



UNIVERSITY OF THE
WITWATERSRAND,
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An Investigation Into The Propulsive Force Generation Of Multiple Flapping Surfaces

Student Name

(Student number: 2496889)

School of Mechanical, Industrial and Aeronautical Engineering

University of the Witwatersrand

Johannesburg, South Africa.

Supervisors: Professor Weihua Ho

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ABSTRACT

The aerodynamic performance of flapping NACA0012 airfoils was analyzed through numerical simulation, focusing on the effects of stagger, gap, phase difference, and the number of airfoils. The simulation was conducted under specific conditions: $U_{\infty} = 0.2m/s$, $f=2Hz$, $\alpha_0=20^{\circ}$, $C=0.04m$, $St=0.2$ and $Re=8000$).

The problem was modeled in ANSYS Fluent using a transient viscous approach with absolute velocity formulation, employing the pressure-based coupled solver (PBCS). PRESTO! interpolation and second-order upwind discretization were applied for pressure, momentum, intermittency, turbulent kinetic energy, and specific dissipation rate. Mesh validation and independence studies confirmed that the results were driven by the physics setup, independent of mesh configuration.

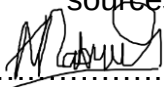
It was discovered that small stagger and gap at $\phi=180^{\circ}$ is not good for thrust production as the airfoils produced thrust less than a single airfoil with $\Delta C_{t_{av}} = -0.94$. However, lift production is increased and $\Delta C_{l_{av}} = 1.2$. At larger spacing ΔC_t , ΔC_l and η generally become constant. One of the worst performing cases ($X=1.0C$; $Y=0.5C$; $\phi=180^{\circ}$) was improved by making the aft airfoil lead ($\phi=-45^{\circ}$). This explains why insects alter ϕ or frequency depending on the situation and flight requirements. The most effective X - Y - ϕ were found to be the ones at which flow separation is suppressed. For the 4 airfoils cases the fore pair performed better than the aft pair for the small spacing case. When spacing was increased the aft pair performed better than the aft pair.

DECLARATION

I (name) Never Mabvuu , Student Number: 2496889, am registered for the (course code) MECN4006 (course name) Research Project in the year 2023. I herewith submit the following task (title) Investigation Into The Propulsive Force Generation Of Multiple Flapping Surfaces.

I hereby declare the following:

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NOMENCLATURE

X -----	Stagger [m].
Y -----	gap [m]
Δt -----	time step [s]
Δx_i -----	inflation layer height.
α_o -----	pitching amplitude
F_n -----	nth airfoil
LE-----	leading edge
TE-----	Trailing edge.
C -----	Chord length [m].
U_∞ -----	free stream velocity [m/s]
f -----	Oscillating frequency [Hz]
ϕ -----	Phase angle [degrees].
T -----	Oscillating period [Seconds].
A -----	Oscillation Amplitude [degrees].
N -----	number of airfoils
I_p -----	performance index [dimensionless].
ΔC_t -----	thrust augmentation [dimensionless]
ΔC_l -----	lift augmentation [dimensionless]
C_d -----	drag coefficient [dimensionless].
C_t -----	thrust coefficient.
C_l -----	lift coefficient [dimensionless]
C_{l_n} -----	lift coefficient for the nth airfoil
C_{d_n} -----	drag coefficient for the nth airfoil.
C_{t_n} -----	thrust coefficient for the nth airfoil.

η -----efficiency [%]

C_p -----pressure coefficient.

Presto! -----PREssure Staggered Option.

PBCS-----Pressure Based Coupled Solver.

k -----Reduced Frequency [dimensionless]

Re -----chord length based Reynolds number [dimensionless]

St -----Strouhal Number [dimensionless]

C_o -----Courant number [dimensionless]

1. INTRODUCTION

1.1. BACKGROUND

This investigation seeks to expand Krige et al's study who investigated the aerodynamic performance of in-tandem flapping hydrofoils [1].

In their research, Krige et al. investigated configurations with up to four tandem hydrofoils and established that a cut-off point exists beyond which adding another flapping hydrofoil yields no further performance benefits. This cut-off was found at three foils, after which the benefits of augmentation diminished due to the weakening of vortex strength.

The current study is carried out on a stagger and gap configuration which is a combination of biplane and tandem arrangements. Gap refers to the distance between two airfoils in the direction of the flow and stagger is the distance normal to the flow. Figure 1-1 below illustrates gap ΔX and stagger ΔY

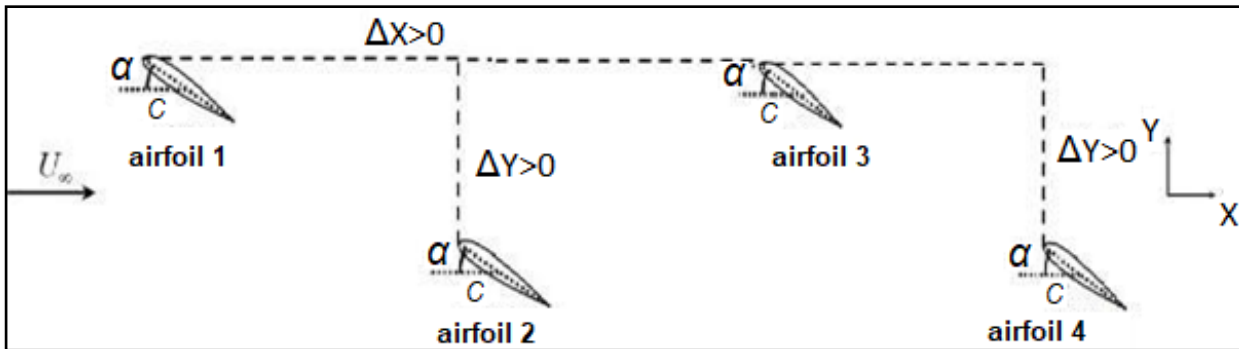


Figure 1-1: Stagger and Gap Illustration.

Of major interest is the effect of stagger and gap on lift and thrust production at low Reynolds number. The effects of phase difference are also studied. The question is can aerodynamic performance and efficiency of single or tandem flapping surfaces at a Reynolds number of 8000 be improved by incorporating stagger and gap configuration.

1.2. IMPORTANCE OF THE STUDY (Research Gap)

There is a growing need to understand how to optimize the performance of multiple airfoils in staggered and gapped configurations, especially for applications like bio-inspired propulsion and energy harvesting. Current research lacks comprehensive insights into the influence of these configurations on lift, thrust, and efficiency, particularly at low Reynolds numbers. Additionally, the effects of phase differences between multiple airfoils remain underexplored. This study is crucial in addressing these gaps and providing guidance on the optimal configuration for enhanced aerodynamic performance

1.3. OBJECTIVES

The main aim of this research is to investigate the flow characteristics of multiple airfoils in stagger and gap configuration so as to determine optimal configuration parameters. This is to be achieved through the following objectives;

- 1) Quantify the effects of stagger and gap on performance characteristics of lift, thrust, and efficiency for different configurations on multiple airfoils
- 2) Determine if the performance and efficiency can be improved by increasing the number of airfoils to 4.
- 3) Extend the study to include different phase differences between the flapping airfoils.

1.4. SCOPE

The scope of this research will be limited to 2D numerical simulation. The study will mainly be computational in nature. Focus will be on the counter-flapping airfoils. Other phase angles will be considered for comparison purposes if necessary.

2. LITERATURE REVIEW

2.1. Introduction

The relentless pursuit of flight has led to the invention of aircraft, missiles and unmanned aerial vehicles (UAV), High Amplitude Unmanned Aerial Vehicles (HAUAV) and micro air vehicle (MAV). As a result, research on the aerodynamic performance of various arrangements and combinations of flapping surfaces has gained traction recently and these are providing valuable insight into how we can improve these designs. Compared to fixed and rotating airfoils, flapping airfoils are complex in terms of unsteadiness but offer greater manoeuvrability and propulsive performance over a wide range of speeds. Lift generation, thrust generation and efficiency under different operating conditions constitute aerodynamic performance. Overall, flapping airfoils are more efficient than traditional propellers because they can generate lift at lower speeds and produce less noise. Natural flyers such as birds and insects produce thrust and lift through flapping wings whilst fish use their pectoral and caudal fins for propulsion [2].

2.2. Weis-Fogh Effect and Flapping Wing Mechanics

In most insects the interaction of the wing with the wake generated in the previous stroke led to a peak in generated aerodynamic forces (Weis-fogh effect). A flapping wing produces aerodynamic forces by at least five mechanisms; added mass effect, absence of stall, rotational circulation, clap and fling and wing-wake interaction [3]. In insects between the down stroke and upstroke is a rotational phase (pronation and supination). Pronation occurs when the wing transitions from upstroke to downstroke whilst supination occurs during transition from downstroke to upstroke. During startup and stroke reversal the fluid closest to the wing surface experiences the greatest acceleration resulting in pressure around the wing. The whole wing structure experiences this pressure as additional wing mass which enables it to flap (added mass effect).

2.3. Effects of Geometry on Lift-Thrust Generation

A flapping bio-inspired airfoil operates in a vortex dominated environment and is able to harvest energy from incoming vortices generated upstream. The interactions between the wings and the vortices greatly influence the force generation and flying efficiency. Some interesting phenomena induced from such vortex-body interactions have gotten a lot of attention in the past few decades.

Flapping motion is inspired from nature such as insects, and fish and is known to produce lift and thrust simultaneously (Knoeller-Betz effect). According to Knoeller and Betz a flapping wing creates an effective angle of attack such that the aerodynamic force generated is

decomposed into lift and thrust component [4, 5]. According to Tay and Lim airfoil lift performance is significantly dependent on the airfoil's shape and thrust production is mostly influenced by the kinematic variables such as reduced frequency, Strouhal number. In order to achieve maximum lift, an airfoil must be designed so that it maximizes the downward deflection of airflow. The performance of non-symmetrical airfoils under varying Strouhal number, frequency, phase angle and pitch angle was compared to that of the symmetric NACA0012 profile which was found to have the highest efficiency and thrust production compared to the asymmetric S1020 [6]. A different hysteresis loop in lift and drag is produced by each airfoil operating below $Re < 10^6$. This is due to the location of laminar separation and transition which in turn is dependent on the airfoil thickness. For best aerodynamic performance value of the maximum thickness should be as small as possible. [6]. Both Ho et al and Flint et al attributed the existence of a hysteresis asymmetry with the pitch down thrust in dragonfly-inspired corrugated airfoils to the shape of the profile. Even though the corrugated shape delays stall smooth airfoils are best for thrust production. This is due to vortices being shed at multiple sites along the corrugated surfaces which augment lift but however reduce thrust [7, 8].

2.4. Effects of Flight Conditions on Propulsive Performance

From various computational and experimental studies, it had been revealed that also critical to flapping airfoil propulsive performance are flight conditions such as Reynold's number, Mach number, Strouhal number and reduced frequency. These have to be defined for any fluid mechanics problem modelling. Below $Re=10^5$ cambered airfoils have better lift and drag characteristics than thick conventional airfoils. Decrease in Re lead to decrease in lift and increase in drag for NACA0012 [6]. Higher Re leads to a more stable airfoil and aerodynamic performance, larger stalling angle. Stall angle is near 12degree for NACA0012 and 5deg for cambered airfoils [9]. This for a non-flapping airfoil is confirmed by Soueid et al who through the optimization a NACA0012 airfoil by sensitivity functions found the effective angle of attack to be 11 degrees. This angle of attack yields maximum lift to drag ratio when the airfoil is not flapping. However, in the low Re regime it has been shown that flapping resulted in excellent aerodynamic performances. This makes low Re aerodynamics important for both natural and artificial flyers. During non-flapping flights birds stretch their wings to generate lift and during gliding thrust is generated by gravity. Most natural flyers have a high lift to drag ration for a wide range of lift and Re in the range ($10^5 - 2 \times 10^5$). Lua et al established that flapping motion thrust generation performance increases with frequency for Strouhal number below a critical value ($S=0.25-0.30$). Above the critical value increase in frequency results in drag production [10]. This was carried out at a chord-based Reynold's number of 5000. This concurred with Flint et al who investigated the flow around a pitching corrugated airfoil and discovered that the

oscillation begins to have significant effect on the flow at reduced frequency, $k=1.24$. Below that it has the same performance as a stationary airfoil and doesn't generate thrust [8]. Viscous effects such as vortex formation and shedding become important to the flow structures as well as the forces acting on the airfoil. In low Reynolds number flows separation and subsequent reattachment are dominated by large scale vortex motions and occur within a short distance [11].

