afsharirad, "A PID sliding mode control for ropeless elevator maglev guiding system," *Energy and Power Engineering*, vol. 4, no. 3, pp. 158–164, 2012.
- [48] A. Eltayeb, M. Rahmat and M. Musa, "Feedback linearization and sliding mode control design for quadrotor's attitude and altitude," *International Conference on Mechatronics, Automation and Cyber-Physical Computer System Feedback*, Owerri, IEEE, pp. 7–8, 2019.
- [49] I. D. Landau, R. Lozano, M. M'Saad and A. Karimi, "Adaptive control: algorithms, analysis and applications," London: Springer Science & Business Media, 2011.

- [50] E. Pop, M. Leba and I. Rascolean, "Maximum productivity adaptive control of a mining elevator," *International Conference on Automatic Control, Modelling and Simulation*, Istanbul, WSEAS, pp. 122–127, 2009.
- [51] J. Zhou and C. Wen, "Adaptive backstepping control of uncertain systems: Nonsmooth nonlinearities, interactions or time-variations," Berlin: Springer, 2008.
- [52] B. Patel, Y. J. Pan and U. Ahmad, "Adaptive backstepping control approach for the trajectory tracking of mobile manipulators," *International Conference on Robotics and Biomimetics*, Macau, IEEE, pp. 1769–1774, 2017.
- [53] C. Eddahmani, H. Mahmoudi, M. El Azzaoui and K. Boudaraia, "Backstepping and adaptive control for variable wind speed turbine based on PM synchronous generator," *International Multi-Conference on Systems, Signals & Devices*, Marrakech, IEEE, pp. 785–789, 2017.
- [54] J. A. K. Suykens, J. P. L. Vandewalle and B. L. de Moor, "Artificial neural networks for modeling and control of non-linear systems," Dordrecht: Springer Science & Business Media, 2012.
- [55] A. Alexandridis, M. Stogiannos, A. Loukidis, K. Ninos, E. Zervas and H. Sarimveis, "Direct versus indirect neural control based on radial basis function networks," *Computer Science and Electronic Engineering Conference*, Colchester, IEEE, pp. 91–96, 2014.
- [56] H. Yu, X. Zhang and Q. Hu, "Application of NN-PID Control in Linear Elevator," *International Conference on Natural Computation*, Tianjin, IEEE, pp. 35–37, 2009.
- [57] L. Behera and I. Kar, "Intelligent systems and control principles and applications," New Dehli: Oxford University Press, 2009.
- [58] Q. Zhao, J. Yin and D. Li, "Intelligent Compound Control of Vehicle Active Suspension Based on RBF Neural Network," *Third International Conference on Measuring Technology and Mechatronics Automation*, vol. 2, IEEE, pp. 441–444, 2013.
- [59] Z. Qing, M. Zhu and Z. Wu, "Adaptive neural network control for a quadrotor landing on a moving vehicle," *Chinese Control And Decision Conference*, Shenyang, IEEE, pp. 28–33, 2018.
- [60] Z. Wang, Z. Shen, C. Cai and K. Jia, "Adaptive control of wind turbine generator system based on RBF-PID neural network," *International Joint Conference on Neural Networks*, Beijing, IEEE, pp. 538–543, 2014.
- [61] Z. Haiyang, S. U. N. Yu, L. I. U. Deyuan and L. I. U. Hao, "Adaptive neural network PID controller design for temperature control in vacuum thermal tests," *Chinese Control and Decision Conference*, Yinchuan, IEEE, pp. 458–463, 2016.
- [62] Y. Chen, B. Cai and G. Cui, "The Design of Adaptive Sliding Mode Controller Based on RB-FNN Approximation for Suspension Control of MVAWT," *2020 Chinese Automation Congress*, Shanghai, IEEE, pp. 1080–1084, 2020.

- [63] Toshiba Elevator and Building Systems Corporation, "Machine-Room-Less Elevators" Toshiba Elevator and Building Systems Corporation, [Online]. Available: https://www.toshiba-elevator.co.jp/elv/infoeng/elevator_basics/machine/index.html. [Accessed 09 December 2020].
- [64] H-M. Ryu, S-J. Kim, S-K. Sui, T-S. Kwon, K-S. Kim, Y-S. Shim and K-R. Seouk, "Dynamic Load Simulator for High-speed Elevator System," *Power Conversion Conference*, Osaka, IEEE, pp. 885–889, 2002.
- [65] WATelectrical.com, "How a Cable Driven or Traction Elevator Works?" WATelectrical.com, 2019 [Online]. Available: <https://www.watelectrical.com/how-does-elevator-works-circuit-diagram-types/>. [Accessed 20 July 2019].
- [66] S. Watanabe, T. Okawa, D. Nakazawa and D. Fukui, "Vertical vibration analysis for elevator compensating sheave," *Journal of Physics: Conference Series*, vol. 1048, no. 1, p. 012012, 2018.
- [67] W. Grondzik, A. Kwok and B. Stein, "Mechanical and Electrical Equipment for Buildings," Hoboken: John Wiley & Sons, 2010.
- [68] H. Rahmani, S. H. M. Najafi, A. Ashori and M. Golriz, "Elastic Properties of Carbon Fibre-Reinforced Epoxy Composites," *Polymers & Polymer Composites*, vol. 23, no. 7, pp. 475–481, 2015.
- [69] Schaeffler Group, "Friction and increases in temperature," Schaeffler Group, [Online].
- [70] SKF, "Deep-groove ball bearings," SKF, [Online]. Available: <http://www.skf.com/africa/en/products/bearings-units-housings/ball-bearings/deep-groove-ball-bearings/index.html>. [Accessed 27 May 2019].
- [71] Schaeffler Group, "Deep-groove ball bearings 6321-M," Schaeffler Group, [Online]. Available: <https://medias.schaeffler.us/product/rotary/rolling-and-plain-bearings/ball-bearings/deep-groove-ball-bearings/6321-m/p/352232>. [Accessed 27 May 2019].
- [72] Schaeffler Group, "Lubrication of Rolling Bearings," Schaeffler Group, [Online]. Available: <https://goo.gl/Cafxgv>. [Accessed 27 May 2019].
- [73] Control Tutorials for MATLAB and Simulink, "DC Motor Speed: Simulink Modeling," University of Maryland Division of Information Technology, 2017 [Online]. Available: <http://ctms.engin.umich.edu/CTMS/index.php?example=MotorSpeed§ion=SimulinkModeling>. [Accessed 29 June 2019].
- [74] T. D. Barkand, "Safe Electrical Design of Mine Elevator Control Systems," United States Department of Labor, [Online]. Available: <https://arlweb.msha.gov/s&hinfo/paper7.htm>. [Accessed 19 July 2019].