The amount of lift generated by flapping airfoils is usually small, but they can be very efficient in terms of lifting capacity relative to their size. A flapping airfoil sustains thrust production by capturing the incoming vortex field. Henceforth creation of a regular wake of vortices is vital for the production and sustenance of aerodynamic forces making the oscillation motion profile critical to airfoil performance. In low Re strange undesirable features are obtained for a symmetrical airfoil at zero degrees angle of attack. Hover et al compared four angle of attack profiles; Simple harmonic heave and pitch, square wave, symmetry saw tooth and the cosine function at Reynolds number of 3000. The cosine profile is found to produce the highest thrust at the highest efficiency, the saw-toothed profile generally produces high thrust but is less efficient [12]

2.5. Effects of Spacing and Phase Difference

The propulsive performance of a pair of flapping airfoils is as sensitive to phase difference as it is to spacing. Lua et al investigated the effects of effects of phase angle (ϕ) and center-to-center distance (L) between the front wing and the rear wing on the aerodynamic force generation at a Reynolds number of 5000. The rear wing was seen to experience maximum thrust for in phase motion interestingly increasing spacing has the same effect as reducing the phase angle [13]. According to Lan and Sun who studied force and flow structures concluded that for in-phase flapping the fore airfoil thrust is increased in downstroke and lift is decreased in upstroke compared to a single airfoil. The aft airfoil thrust and lift decreased in downstroke and upstroke respectively for counter-flapping. The resultant force was found to fall by 20%. For a phase difference of 90° -phase-difference lift on the aft airfoil in downstroke and lift on the aft airfoil in upstroke greatly decrease. The resultant force decreases by as much as 28%. Result the magnitude of the resultant force is decreased by about 28%. The 90° -phase-difference flapping was found to produce the largest lift but has the least resultant force [14]. Akhter et al used an immersed boundary (IB) solver to carry out numerical simulation on the interaction between the dorsal fin and tail in swimming bluegill sunfish and discovered that vortex shedding upstream in the dorsal fin can significantly increase thrust downstream at the tail [2]. However, this is greatly dependent on the phase difference between the dorsal fin and the wing.

This is in agreement with Lee's finding who discovered the LEV formation on the downstream airfoil doesn't fully develop for both in-phase and out-of-phase because it is disrupted by the downwash induced in the upstream airfoil. This leads to reduced lift, thrust and momentum on the rear airfoil as compared to that observed on the upstream. However, depending on the spacing-phase difference combination the rear foil can move from producing insignificant thrust to twice the thrust of a single foil. Maximum thrust production is observed when the rear foil moves in-between the vortices shed by the fore foil, and low thrust is produced when it intercepts these vortices [15]. Out of phase flapping produces better aerodynamic performance than in-phase flapping [16]. Dragonflies are able to do a quick transition from one flight mode to another by manipulating the phase difference between the fore and hind wings [17]. According to Alexander they tend to employ in phase flapping in situations that require above normal force production [17]. This is different from Akhtar et al's finding that thrust production is maximum at a phase angle of 48° . Some damselflies produce thrust by having the hindwing in lead. [18]

2.6. Flapping Configurations

Common multiple flapping surface configurations include tandem, biplane as well as stagger and gap. A stagger and gap configuration as used in this study is a combination of both tandem and biplane configurations with airfoils offset from each other and have a small vertical gap between them. Since in tandem and stagger and gap arrangements the leading edge vortices (LEV) of the fore airfoil enter the wake of the aft airfoil the resultant wake structure is a due to LEV-TEV interaction. The positional relationship of adjacent foils is therefore vital since the aft foil is situated in the wake of the fore airfoil. The effects of stagger and gap on aerodynamic performance had been studied both by experiment [19, 20] and numerical simulation [21, 22, 23]. However, all these studies were limited to configuration of not more than two airfoils. Therefore, it can't be established from literature whether the stagger and gap aerodynamic performance can be improved by incorporating additional flapping or stationary airfoils. The fore foil influence on the aft foil LEV ultimately affect its aerodynamic performance. Changes in stagger and gap therefore affect the interaction timing between the vortices shed from the fore and aft foils. When there are two flapping surfaces in close proximity, the interaction of the flow leads to more interesting and complex phenomenon. This interaction could augment or reduce the performance of individual surfaces

The biplane flapping configuration is beneficial to the power extraction of flapping airfoils [22]. Deng et al compared a biplane counter-flapping to a single airfoil at a Reynolds number of 10 000, reduced frequency of 2, Strouhal number of 1.3 and pitching angle between 50° and 15° . It was established that during outstroke a low-pressure region

between the airfoils leads to a strong TEV which is absent in a single wing. These shed vortices lead to drag production. However, during instroke, the vortices are gradually squeezed towards the TE leading to thrust production [24].

According to Zhu and Lei [21] stagger and gap produce between 56-77% more thrust than single airfoils at a phase difference of 60° - 90° . Generally, lift increases with stagger due to the increase in high pressure area near the leading-edge surface of the upper airfoil. Staggered flapping airfoils are more efficient than in-tandem flapping airfoils, but they have lower lift-to-drag ratios. Tuncer and Kaya [25] carried out a number of studies on flapping biplane configurations. In the first study a Reynolds-averaged Navier-Stokes (RANS) with overset grids was used simulate unsteady viscous flow over biplane flapping airfoils and it was discovered they can produce up to 40% more thrust than a single (flapping) airfoil. However, this thrust can be produced at the expense of efficiency. In the other study optimal thrust production conditions were determined using a gradient based optimization process. At low frequency more thrust is produced compared to a single airfoil. However, at high frequency, an early LEV formation is promoted as the pitch amplitude tends to zero, leading to limited thrust production. [26].

Systems with more than two flapping surfaces are common in nature. Most fish have more than two fins pectoral/caudal fins for propulsion(Figure 2-1 below).

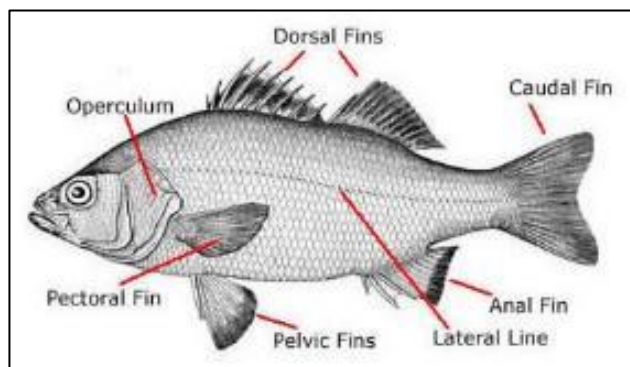


Figure 2-1: Multiple Stagger and Gap Flapping Surfaces In Fish

They have paired fins (pectoral and pelvic) as well as median fins (dorsal, caudal, and anal). These help fish achieve various locomotive functions such as swim, turn and balance. According to Akhtar et al the vorticity generated in the bluegill sunfish, dorsal fin is capable of significantly increasing thrust at the tail [2]. Insects such as dragonflies also have a pair of wings on each side.

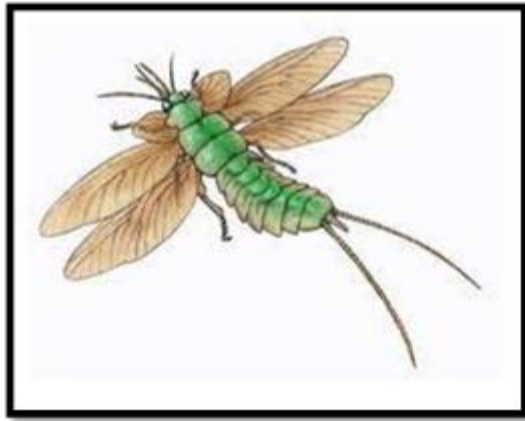


Figure 2-2: Palaeodictyoptera "Six-Winged" Insect

The now extinct Palaeodictyoptera had three pairs of wings with the front pair being a smaller winglet. Figure 2-2 above show what it looks like [27].

2.7. Performance Index

Aerodynamic performance is not only achieved through thrust generation, efficiency and lift are equally important. Lim & Tay adopted a relative performance index, I_p to compare the aerodynamic performance of various case configurations. The performance index was for a case with stagger, d , and number of airfoils, n was be presented as;

$$I_p = \frac{\eta_{0(d_{12}, \theta_{12})}}{\max(\text{all } \eta_{0(d_{12}, \theta_{12})})} + \frac{\bar{C}_{t,0(d_{12}, \theta_{12})}}{\max(\text{all } \bar{C}_{t,0(d_{12}, \theta_{12})})} + \frac{\bar{C}_{l,0(d_{12}, \theta_{12})}}{\max(\text{all } \bar{C}_{l,0(d_{12}, \theta_{12})})} \dots \dots \dots [1]$$

Where $\eta_{0(d_{12}, \theta_{12})}$, $\bar{C}_{t,0(d_{12}, \theta_{12})}$ and $\bar{C}_{l,0(d_{12}, \theta_{12})}$ are the average values for efficiency, thrust coefficient and lift coefficient respectively. For a case with n airfoils these are calculated from the equations below.

$$\eta_o = \frac{\bar{C}_{t,fore \text{ airfoil}}}{\bar{P}_{t(fore \text{ airfoil})}} + \frac{\bar{C}_{t,aft \text{ airfoil}}}{\bar{P}_{t(aft \text{ airfoil})}} \dots \dots \dots [2]$$

$$\bar{C}_{t,0} = \bar{C}_{t,fore \text{ airfoil}} + \bar{C}_{t,aft \text{ airfoil}} \dots \dots \dots [3]$$

$$\bar{C}_{l,0} = \bar{C}_{l,fore \text{ airfoil}} + \bar{C}_{l,aft \text{ airfoil}} \dots \dots \dots [4]$$

3. CFD APPLICATION IN FLAPPING AIRFOILS SIMULATIONS

3.1. INTRODUCTION

Computational Fluid Dynamics (CFD) has emerged as a powerful research method for investigating flow dynamics in various fields. This chapter provides a comprehensive overview of CFD as a research tool for studying flow dynamics and focuses specifically on its application in simulating flapping motion. The chapter explores different CFD methods, discusses their advantages, compares their effectiveness in simulating flapping motion, and highlights the significance of CFD in analyzing the complex aerodynamic behavior of flapping motion. Furthermore, the chapter highlights the critical role of CFD in analyzing the intricate aerodynamic behavior involved, ultimately guiding the selection of the most suitable methods for the current study.

3.2. CFD: OVERVIEW AND METHODS

Computational Fluid Dynamics (CFD) encompasses various numerical methods that can be used to analyze and simulate fluid flow phenomena [28]. These methods include the panel method, stream function vorticity, particle vortex method, and other CFD-based approaches. Each method has its own advantages and limitations, but CFD is widely regarded as a versatile and applicable tool for studying a wide range of flow dynamics problems.

One of the advantages of CFD is its ability to handle complex geometries. Traditional experimental methods may encounter difficulties when dealing with intricate or irregular shapes, but CFD can easily accommodate complex geometries through the use of numerical discretization techniques [28]. This allows researchers to model and analyze flow behavior around objects with intricate aerodynamics, such as flapping wings.

CFD also offers the advantage of providing detailed visualizations of flow behavior. Through the use of computational algorithms, CFD simulations can generate graphical representations of fluid flow phenomena, including velocity distributions, pressure contours, and streamlines [28]. These visualizations aid researchers in understanding the underlying physics of the flow, identifying areas of interest, and making informed design decisions.

3.3. SOLVER METHODS IN CFD

Solver models play a critical role in CFD simulations as they determine the mathematical and numerical techniques used to solve fluid flow equations. In the context of simulating flapping motion, two common solver models are employed: Pressure Based and Density Based. A Pressure Based was preferred for the current study due to its superior handling of incompressible and low-speed flows, which are typical in flapping dynamics. They offer

flexibility in the solution procedure and can handle a wide range of flow regimes. They can be solved either sequentially using a segregated solver or simultaneously employing a Coupled Solver. Pressure Based solvers, as described by [30], are particularly adept at managing pressure-velocity coupling through iterative methods, making them well-suited for capturing the intricate unsteady behaviors associated with flapping motions.

In contrast, Density Based solvers, while effective for high-speed and compressible flows, can introduce complexities that are unnecessary for the current study. Density Based methods often require more computational resources and sophisticated settings for shock capturing, which may not be applicable to the primarily incompressible regime of flapping motion [31]

Additionally, Pressure Based solvers generally offer enhanced stability and convergence properties for unsteady simulations, making them more efficient for complex geometries typically encountered in flapping simulations [29]. Their ability to accurately resolve pressure gradients without extensive memory requirements makes them ideal for this type of analysis. Overall, the selection of a Pressure Based solver aligns with the current research's specific needs, ensuring accurate and reliable results in modeling the flapping motion.

3.4. TURBULENCE MODELING TECHNIQUES

Turbulence is a complex and multifaceted phenomenon that significantly affects many fluid flows, particularly in the context of flapping motion. Accurately modeling turbulence is essential for reliable CFD simulation results, as it directly influences predictions of flow separation, wake behavior, and aerodynamic forces. Three widely employed turbulence modeling approaches in CFD are Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), and Reynolds-Averaged Navier-Stokes (RANS).

DNS offers the highest level of accuracy by resolving all turbulent scales directly, making it ideal for academic research and validation studies where detail is crucial. However, its extreme computational demands restrict its practical use to low Reynolds number flows and simple geometries [32]. Because of the complexity of flows like those in flapping wings at higher Reynolds numbers, LES provides a more feasible alternative. LES resolves the larger turbulent eddies while modeling the smaller, more isotropic ones, thus balancing accuracy and computational cost [33]. However, even LES can be computationally expensive, particularly for unsteady, high-Reynolds-number flows.

For engineering applications and high-Reynolds-number flows, RANS models remain the most commonly employed due to their computational efficiency and the availability of turbulence models that can simulate a variety of flow conditions with acceptable accuracy [34]. Among the various RANS models, the Transition Shear Stress Transport (Transition

SST) model has become a popular choice for simulating flows where the laminar-to-turbulent transition plays a significant role—such as in the current study involving flapping NACA0012 airfoils in staggered mode.

The Transition SST model, developed by Menter, is particularly well-suited for the complex flow regimes seen in flapping motion because it incorporates terms that handle both fully turbulent and transitional flows [35]. Flapping wings often experience repetitive laminar-to-turbulent transitions due to the unsteady nature of the flow and the dynamic motion of the airfoil, which can involve alternating cycles of acceleration and deceleration. This transitional flow behavior is especially prevalent in staggered or tandem airfoil configurations where vortices shed from the leading airfoil can interact with the trailing airfoil's boundary layer, affecting its transition from laminar to turbulent flow [35]. By capturing the onset and length of transition more accurately than fully turbulent models like the $k-\omega$ SST, the Transition SST model provides more precise predictions of separation points, vortex formation, and wake dynamics, which are critical for understanding flapping wing aerodynamics [31].

Additionally, the SAS (Scale-Adaptive Simulation) viscous model, though excellent at capturing small eddies and unsteady turbulence, has certain limitations when it comes to compatibility with newer mesh techniques such as overset meshing, a method that is increasingly used in dynamic and moving-body simulations. This limitation also extends to models like the Detached Eddy Simulation (DES), which, while capable of resolving large-scale turbulence, is not yet compatible with all meshing approaches in ANSYS. As a result, the beta version of the Transition SST model is employed in this study, offering both compatibility with overset meshes and a refined approach for capturing the laminar-turbulent transitions in flapping airfoil dynamics [36]. This makes it an ideal choice for the current study involving flapping NACA0012 airfoils in staggered mode, where the accurate capture of transitional flows is crucial.

The Transition SST model's ability to handle both laminar and turbulent regions of flow while maintaining computational efficiency ensures that it provides a more accurate representation of the flow physics around the NACA0012 airfoil during staggered flapping motion. This balance between accuracy and computational efficiency has been noted by researchers in various applications, including airfoil simulations and other aerodynamic studies where the interaction of turbulent wakes and transition is essential [37].

3.5. SIMULATING FLAPPING MOTION USING CFD

Simulating flapping motion using Computational Fluid Dynamics (CFD) involves various methods and techniques that allow researchers to study the complex fluid dynamics associated with flapping-wing systems. These methods include structured and

unstructured grid approaches, immersed boundary methods, and dynamic mesh techniques. By comparing and analyzing these methods, researchers can gain insights into their effectiveness and frequency of use in simulating flapping motion, leading to improved understanding and optimization of flapping-wing systems.

Structured grid approaches involve dividing the computational domain into a structured grid, where the grid lines align with the geometry of the system. These methods, such as the finite difference method, offer accuracy and efficiency in simulating flapping motion [39]. However, they may face challenges in handling complex geometries and boundary conditions, particularly when dealing with intricate wing shapes or fluid-structure interactions.

Unstructured grid approaches, on the other hand, offer flexibility in handling complex geometries. These methods, such as the finite volume method, use an unstructured mesh that allows for efficient discretization of the computational domain [40]. Unstructured grid approaches are commonly employed in CFD simulations of flapping-wing systems due to their ability to handle complex fluid-structure interactions and capture intricate flow phenomena.

Immersed boundary methods are another class of techniques used in simulating flapping motion. These methods treat the solid body, such as the flapping wing, as an immersed boundary within the fluid domain. The immersed boundary method enables the modeling of fluid-structure interactions and the accurate representation of the motion and forces exerted by the flapping wing [41].

Dynamic mesh techniques are employed when the flapping motion leads to significant deformation of the computational domain. These methods allow for the mesh to dynamically adapt and deform along with the motion of the wing, ensuring accurate representation of the flow field [42]. Dynamic mesh techniques are particularly useful when studying large-amplitude flapping motion or complex wing kinematics.

4. METHODOLOGY

4.1. NUMERICAL SIMULATION

Numerical simulation is to be performed using Ansys Fluent on different parameter combinations of stagger and gap with the aim of quantifying the thrust, lift and efficiency. The counter-flapping case will be used as the baseline where some cases will be selected for phase shift simulation. 3D analysis comes with a lot of complexities so the study will be done in 2D with fluent set to double precision. An in-built expressions function in fluent will be used to define the motion of the airfoils as opposed to the traditional user-defined-functions. This is quick, easy to de-bug and convenient since no external file is required to be uploaded.

The problem is to be modeled as a transient viscous with absolute velocity formulation and it is best practice to set the fluent solver to double precision for transient analysis. The Pressure based coupled solver (PBCS) is to be applied for this research. The coupled scheme has superior accuracy as compared to the standard pressure-based solver. For pressure interpolation the PRESTO! Interpolation is preferred because of its accuracy and it presents no boundary interpolation and pressure gradient assumption errors. Second Order-Upwind discretization is to be selected for momentum spatial discretization, intermittency turbulent kinetic energy, and specific dissipation rate and momentum thickness. For gradient values the Least-Squares Cell-Based method is best for this study since it takes less computational power.

The simulation is to be repeated for four airfoils and results are to be plotted against normalized time. The flapping motion is in nature complicated however for this study the angle of attack is to be modeled as a cosine function shown below.

$$\alpha(t) = \alpha_o \cos(2\pi ft + \phi) \dots \dots \dots [5]$$

$$h(t) = h_o \cos(2\pi ft + \phi) \dots \dots \dots [6]$$

$\alpha(t)$ ----- *pitching angle,*

α_o -----*pitching amplitude,*

$h(t)$ ----- *plunging displacement,*

h_o ----- *heaving amplitude,*

f ----- *flapping frequency,*

t ----- *Flow time*

ϕ ----- *Phase difference.*

The airfoil is pitched about 0.25c axis

A performance index based on Lim & Tay's method will be used for evaluating the performance of each scenario [43].

Since this study acts as a continuation to Krige et al's study hence reference will be made for the turbulent flow conditions, which are; a free stream velocity of 0.2 m/s , a flapping amplitude of 20°, frequency of 2Hz. These correspond to Strouhal and chord-based Reynold's numbers of 0.2 and 8000 respectively.

The Reynold's number is calculated as below:

$$Re = \frac{\rho UC}{\mu} \dots \dots \dots [7]$$

Re----- *Reynold's number,*

ρ----- *fluid density [kg/m³]*

U-----*free stream velocity [m/s]*

C -----*airfoil chord length [m]*

μ ----- *kinematic viscosity [m²s⁻¹]*

Stagger is to be varied from 0.5C-1.0C for a gap of 0.5C-1.5C. Most literature studied for this research used the same range. Although there is no consensus from literature on what is positive or negative stagger in this study stagger is taken to be positive when the upper airfoil is fore of the lower.

4.2. GEOMETRY AND MESHING

The meshing can be achieved through dynamic, overset or sliding meshing. Dynamic meshing use algorithm which controls the flapping motion of the airfoil by splitting cells as they stretch and merge. It can be difficult to control how re-meshing takes place and can thus be unpredictable. As much as it is difficult to setup and uses a lot of computational power, dynamic meshing can achieve any form of motion. Sliding mesh on the other hand, has an inner region containing the airfoil which slides past an outer stationary one. Information is passed between the two regions interface. It is best practice to have a minimum diameter of approximately 1.5C for the inner domain containing the airfoil and this puts a limit to the range of stagger values which can be investigated

For the current study, overset meshing was chosen due to its effectiveness in simulating multiple, independently moving bodies, such as staggered airfoils. Unlike sliding mesh, which transfers information across edges, overset meshing exchanges data over entire overlapping areas, which can slightly increase the risk of error propagation [40]. However, overset meshing significantly reduces the need for frequent remeshing and lowers

computational costs, especially in scenarios involving complex wake interactions between multiple flapping airfoils [28].

Its ability to maintain grid quality, enabling better local mesh refinement, is particularly beneficial for capturing fine details such as vortices and transitions in staggered configurations, making it a highly suitable method for this simulation [44]. The compatibility of overset meshing with ANSYS also enhances its utility in this context

4.3. METHOD VALIDATION AND MESH INDEPENENCE STUDY

Krige et al setup for a single airfoil case is replicated and results validated against published data. The simulation is run at $k=1.26$ and $A=20^0$. To test the effects of Courant number the simulation was carried out courant numbers of 5.26 and 2.63 which correspond to time steps of $T/500$ and $T/1000$ respectively where T is the period of oscillation. The Courant number is calculated relative to the height of the first inflation layer and is defined as:

$$C_o = \frac{U\Delta t}{\Delta x_i} \dots \dots \dots [8]$$

where Δt is the time-step for the simulation and Δx_i is the first inflation layer height. For an implicit scheme to get a stable time dependent solution the requirement to have $C\leq 1$ is not important [8]. The results are shown in the table Table 4-1below.