- [75] G. Fernando, "Governors on Diesel Locomotive Engines," Gyan C A Fernando, [Online]. Available: <https://gyantrains.blogspot.co.za/2013/01/governors-on-diesel-locomotive-engines.html>. [Accessed 19 July 2019].
- [76] ThyssenKrupp, "Governor Module," ThyssenKrupp, [Online]. Available: <https://www.thyssenkruppelevator.com/webapps/classroom-on-demand/LessonViewer.aspx?lesson=16405>. [Accessed 19 July 2019].
- [77] Baldor, "Direct Current Motors and Drives," Baldor.
- [78] Wurtec Inc., "Tachometer Wheel," Wurtec Inc., 2015 [Online]. Available: <https://www.wurtec.com/en/product/test-measuring-equipment-meters/tachometer-wheel-12-circ-12-240-A1>. [Accessed 27 July 2019].
- [79] B. Makaa, "Types of Elevators | Lifts," Electrical Engineering in Kenya, [Online]. Available: <https://www.eeekenya.com/types-of-elevators-lifts>. [Accessed 05 January 2021].
- [80] B. S. Ben, B. A. Ben, K. Adarsh, K. A. Vikram and C. Ratnam, "Damping measurement in composite materials using combined finite element and frequency response method," *International Journal of Engineering Science Invention*, pp. 89–97, 2013.
- [81] Y-M. Lee, S-K. Sul and J-K. Kang, "Acceleration Feedback Control Strategy for Improving Riding Quality of Elevator System," IEEE, Seoul, pp. 1375–1379, 1999.
- [82] Siemens, "DC Motors Catalog DA 12," Siemens AG, 2008.
- [83] Oriental Motor, "Technical Reference," Oriental Motor, 2013.
- [84] M. Y. H. Bangash and T. Bangash, "Lifts, elevators, escalators and moving walkways/travelators," London: Taylor & Francis, 2007.
- [85] N. Minorsky, "Directional Stability of Automatically Steered Bodies," pp 280, Wiley Online Library, goo.gl/LRzbwy, [Accessed 24 March 2017]
- [86] I. L. Krivits and G. V. Krejnin, "Pneumatic Actuating Systems for Automatic Equipment: Structure and Design," Boca Raton: Taylor & Francis Group, 2006.
- [87] I. Z. Nikolić and I. Milivojević, "Application of pseudo-derivative feedback in industrial robots controllers," *Facta Universitatis*, vol. 2, no. 8, pp. 741–756, 1998.
- [88] O. D. Nwokah, "Pseudo-derivative feedback control," *American Control Conference*, IEEE, pp. 1811–1814, 1987.
- [89] R. D. Peters, "Vertical transportation planning in buildings," *Department of Electrical Engineering and Electronics, Brunel University*, 1998.

- [90] J. Sorsa, H. Ehtamo, J-M. Kuusinen, M. Ruokokoski, and M-L. Siikonen, "Modelling uncertain passenger arrivals in the elevator dispatching problem with destination control," *Optimization Letters* 12, pp. 171–185, 2018.
- [91] E. Cowern, "The Highs and Lows of Motor Voltage," Endeavor Business Media, LLC., [Online]. Available: <https://www.ecmweb.com/design/article/20901278/the-highs-and-lows-of-motor-voltage>. [Accessed 13 September 2020].
- [92] J. Sorsa, M. Ruokokoski and M.-L. Siikonen, "Human Body Size in Lift Traffic Design," 4th Symposium on Lift & Escalator Technologies, Northampton, pp. 213–223, 2015.
- [93] W. Roetzel, X. Luo, and D. Chen, "Design and Operation of Heat Exchangers and their Networks," London: Academic Press, 2020.
- [94] M. Laurino, T. Menara, A. Stella, M. Betta and A. Landi, "Procoagulant control strategies for the human blood clotting process," IEEE Engineering in Medicine and Biology Society, Milan, pp. 4439–4442, 2015.
- [95] S. Wang, "Adaptive Fuzzy Sliding Mode and Robust Tracking Control for Manipulators with Uncertain Dynamics," *Complexity*, vol. 2020, pp. 1–9, 2020.
- [96] ODYSSEE-MURE, "SECTORAL PROFILE - HOUSEHOLDS," Enerdata, [Online]. Available: <https://www.odyssee-mure.eu/publications/efficiency-by-sector/households/electricity-consumption-dwelling.html> [Accessed 10 February 2021].
- [97] KONE Corporation, "KONE regenerative solutions," KONE Corporation, 2009 [Online]. Available: http://rbplifts.com/wp-content/uploads/2017/11/1797_Regenerative_solutions_MidRange_fact_sheet.pdf. [Accessed 12 February 2021].
- [98] M. Fujiyoshi, Y. Nonomura, F. Arai and T. Fukuda, "Analysis and Design of a New Micro Jerk Sensor with Viscous Coupling," *Journal of Robotics and Mechatronics*, vol. 15, no. 6, pp. 582–587, 2002.
- [99] D. Eager, "Accelerometers used in the measurement of jerk, snap, and crackle," *Australian Acoustical Society Annual Conference*, pp. 300–304, 2018.
- [100] Y. Yin, H. Niu and X. Liu, "Adaptive neural network sliding mode control for quad tilt rotor aircraft," *Complexity*, vol. 2017, pp. 1–13, 2017.
- [101] R. I. Alfian, A. Ma'arif and S. Sunardi, "Noise Reduction in the Accelerometer and Gyroscope Sensor with the Kalman Filter Algorithm," *Journal of Robotics and Control*, vol. 2, no. 3, pp. 180–189, 2021.
- [102] Y-T. Bai, X-Y. Wang, X-B. Jin, Z-Y. Zhao and B-H. Zhang, "A neuron-based kalman filter with nonlinear autoregressive model," *Sensors*, vol. 20, no. 1, p. 299, 2020.

- [103] J. O. Pedro and A. J. Crouse, "Direct adaptive neural control of a quadrotor unmanned aerial vehicle" *10th Asian Control Conference*, Sabah, IEEE, pp. 1982–1987, 2015.

10 Appendices

10.1 Supplementary Zoomed Figures

10.1.1 Supplementary zoomed figures – Control of Elevator B (balanced fitness function)

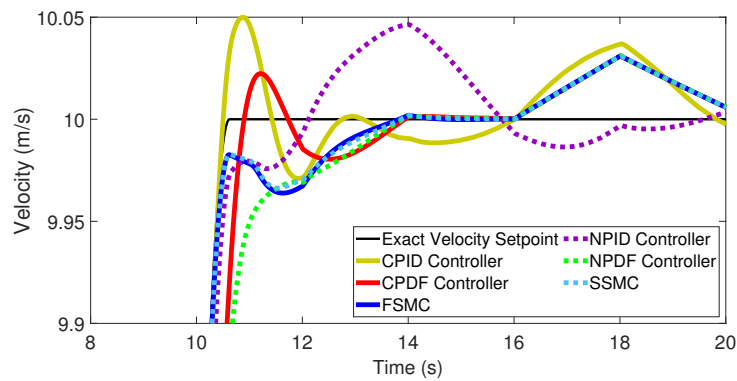


Figure 10.1: Velocity response of the 3200 kg cabins (zoomed into the moment of transition from acceleration to steady-state travel) – Elevator B (balanced fitness function)