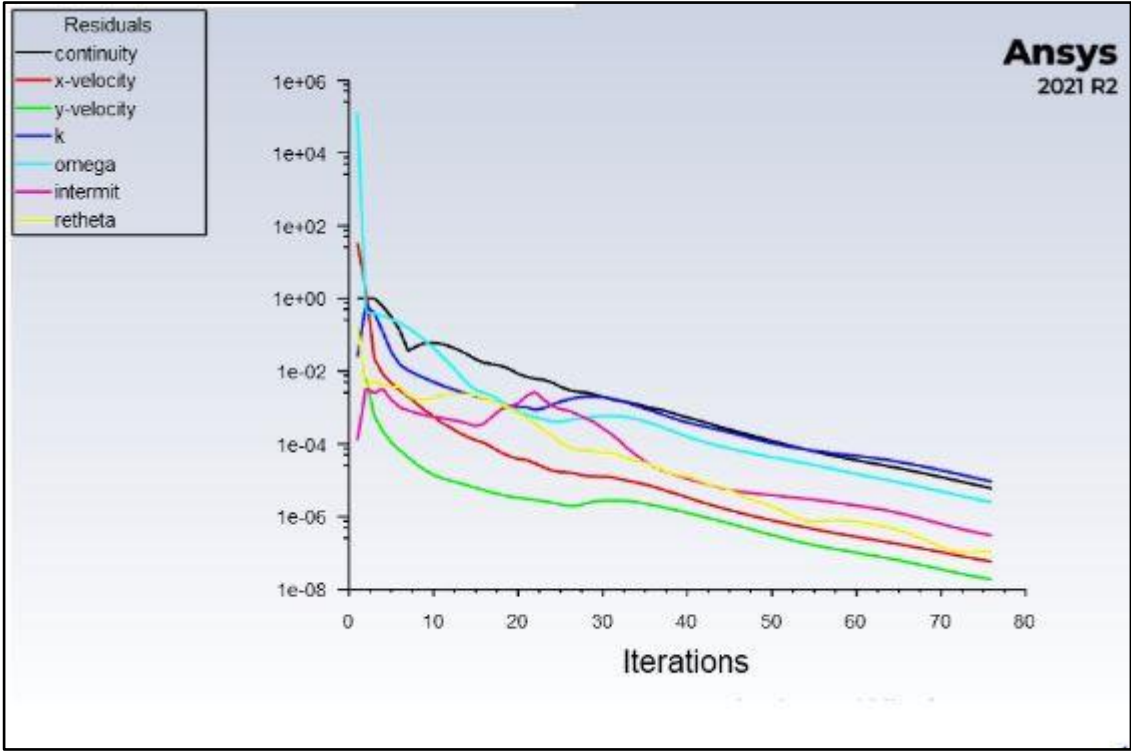


Figure 4-1: Residuals

Convergence criteria is set to all residuals falling to below 10^{-5} as shown in Figure 1-1 above. Each case is first run at steady state until it converges.

Table 4-1: Mesh Independence Study

Table 4-PROPERTY	KRIGE	C=5.26		C=2.63	
		Value	% Difference	Value	% Difference
Maximum Lift Coefficient	2.704	2.773	-2.56	2.596	-4.01
Minimum Lift Coefficient	-2.793	-2.792	-0.03	-2.927	4.81
Average Lift Coefficient	-0.057	-0.055	3.51	0.057	0.73
Maximum Drag Coefficient	0.530	0.518	-2.33	0.514	-3.06
Minimum Drag Coefficient	-0.280	-0.269	-4.10	-0.261	-6.91
Average Drag Coefficient	0.089	0.093	4.49	0.084	-5.62

The force coefficients are plotted in figure 5 and 6 below.

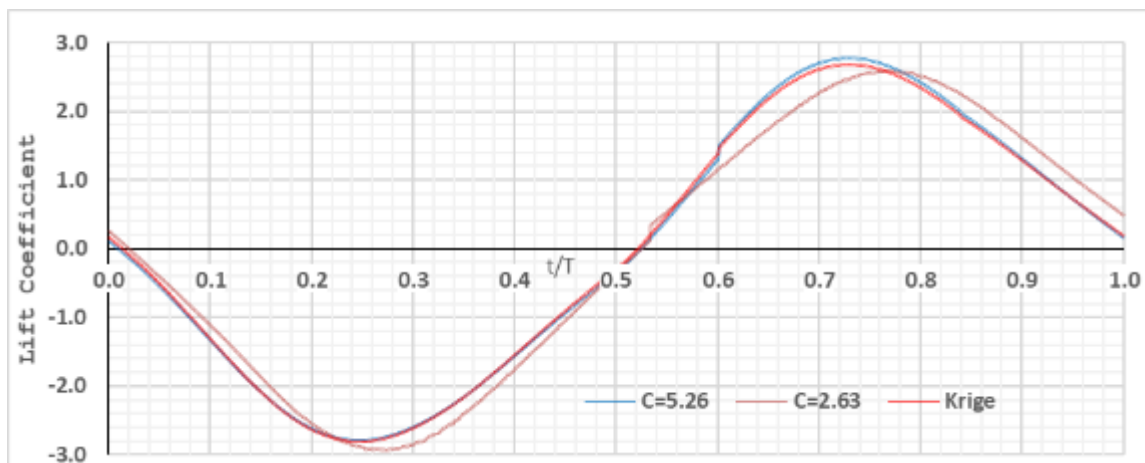


Figure 4-2: Lift Coefficients Plots for Method Validation And Mesh independence Study

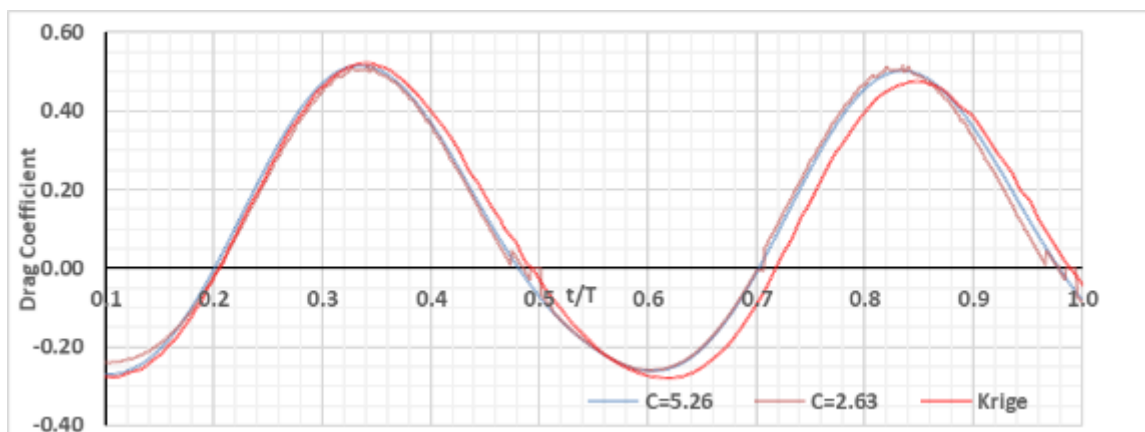


Figure 4-3: Thrust Coefficients For Method Validation And Mesh independence Study

As shown in Table 4-1 Lift and drag coefficients recorded for both courant numbers are within the range $\pm 5\%$ which indicates that flow solution is grid converged and is independent of the time step. This also suggests that the solution is independent of the mesh density.

The double airfoils case is also validated against results from Zhu and Lei. Mesh independence study is used make sure that the results are absolutely due to the physics setup and not because of mesh setup and resolution. The results obtained were tabulated in Table 4-2 below.

Table 4-2: Method Validation For Double Airfoils

PROPERTY	Zhu	Ct	
		Value	% Difference
Maximum Thrust Coefficient	9.221	8.968	-2.82
Minimum Thrust Coefficient	-3.730	-3.806	-2.038
Average Thrust Coefficient	3.172	2.989	-5.769

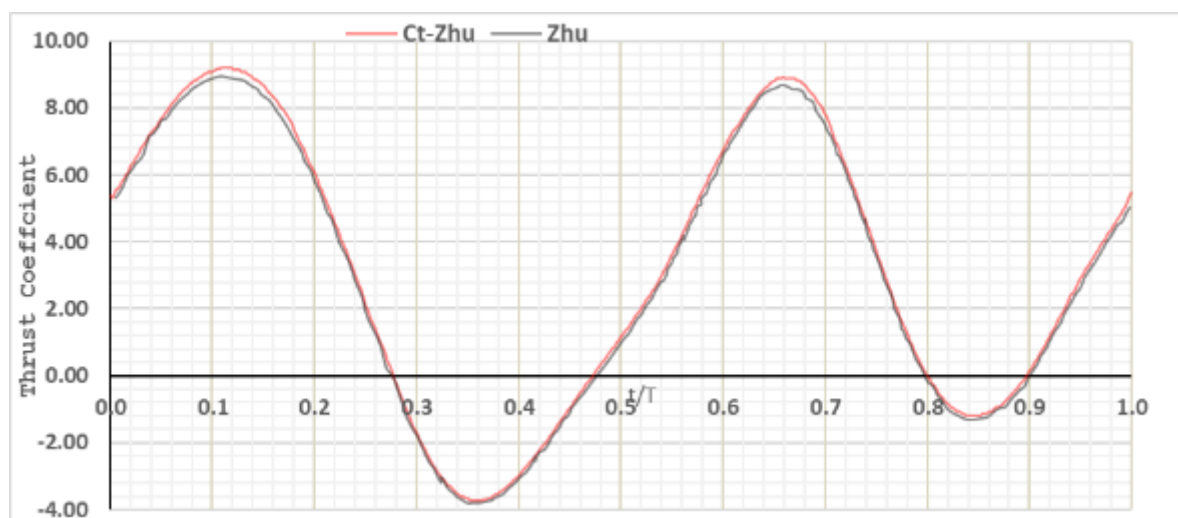


Figure 4-4:Thrust Coefficient For Double Airfoil Method Validation

As shown in Table 4-2 and Figure 4-4 and Table 4-2: Method Validation For Double Airfoils the variance in C_t is within acceptable levels. The final mesh used in this study has an element size of 5mm and edge sizing of 2.5mm. The growth rate was set to 1.2. The resultant number of elements was 44699 with a total of 45167 nodes. The inflation layer had 9 layers and the first layer thickness was 0.038mm

4.4. OVERVIEW OF CASES.

The cases are numbered according to the setup parameters as shown in the Table 4-3 below.

Table 4-3: Case numbers and setup parameters, $\phi=180^\circ$

CASE	STAGGER	GAP	ϕ
1	0.5	0.5	180
2	0.5	0.75	180
3	0.5	1	180
4	0.5	1.25	180
5	0.5	1.5	180
6	0.75	0.5	180
7	0.75	0.75	180
8	0.75	1	180
9	0.75	1.25	180
10	0.75	1.5	180
11	1	0.5	180
12	1	0.75	180
13	1	1	180
14	1	1.25	180
15	1	1.5	180

5. RESULTS

The investigation of counter-flapping airfoils commences at the point of maximum separation of their leading edges during the instroke phase. Instantaneous force data for all cases is presented in Appendix A to G. The impact of gap and stagger on counter-flapping airfoils is scrutinized in sections 5.1 and 5.2, respectively, drawing from observations derived from aerodynamic force plots. In-depth analysis of vortical structures and flow patterns in the counter-flapping cases is conducted in section 5.3. Section 5.4 delves into the discussion of lift and thrust out-of-phase behavior, while sections 5.5 and 5.6 focus on the overall efficiency and performance index, respectively. Subsequently, the investigation expands to four airfoils in section 5.7, where the results are further analyzed.

The mutual aerodynamic interactions between the upper and bottom airfoils are of paramount importance in this study. In theory, with a significant stagger and gap between two airfoils, they should produce equivalent lift and thrust. However, in the cases examined, the spacing between the airfoils is such that they strongly affect each other's performance. This influence is visually demonstrated through surface pressure distribution plots for specific time steps in depicted in Figure 5-1 below.

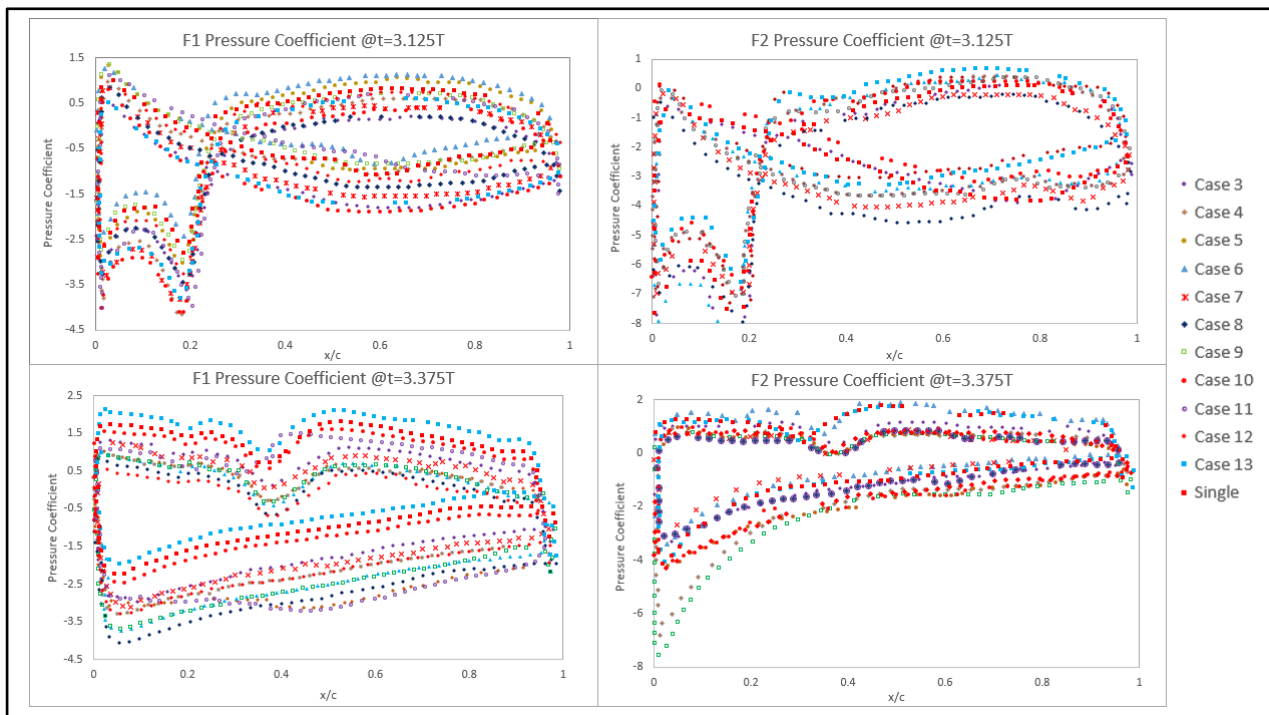


Figure 5-1: Surface pressure distribution

As depicted in Figure 5-1, initially, the pressure distribution for both airfoils appears identical. However, as the flow progresses, interactions between the wings come into effect, leading to significant variations in the pressure distribution. It is worth noting the pressure crossover occurring at $x = 0.25C$, which corresponds to the pitching axis. This

phenomenon arises due to the downward motion of the left side of the airfoil for F1, while the right side moves upwards, causing the displacement of fluid in different directions. The opposite is true for airfoil F2.

While the upper airfoil profoundly impacts the upper surface of the lower airfoil, the introduction of the lower airfoil considerable effects on both surfaces of the upper airfoil. Results from the single airfoil case are therefore employed as the baseline so as to establish a consistent reference for performance comparisons, as opposed to utilizing the leading airfoil in a multi-airfoil arrangement. This choice streamlines the evaluation of performance variations.

Additionally, the research incorporates the tandem in-phase and counter-flapping cases investigated by Krige et al [1] to provide valuable insights into the aerodynamic behavior of the airfoil configurations under specific conditions and serve as essential benchmarks for the present investigation. By drawing upon these established cases, the study enhances its technical rigor and expands the understanding of the complex aerodynamic phenomena associated with multi-airfoil interactions.

5.1. EFFECT OF GAP

The effects of gap on lift and thrust in a stagger and gap configuration are illustrated in Figure 5-2 to Figure 5-7 below. For all the cases studied the stagger and gap configuration produced more lift compared to the single, tandem counter-flapping and tandem in-phase cases. However, although stagger and gap thrust performance is better than tandem counter-flapping and tandem in-phase for all gap values, it is worse than a single airfoil for $\text{gaps} \leq 0.75C$. Both total thrust and lift shows little sensitivity with gap compared to the individual airfoils. Below $\text{gap} = 1.0C$ slight changes in gap lead to significant changes in both thrust coefficients whilst for gaps beyond $1.0C$ they become less sensitive to changes in gap and are almost constant.

The general thrust trend for both airfoils where both fore and aft airfoil thrusts increase to peak before becoming almost constant at larger gaps are in agreement with observations by Tay et al [45]. Figure 5-2 below shows that when gap is increased from $0.5C$ to $0.75C$, ΔC_{t1} drops 31.4% for $X=0.5C$ and ΔC_{t2} increases by 31.2%. However, for $X=0.75$ and $X=1.0C$ the drop in ΔC_{t1} is halved to 15%. The increase in ΔC_{t2} is doubled (59.8% and 55% respectively). As a result, in this small gap region little change is observed in ΔC_t (6.8%, 1.9% and -3.8% for $X=0.5C$, $X=0.75C$ and $X=1.0$ respectively). For $0.75C \leq 1.0C$ ΔC_{t1} shows the same trend as in the previous gap range increasing by 105%, 48% and 45%, for $X=0.5C$, $X=0.75C$ and $X=1.0C$ respectively. ΔC_{t2} increases by 36%, 38.5% and 55% respectively.

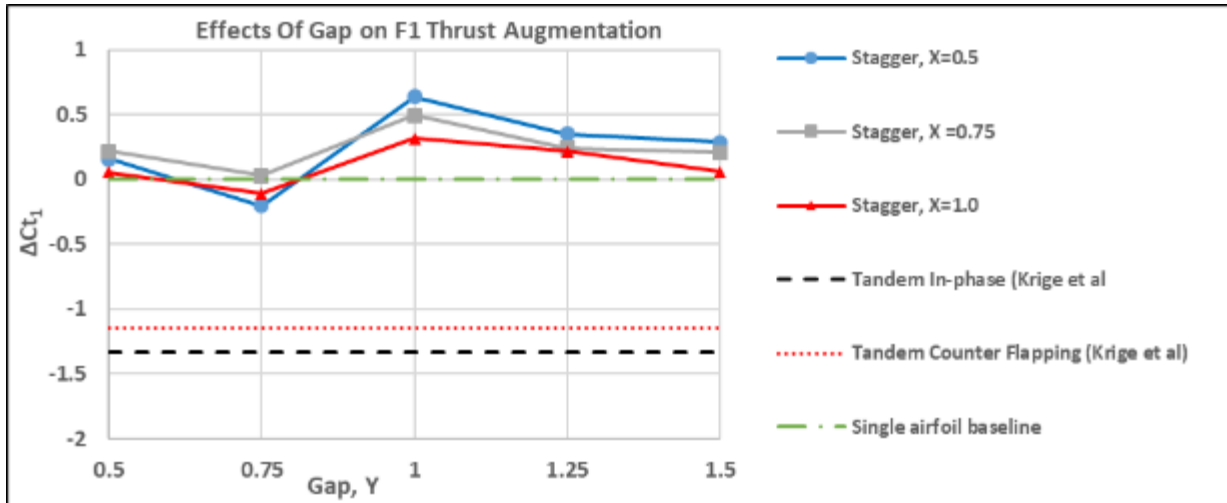


Figure 5-2: Effects of gap on stagger and gap counter-flapping ΔCt_1 .

Ct_1 and Ct_2 peak at $Y=1.0C$ for all the stagger values except for $X=1.0C$ which have Ct_2 peaking at $Y=1.25C$ as indicated in Figure 5-3 below. For the studied stagger values, at optimal gap the fore airfoil produced 32-64% more than a single airfoil thrust. The aft airfoil generated 15-43% thrust more than a single flapping airfoil. It is important to note that the Strouhal number (0.2) is in the lower region of thrust producing Strouhal numbers. Both airfoils performed better than Krigé's tandem and in-phase cases [1]. The overall maximum overall thrust is 30-48% more than a single airfoil thrust.

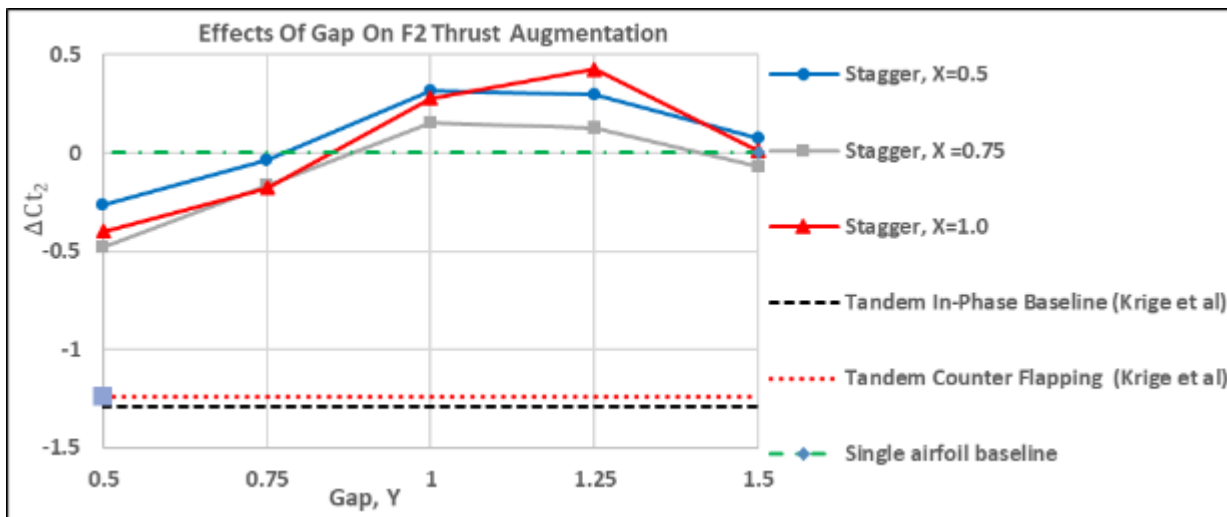


Figure 5-3: Effects of gap on stagger and gap F2 counter-flapping ΔCt_2 .