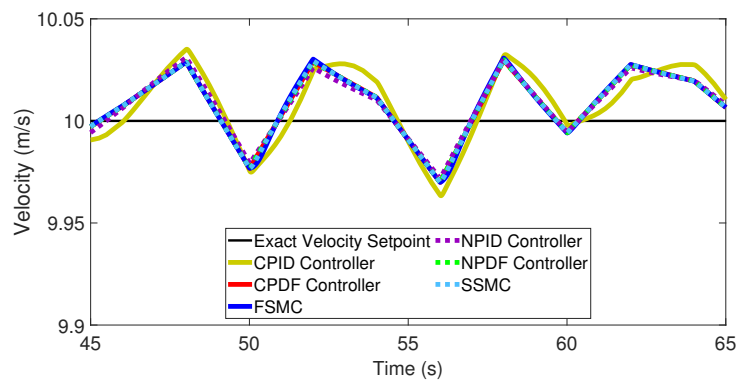


Figure 10.2: Velocity response of the 3200 kg cabins (zoomed into a section during the period of steady-state travel) – Elevator B (balanced fitness function)

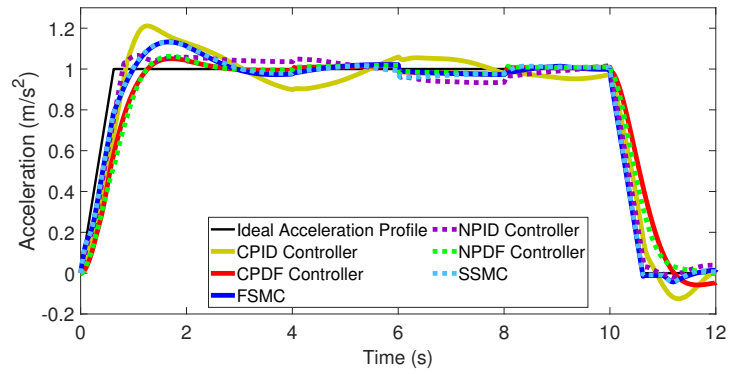


Figure 10.3: Acceleration response of the 3200 kg cabins (zoomed into the period of acceleration) – Elevator B (balanced fitness function)

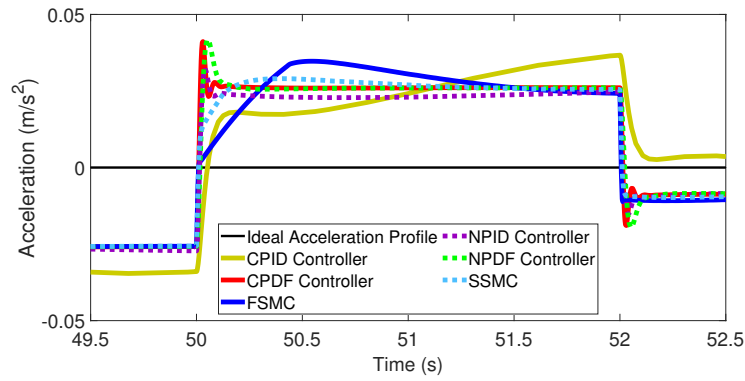


Figure 10.4: Acceleration response of the 3200 kg cabins (zoomed into a section during the period of steady-state travel) – Elevator B (balanced fitness function)

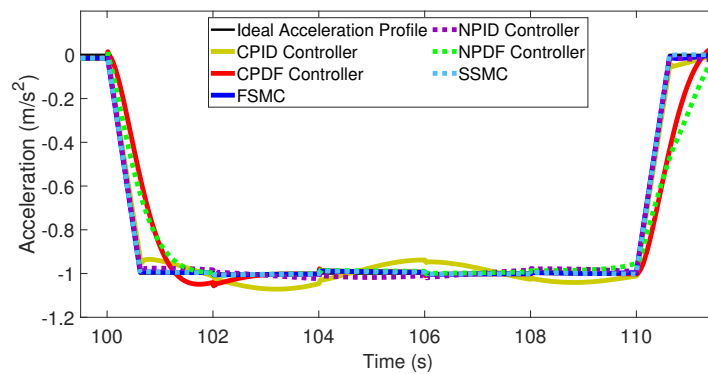


Figure 10.5: Acceleration response of the 3200 kg cabins (zoomed into the period of deceleration) – Elevator B (balanced fitness function)

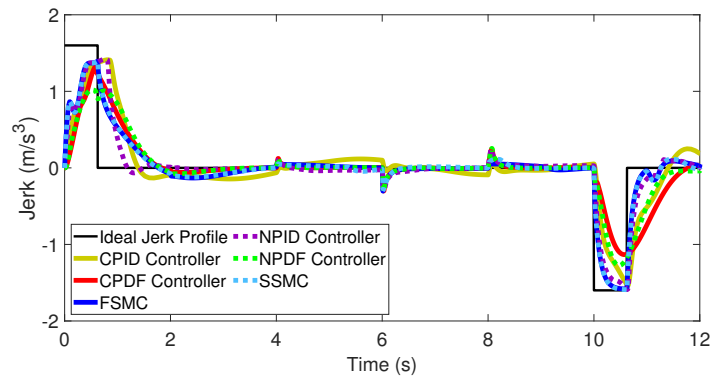


Figure 10.6: Jerk response of the 3200 kg cabins (zoomed into the period of acceleration) – Elevator B (balanced fitness function)

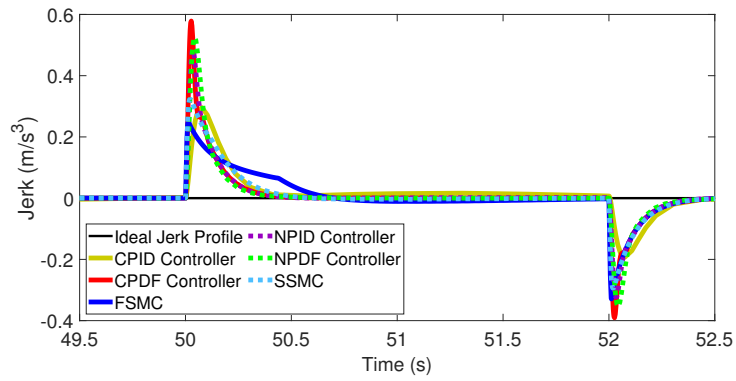


Figure 10.7: Jerk response of the 3200 kg cabins (zoomed into a section during the period of steady-state travel) – Elevator B (balanced fitness function)

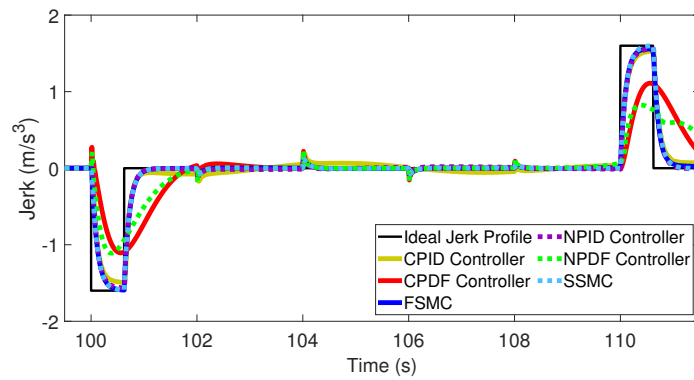


Figure 10.8: Jerk response of the 3200 kg cabins (zoomed into the period of deceleration) – Elevator B (balanced fitness function)