For $1.0C \leq Y \leq 1.25C$ Ct_1 drops by 18% for $X=0.5C$ and $X=0.75C$ with a minimal drop of 7.6% for $X=1.0C$. Ct_2 falls by 1.5% and 2.5% for $X=0.5C$ and $X=0.75C$ respectively, however it increases by 11.6% for $X=1.0C$. As a result, Ct_1 drops 10.6% for $X=0.5C$ and $X=0.75C$ respectively. For $X=1.0C$ it increases by only 1.8%. For $1.25C \leq Y \leq 1.5C$ thrust augmentation is almost equal for all the stagger values. ΔCt_1 decreases by an average of 23% whilst ΔCt_2 drops by an average of 16%.

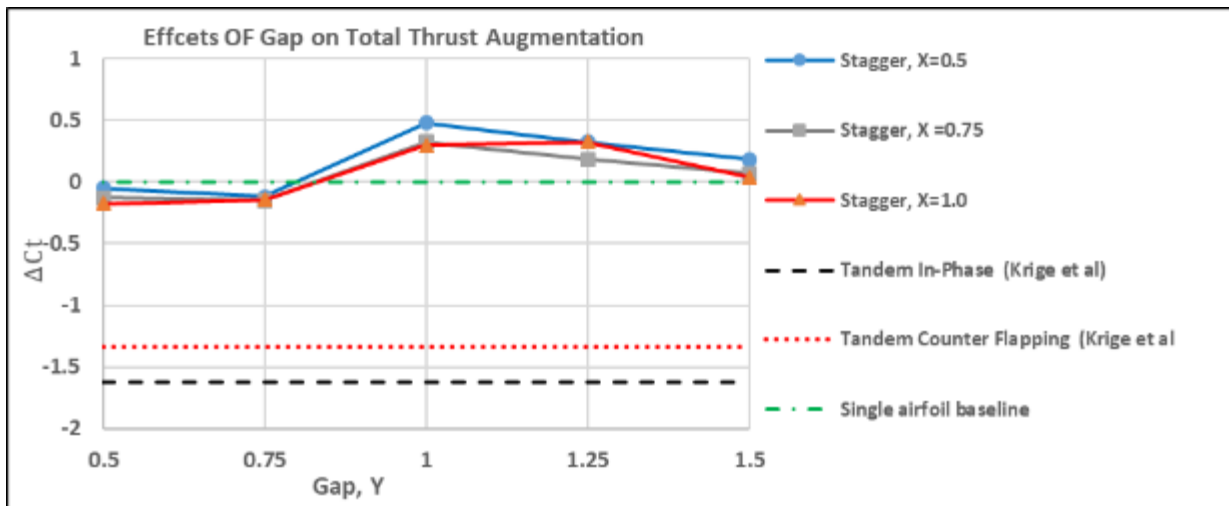


Figure 5-4: Effects of gap on stagger and gap counter-flapping ΔC_t .

The decline of the thrust curve slope at larger gaps is attributable to little wing-wing interaction at large spacing resulting in the airfoils beginning to behave more independently of each other. This is consistent with Nguyen et al who optimized a Busemann airfoil and discovered that bottom airfoil contribution to aerodynamic performance is almost constant for large spacing [46].

Lift augmentation characteristics for a stagger and gap configuration are shown in Figure 5-5 and Figure 5-6 below. It is notable that ΔC_{l1} and ΔC_{l2} are affected differently by changes in gap.

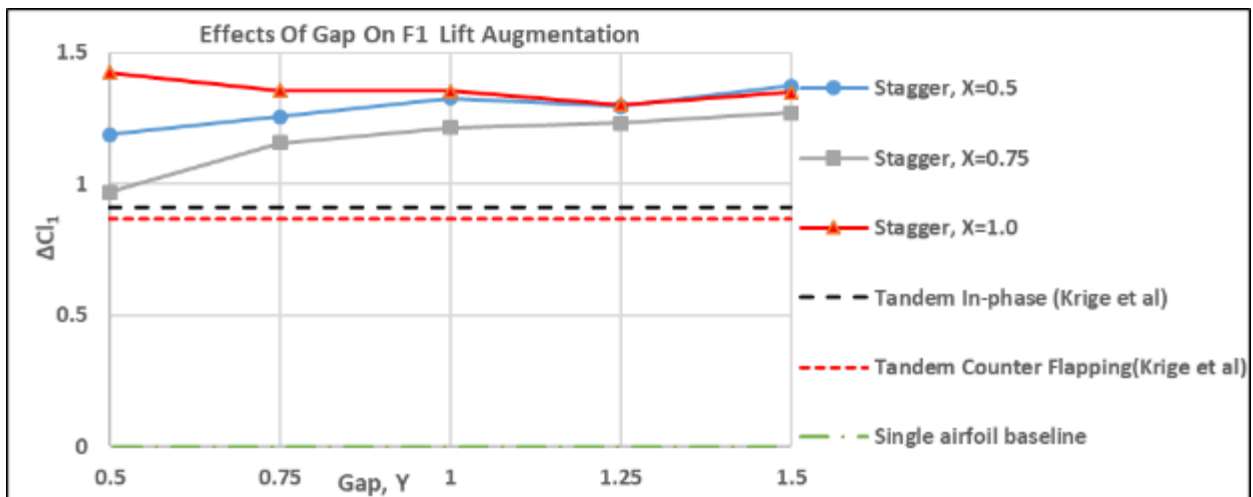


Figure 5-5: Effects of Gap on stagger and gap counter-flapping ΔC_{l1} .

ΔC_{l1} is less affected by changes in gap as in the range $0.5C \leq \text{gap} \leq 1.5C$ it increases by an average of 11% for all the stagger values. On the other hand, ΔC_{l2} is relatively constant for $0.5C \leq \text{gap} \leq 0.75C$ before increasing to peak at $\text{gap} = 1.0C$. Larger gaps are less

favourable to the aft and consequently total lift augmentation as beyond gap=1.0C ΔCl_2 drops by an average of 31% as shown in Figure 5-6 and Figure 5-7 below.

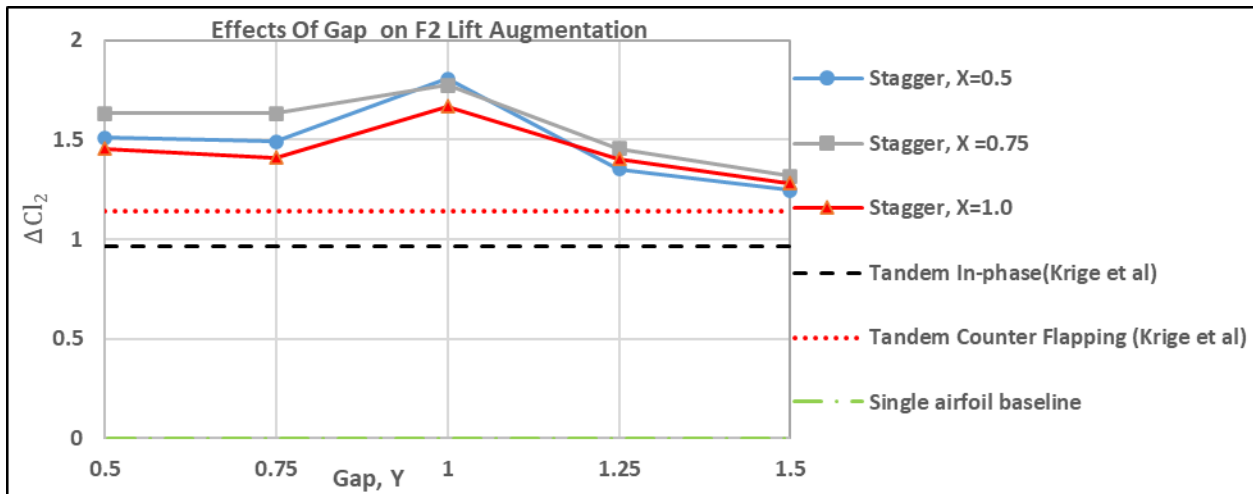


Figure 5-6: Effect of gap on stagger and gap counter-flapping ΔCl_2 .

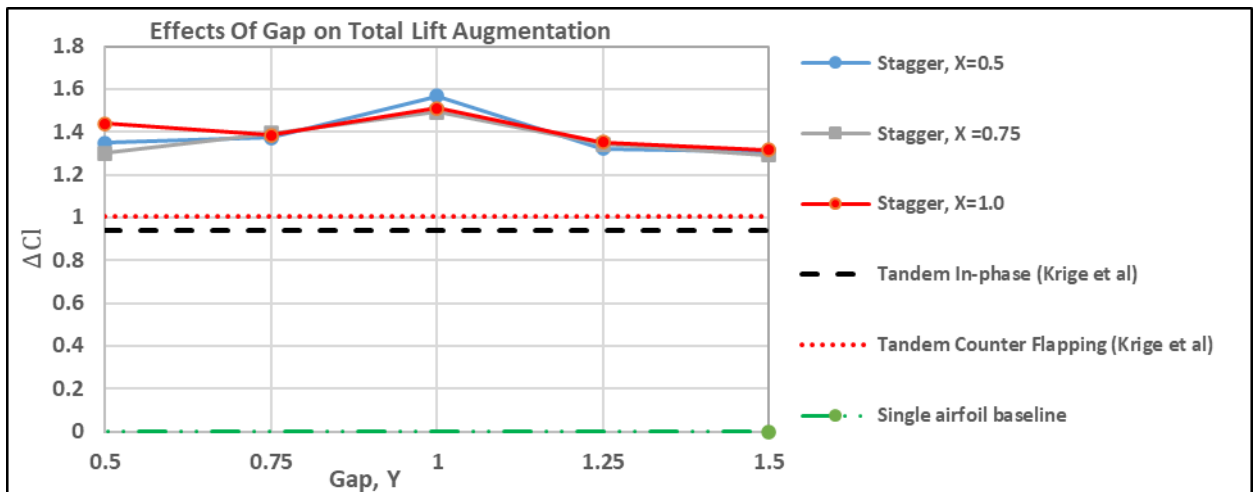


Figure 5-7: Effect of gap on biplane counter-flapping ΔCl .

The lift performance for all cases is greater than that of single and tandem in-phase cases. The maximum lift is between 2.4 times more than single airfoil thrust.

5.2. EFFECT OF STAGGER

In this section the effects of changing stagger are investigated. The gap is held constant at various values from 0.5C to 1.5C. It is observed that for each airfoil a change in stagger that brings thrust increase does so at the expense of lift production and vice-versa.

Thrust vs stagger characteristics are plotted in Figure 5-8 to Figure 5-10 below. At Y=0.75C the fore foil produced less thrust than a single airfoil for all stagger values.