10.1.2 Supplementary zoomed figures – Control of Elevator B (comfort-oriented fitness function)

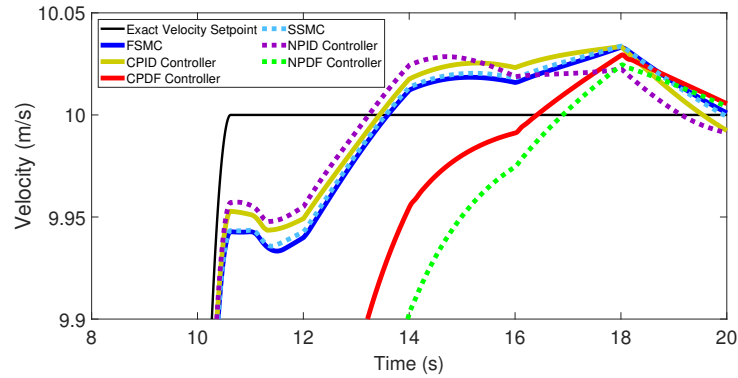


Figure 10.9: Velocity response of the 3200 kg cabins (zoomed into the moment of transition from acceleration to steady-state travel) – Elevator B (comfort-oriented fitness function)

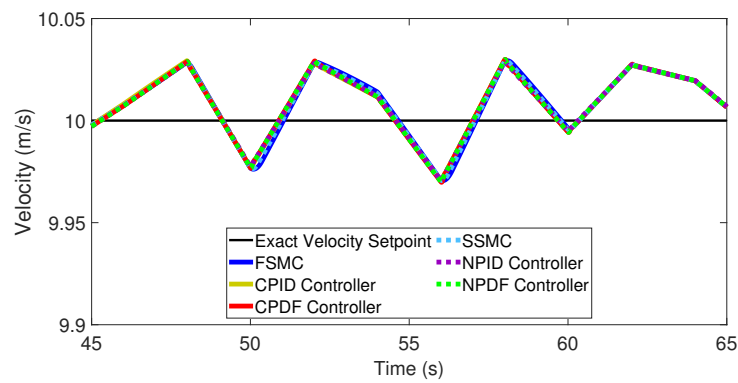


Figure 10.10: Velocity response of the 3200 kg cabins (zoomed into a section during the period of steady-state travel) – Elevator B (comfort-oriented fitness function)

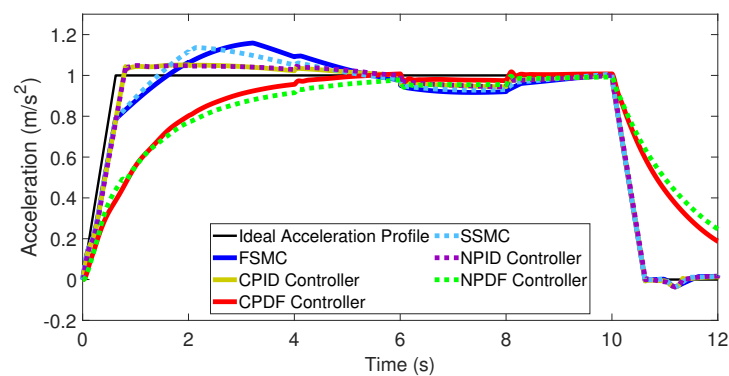


Figure 10.11: Acceleration response of the 3200 kg cabins (zoomed into the period of acceleration) – Elevator B (comfort-oriented fitness function)

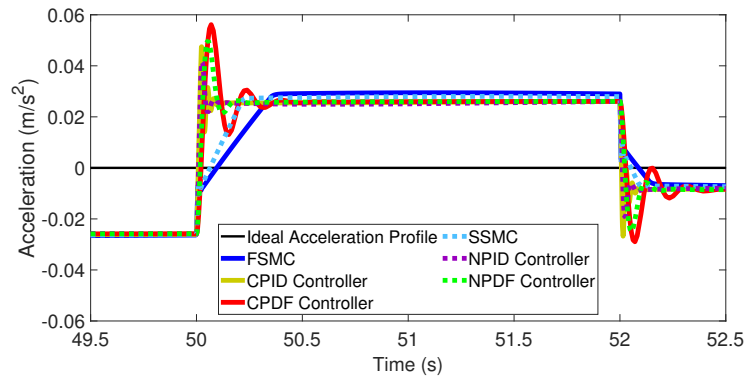


Figure 10.12: Acceleration response of the 3200 kg cabins (zoomed into a section during the period of steady-state travel) – Elevator B (comfort-oriented fitness function)

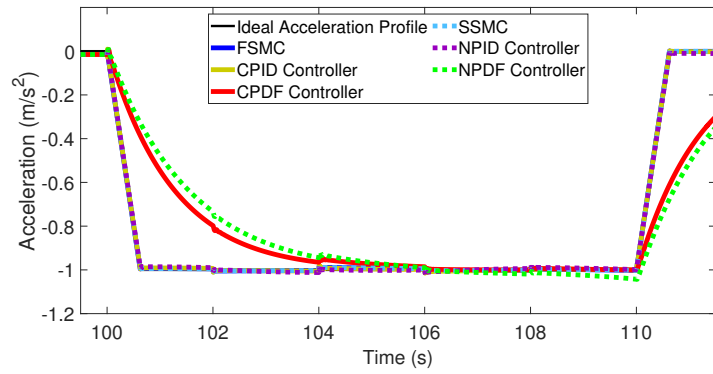


Figure 10.13: Acceleration response of the 3200 kg cabins (zoomed into the period of deceleration) – Elevator B (comfort-oriented fitness function)

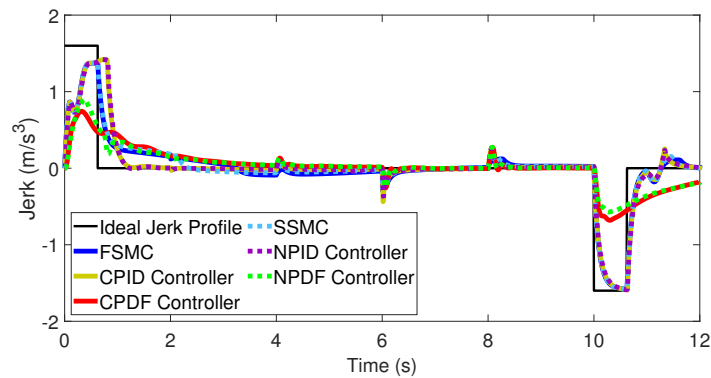


Figure 10.14: Jerk response of the 3200 kg cabins (zoomed into the period of acceleration) – Elevator B (comfort-oriented fitness function)

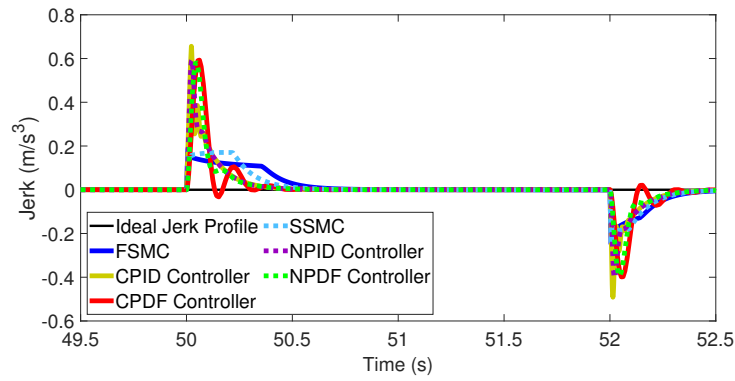


Figure 10.15: Jerk response of the 3200 kg cabins (zoomed into a section during the period of steady-state travel) – Elevator B (comfort-oriented fitness function)

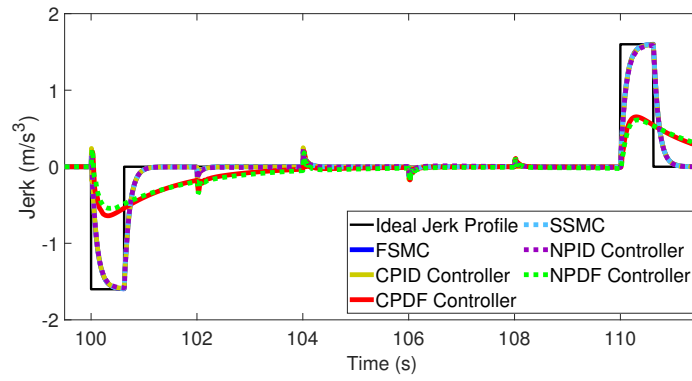


Figure 10.16: Jerk response of the 3200 kg cabins (zoomed into the period of deceleration) – Elevator B (comfort-oriented fitness function)

10.1.3 Supplementary zoomed figures – Control of Elevator B (sustainability-oriented fitness function)

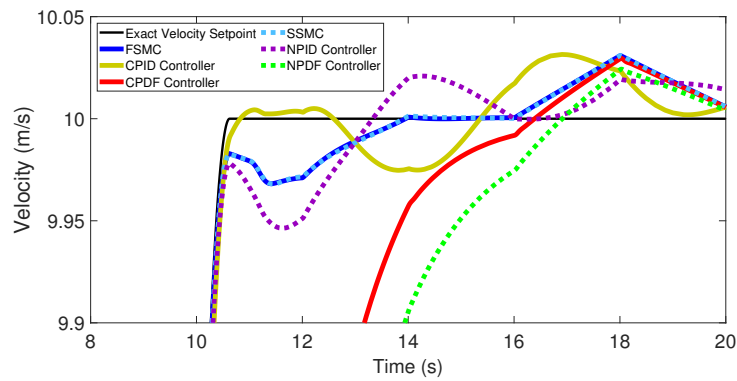


Figure 10.17: Velocity response of the 3200 kg cabins (zoomed into the moment of transition from acceleration to steady-state travel) – Elevator B (sustainability-oriented fitness function)

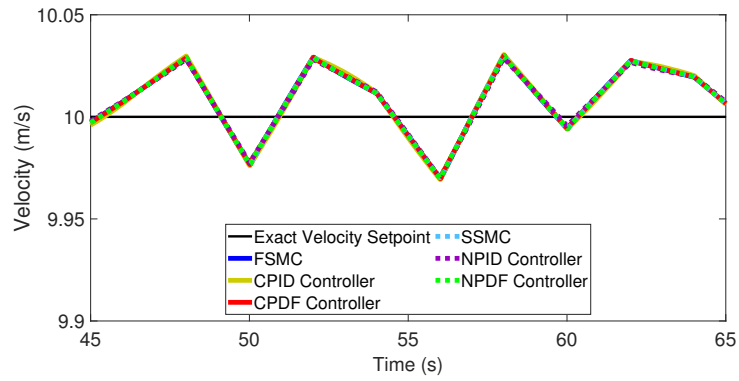


Figure 10.18: Velocity response of the 3200 kg cabins (zoomed into a section during the period of steady-state travel) – Elevator B (sustainability-oriented fitness function)

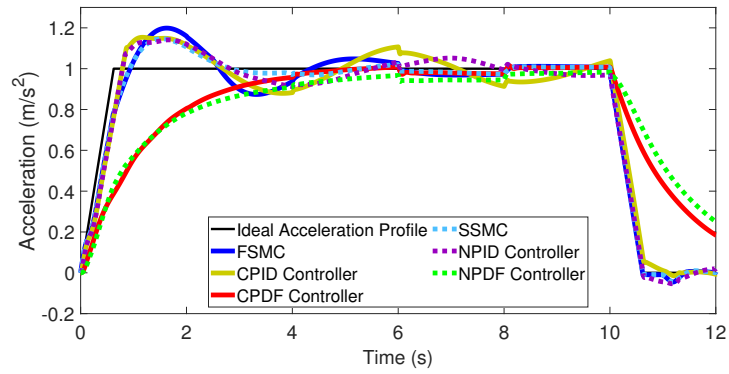


Figure 10.19: Acceleration response of the 3200 kg cabins (zoomed into the period of acceleration) – Elevator B (sustainability-oriented fitness function)

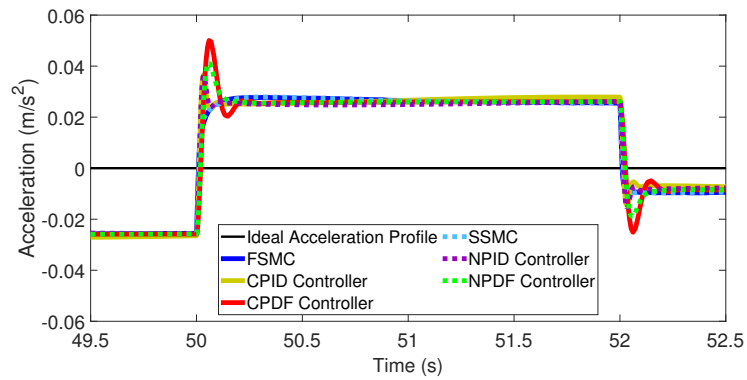


Figure 10.20: Acceleration response of the 3200 kg cabins (zoomed into a section during the period of steady-state travel) – Elevator B (sustainability-oriented fitness function)

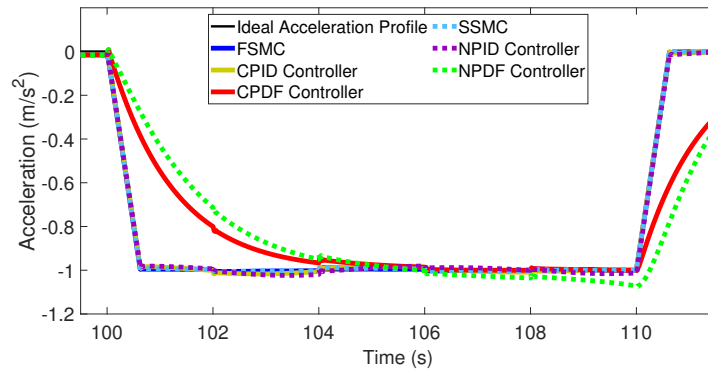


Figure 10.21: Acceleration response of the 3200 kg cabins (zoomed into the period of deceleration)
– Elevator B (sustainability-oriented fitness function)