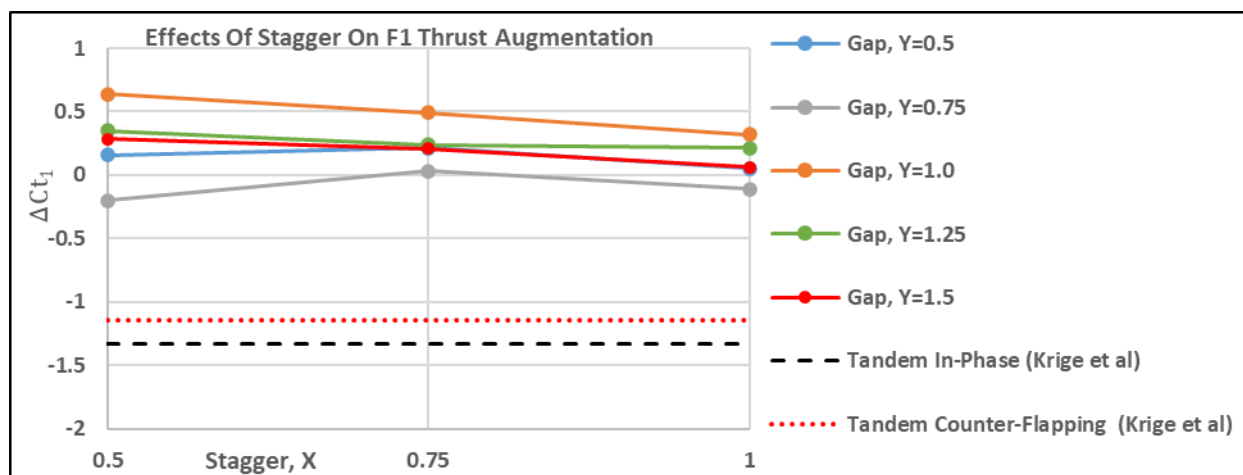


Figure 5-8: Effects of stagger on stagger and gap counter-flapping ΔC_{t1} .

The statement was corrected to read - By increasing stagger from 0.5C to 0.75C the increase ΔC_{t1} is cancelled by the drop in ΔC_{t2} . This results in ΔC_t dropping between 8.5-10%. However further increasing the stagger from 0.75C to 1.0C leads to ΔC_{t1} dropping and ΔC_{t2} increasing. Consequently ΔC_t changes by -2.4-8%.

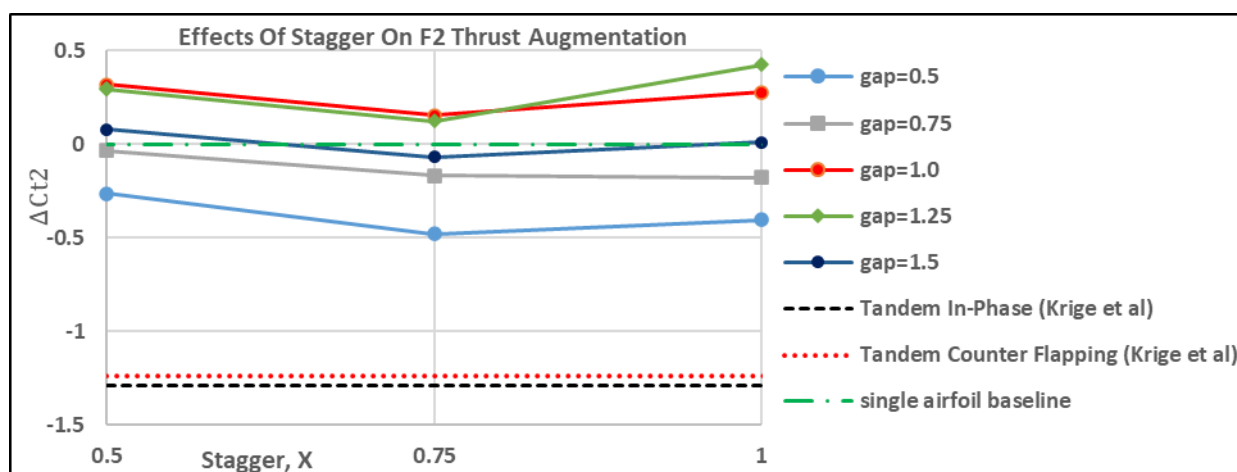


Figure 5-9: Effects of gap on stagger and gap counter-flapping ΔC_{t2} .

When the gap is less than $1.0C$ increase in stagger doesn't bring significant thrust augmentation. Overall thrust performance remains worse than that of a single airfoil.

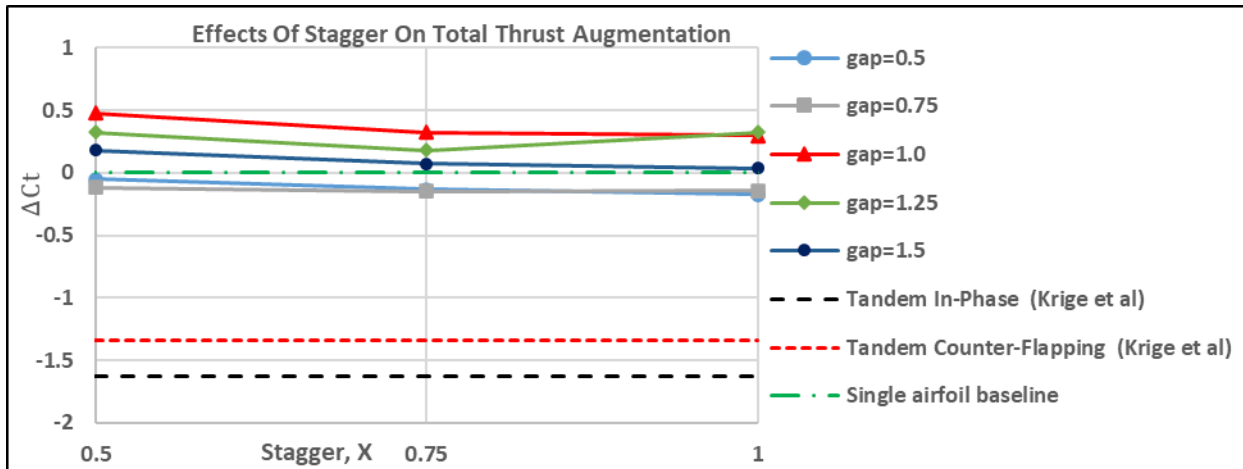


Figure 5-10: Effects of stagger on stagger and gap counter-flapping ΔC_t .

Figure 5-11 to Figure 5-13 below show the lift augmentation-stagger characteristics. ΔC_{l1} and ΔC_{l2} are affected in extremely opposite ways by changes in stagger. As stagger is increased from $0.5C$ to $0.75C$ the drop in ΔC_{l1} cancels out the increase ΔC_{l2} resulting in almost flat lift-slopes as shown in Figure 5-13 below. For $Y=0.5$ ΔC_{l1} drop by 22% as ΔC_{l2} increase by 18% whilst the total lift drops 5.8%.

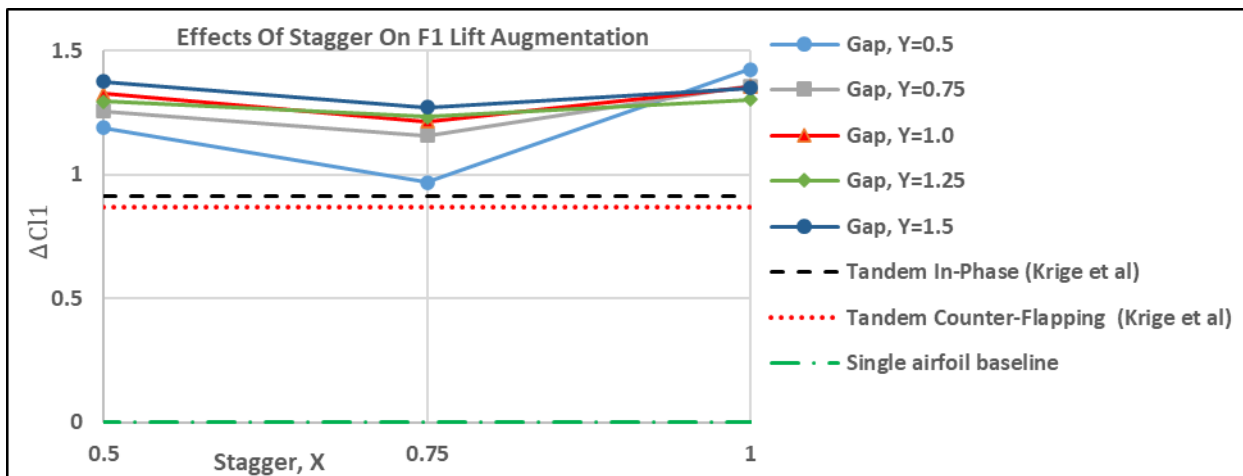


Figure 5-11: Effects of stagger on stagger and gap counter-flapping ΔC_{l1} .

For gap= $0.75C$ ΔC_{l1} drops 8%, ΔC_{l2} increases by 22% and ΔC_l decreases by 2.4%. At gaps of $1.0C$, $1.25C$ and $1.5C$ ΔC_{l1} drop by 8%, 6% and 7% respectively. ΔC_{l2} changes by -1.8%, 8% and 9% respectively. This results in changes of -7%, 2.6% and 2% in ΔC_l respectively.

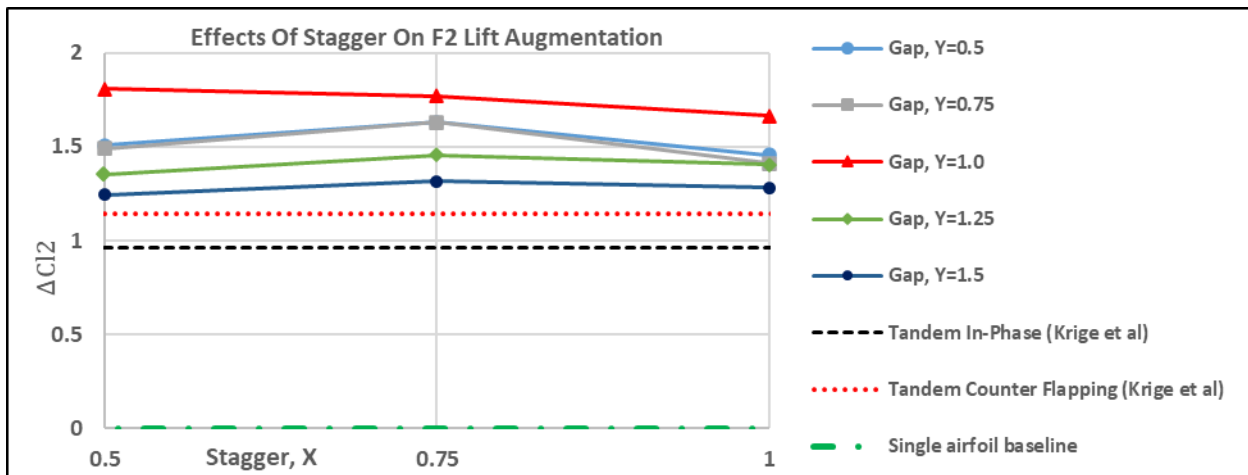


Figure 5-12: Effect of stagger on stagger and gap counter-flapping ΔCl_2 .

As stagger is increased from 0.75C to 1.0C the total lift generally increases with stagger for gap. Overall lift characteristics show almost flat slopes due to increase in ΔCl_1 being almost equal to the magnitude of drop in ΔCl_2 as shown in Figure 5-13 below.

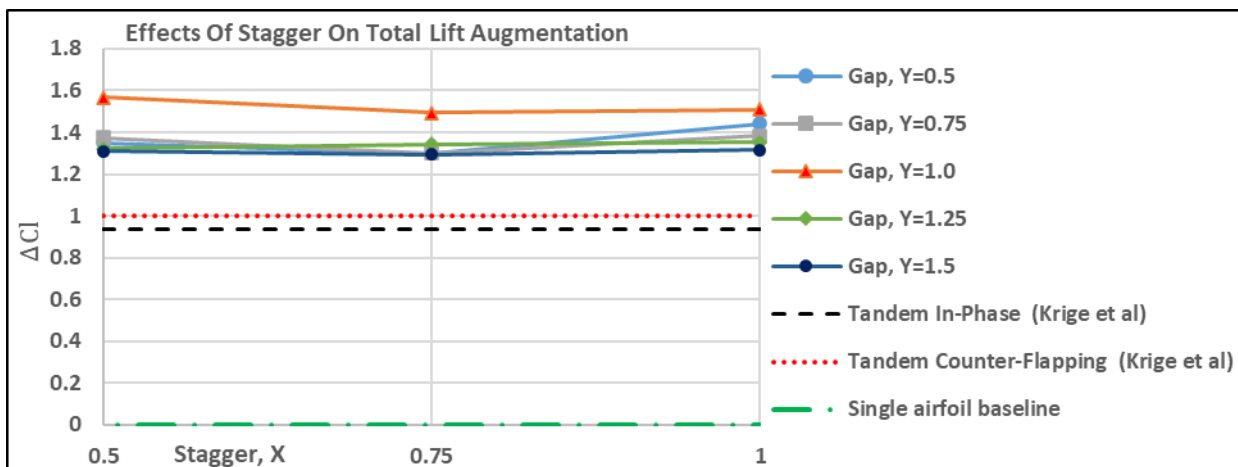


Figure 5-13: Effect of stagger on stagger and gap counter-flapping ΔCl .