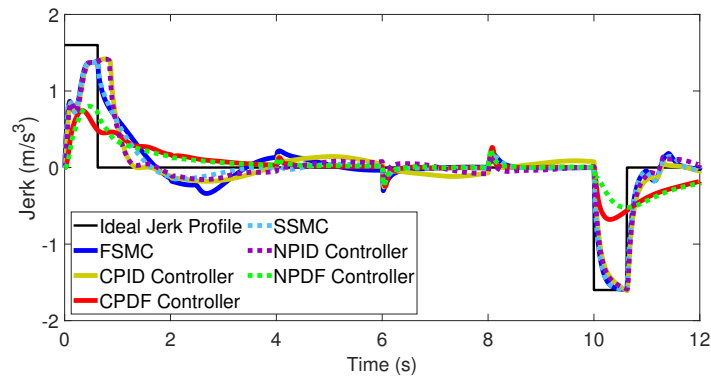


Figure 10.22: Jerk response of the 3200 kg cabins (zoomed into the period of acceleration) – Elevator B (sustainability-oriented fitness function)

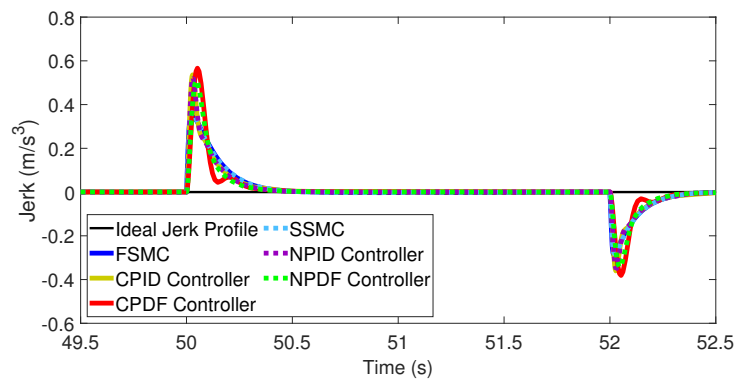


Figure 10.23: Jerk response of the 3200 kg cabins (zoomed into a section during the period of steady-state travel) – Elevator B (sustainability-oriented fitness function)

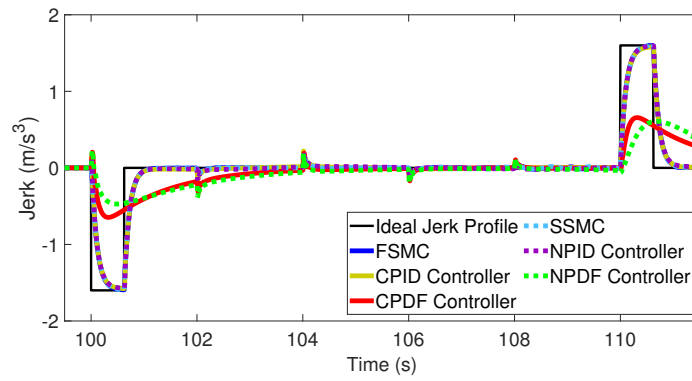


Figure 10.24: Jerk response of the 3200 kg cabins (zoomed into the period of deceleration) – Elevator B (sustainability-oriented fitness function)

10.1.4 Supplementary zoomed figures – Control of Elevator C

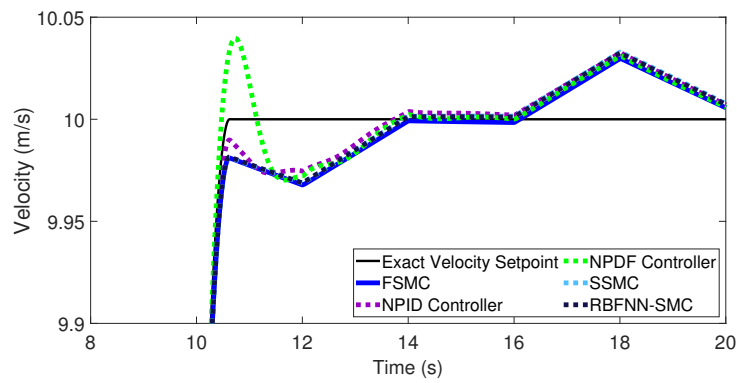


Figure 10.25: Velocity response of the 3200 kg cabins (zoomed into the moment of transition from acceleration to steady-state travel) – Elevator C

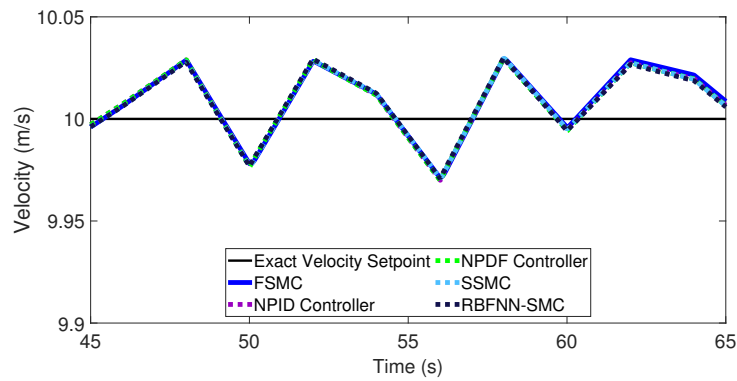


Figure 10.26: Velocity response of the 3200 kg cabins (zoomed into a section during the period of steady-state travel) – Elevator C

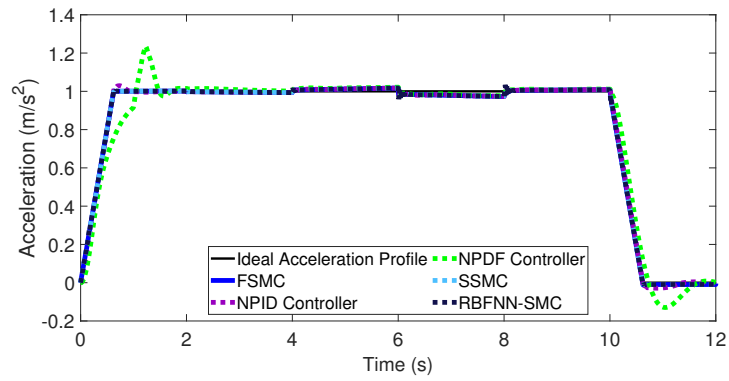


Figure 10.27: Acceleration response of the 3200 kg cabins (zoomed into the period of acceleration)
– Elevator C

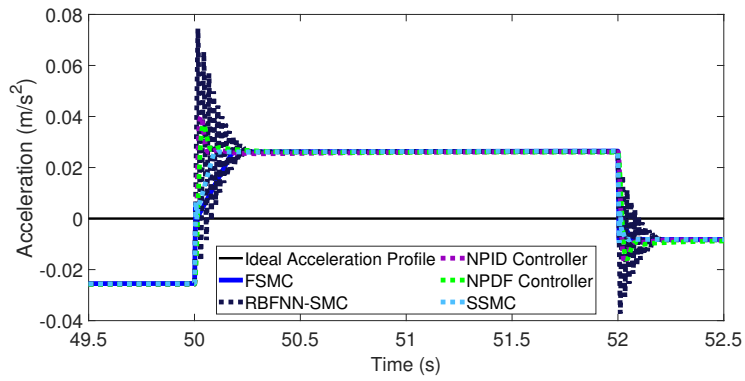


Figure 10.28: Acceleration response of the 3200 kg cabins (zoomed into a section during the period of steady-state travel) – Elevator C

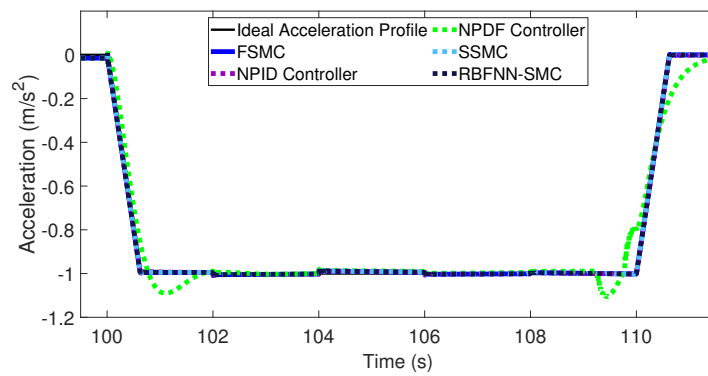


Figure 10.29: Acceleration response of the 3200 kg cabins (zoomed into the period of deceleration)
– Elevator C

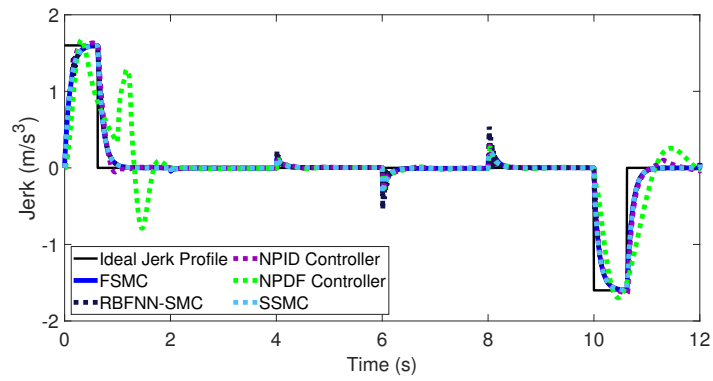


Figure 10.30: Jerk response of the 3200 kg cabins (zoomed into the period of acceleration) – Elevator C

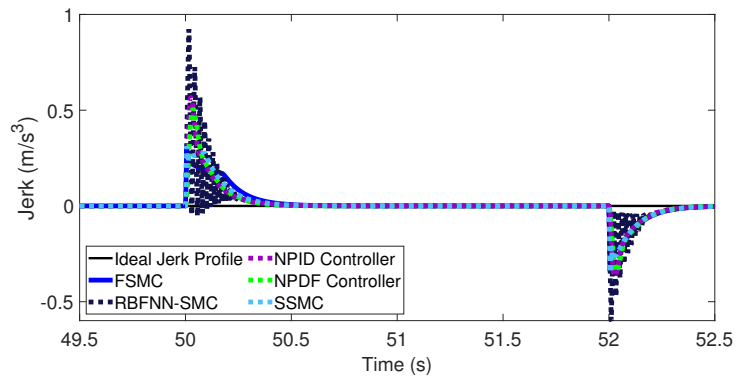


Figure 10.31: Jerk response of the 3200 kg cabins (zoomed into a section during the period of steady-state travel) – Elevator C

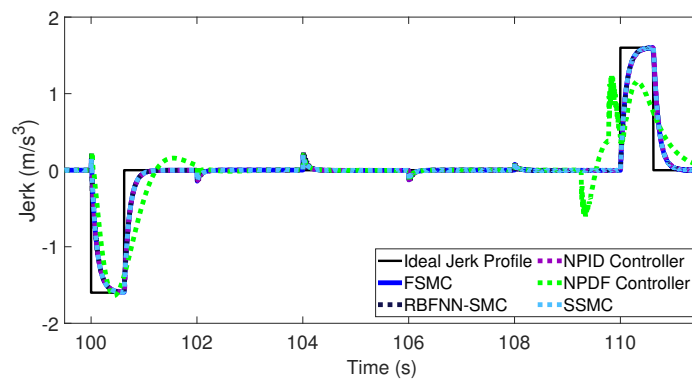


Figure 10.32: Jerk response of the 3200 kg cabins (zoomed into the period of deceleration) – Elevator C

10.1.5 Supplementary zoomed figures – Control of Elevator C (SMC chattering analysis)

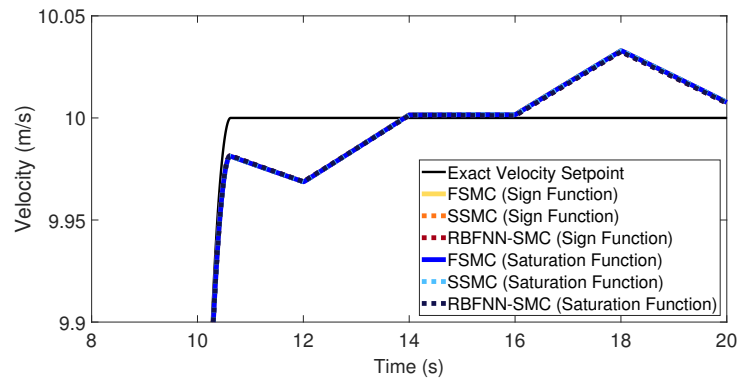


Figure 10.33: Velocity response of the 3200 kg cabins (zoomed into the moment of transition from acceleration to steady-state travel) – Elevator C (SMC chattering analysis)

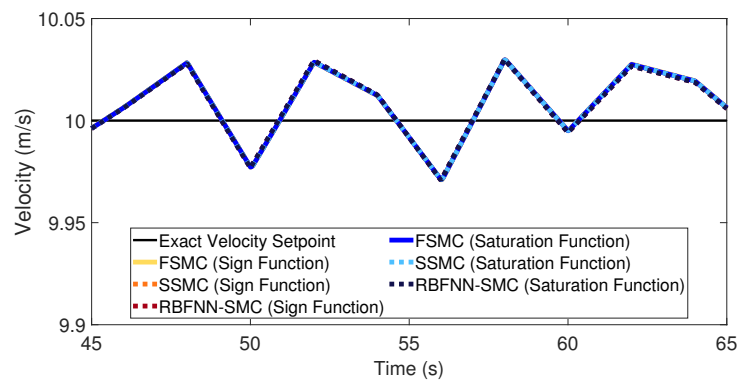


Figure 10.34: Velocity response of the 3200 kg cabins (zoomed into a section during the period of steady-state travel) – Elevator C (SMC chattering analysis)

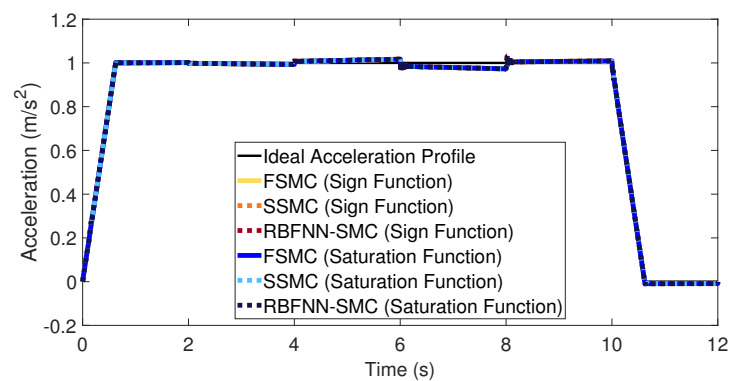


Figure 10.35: Acceleration response of the 3200 kg cabins (zoomed into the period of acceleration) – Elevator C (SMC chattering analysis)

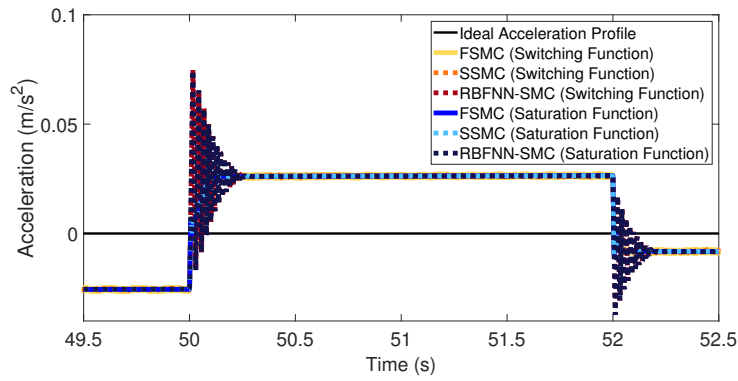


Figure 10.36: Acceleration response of the 3200 kg cabins (zoomed into a section during the period of steady-state travel) – Elevator C (SMC chattering analysis)

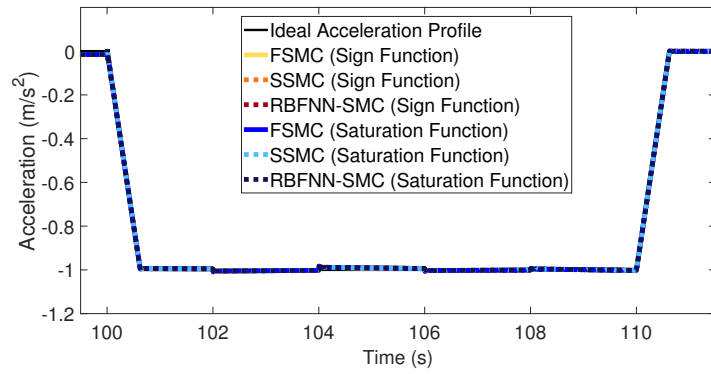


Figure 10.37: Acceleration response of the 3200 kg cabins (zoomed into the period of deceleration) – Elevator C (SMC chattering analysis)

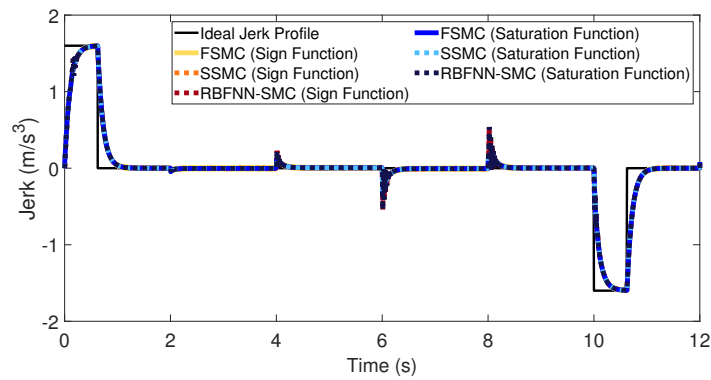


Figure 10.38: Jerk response of the 3200 kg cabins (zoomed into the period of acceleration) – Elevator C (SMC chattering analysis)

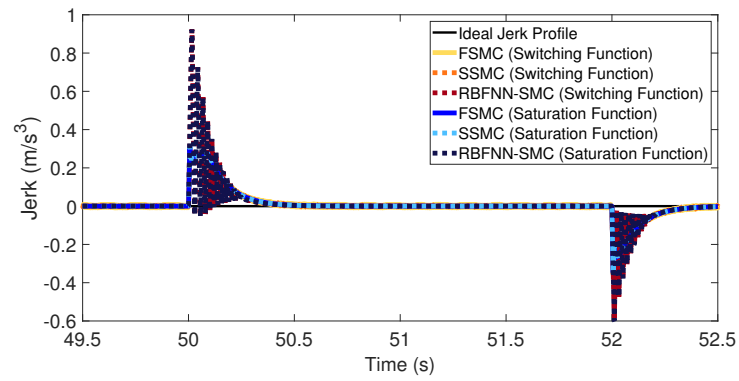


Figure 10.39: Jerk response of the 3200 kg cabins (zoomed into a section during the period of steady-state travel) – Elevator C (SMC chattering analysis)

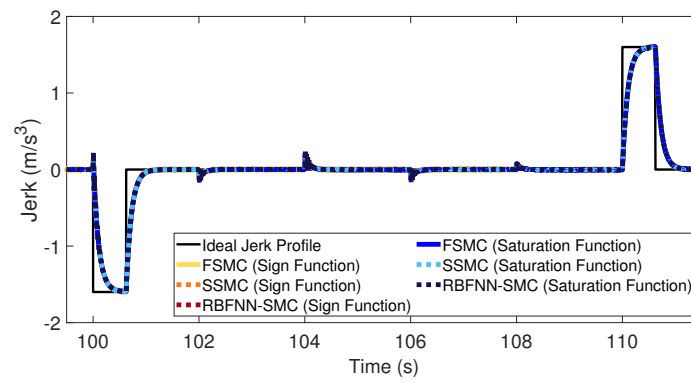


Figure 10.40: Jerk response of the 3200 kg cabins (zoomed into the period of deceleration) – Elevator C (SMC chattering analysis)

10.2 SMC Run Time Comparison

Table 10.1: SMC run time comparison during control of Elevator B

Run	Run Time [s]					
	FSMC	SSMC	Difference	FSMC	SSMC	Difference
	(Saturation Function)	(Saturation Function)		(Sign Function)	(Sign Function)	
1	3982.30	3527.70	454.60	5946.00	5296.80	649.20
2	3981.42	3525.60	455.82	5943.80	5295.10	648.70
3	3994.10	3528.10	466.00	5948.20	5298.20	650.00
4	3988.20	3528.10	460.10	5948.70	5297.90	650.80
5	3981.50	3526.80	454.70	5944.80	5290.20	654.60
6	3980.30	3527.10	453.20	5946.10	5295.30	650.80
7	3980.20	3526.40	453.80	5946.90	5298.30	648.60
8	3988.70	3529.90	458.80	5945.70	5296.20	649.50
9	3981.90	3525.10	456.80	5944.50	5290.70	653.80
10	3981.80	3529.60	452.20	5948.10	5297.70	650.40
Average	3984.04	3527.44	456.60	5946.28	5295.64	650.64
Standard Deviation	4.41	1.49	3.90	1.59	2.81	1.94