ΔCl_1 rate increases by 29%, 17% and 12%, for gaps 0.5C, 0.75C and 1.0C respectively whilst ΔCl_2 decreases by 11%, 10% and 6%. At gap = 1.0C and gap = 1.25C, ΔCl_1 increases by 5% and 6% as ΔCl_2 decreases by 4% and 3%. This leads to an almost constant ΔCl changing by 6.6%, 1.8%, 1.7%, 1% and 2.7% respectively.

5.3. STAGGER AND GAP COUNTER-FLAPPING AIRFOILS FLOW ANALYSIS

The observed force behavior is here explained by analyzing the intricate vortices and pressure dynamics. Lift generation can be explained by Bernoulli's principle, Newton's third law and vortex behavior.

During instroke the area between the leading edges at the inlet is reduced as shown in Figure 5-14 below. This creates an orifice effect whereby fluid between the foils is accelerated and the pressure in the region decreases.

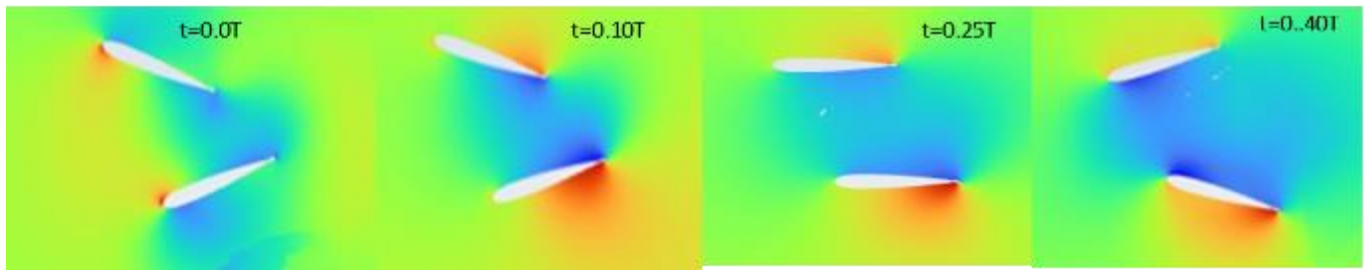


Figure 5-14: Pressure contours during in-stroke

Differential pressure decreases for the top airfoil (F1) and increases for the bottom airfoil (F2) therefore F1 lift decreases and F2 lift increases.

Since the airfoil is pitching about the point $x=0.25C$. During instroke F2 is pitching-up and the larger area behind the pitching point exerts a downward force on the fluid below as it pushes down. According to Newton's third law of motion the fluid also exerts an upward force (buoyance) on F2 bottom surface resulting in lift augmentation. This is illustrated in Figure 5-15 below.

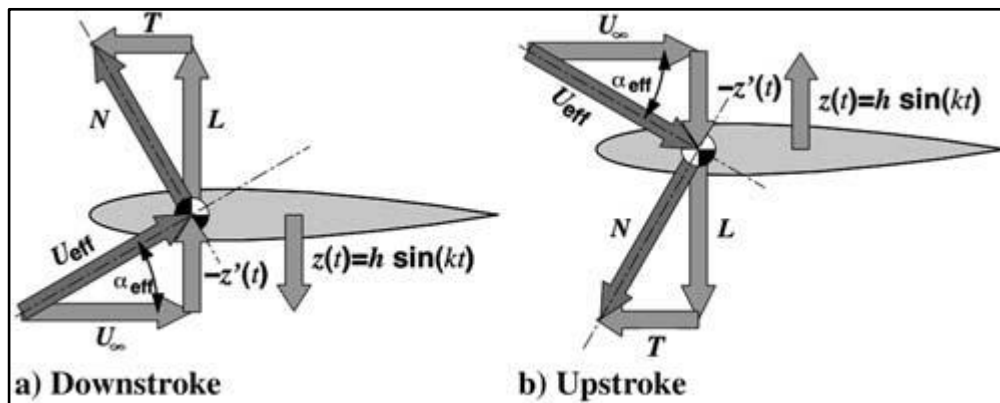


Figure 5-15: Lift generation illustration by Newton's third law.

As F1 pitches-down the larger area behind the pitching point exerts an upward force on the fluid below as it pushes up resulting in the fluid also exerting a downward force F1 top. This results in F1 lift dropping.

The opposite happens during out-stroke.

During outstroke the area between the leading edges at the inlet increases and the fluid is decelerated between the foils. The pressure in the region increases resulting in, as illustrated in Figure 5-16 below, differential pressure increase for F1 and decrease for F2 therefore F1 lift increase and F2 lift drop.

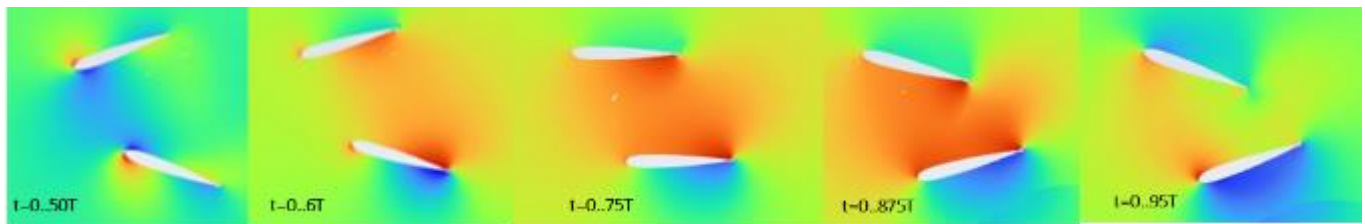


Figure 5-16: Pressure contours during out-stroke

The peak / trough values are reached at close to $t=0.5T$.

The vorticity diagrams for case 1 (small stagger, small gap, most lift), case 3 (small stagger, large gap, most thrust, most lift) and case 11 (large stagger, small gap, least thrust) are shown in Figure 5-17 below. Features from the previous cycle such as B1, C1 and A2 are present at the onset of instroke.

F1 and F2 are always in opposite incidences of position and direction of motion and two dipoles made of two pairs of LEVs & TEVs of opposite rotation move downstream with momentum thus giving continuous rise to the suction region in F2 LE. This suction gives rise to increase in F2 thrust and improved aerodynamic performance compared to a single airfoil where a single vortex street is observed. A larger pressure difference is experienced by airfoils in stagger and gaps compared to a single airfoil.

At $t=0.00T$ the vortices structures on the top side of the F1 are identical. Slight differences show as the motion progresses. F1 top LEV is strongest in Case 1 and weakest in Case 11. This is because the transient behavior of the flow can be altered by introducing a body closer to the airfoil. The area between the airfoils at the inlet influence the velocity profile and therefore the pressure distribution downstream. For a small spacing (case 3) the fluid is accelerated more than for a larger therefore case 3 has a larger pressure suction area on the LE edge.

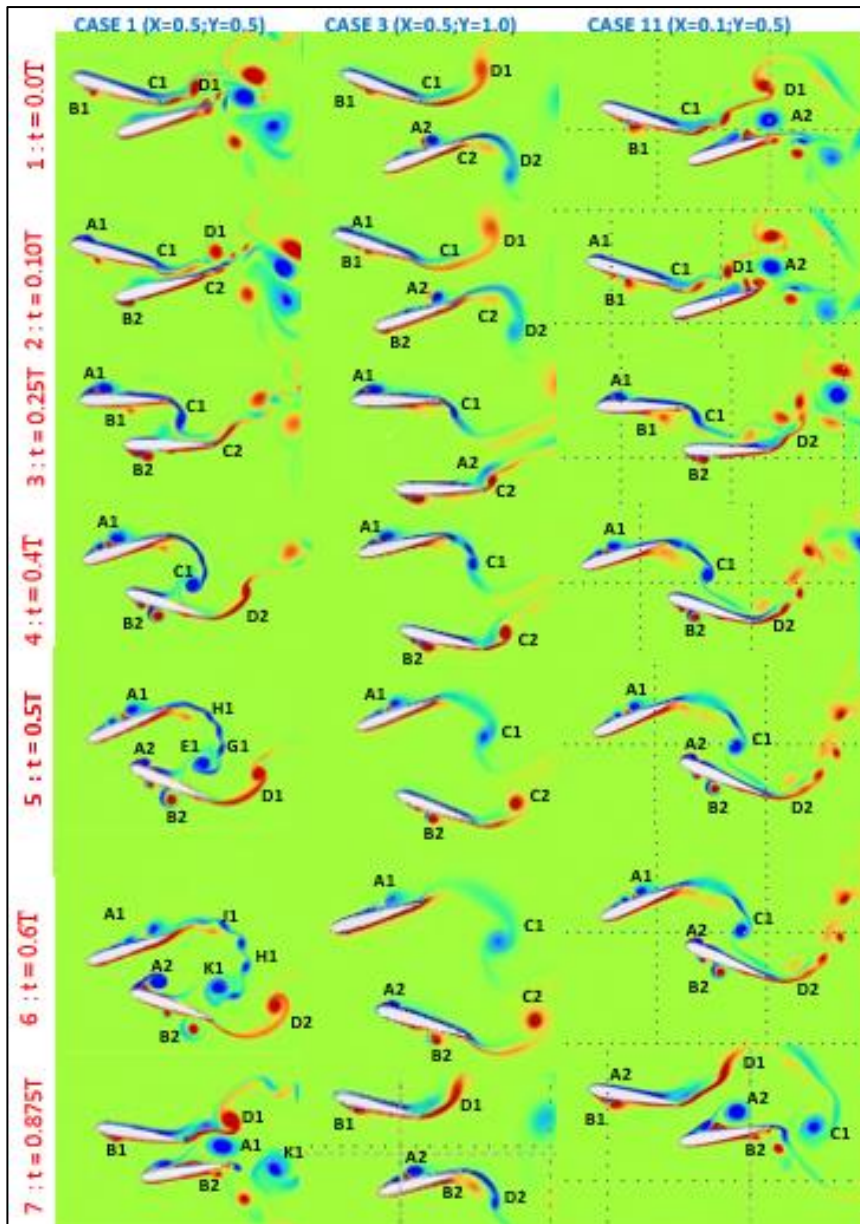


Figure 5-17: Stagger and gap counter-flapping vorticity diagrams.

In all cases, for both foils, positive and negative vortices streams are seen to form on the top and bottom surfaces respectively. These roll downstream into rear vortices such as C1, C2, D1 and D2. Spacing greatly influence the formation and subsequent progression of these LE features A1, B1, A2 and B2. These start growing between $t=0.1T$ and $t=0.25T$ leading to C_{L1} increase and C_{L2} drop as further clarified by time plots for C_t and C_l time plots in Figure 5-18 to Figure 5-20 below.

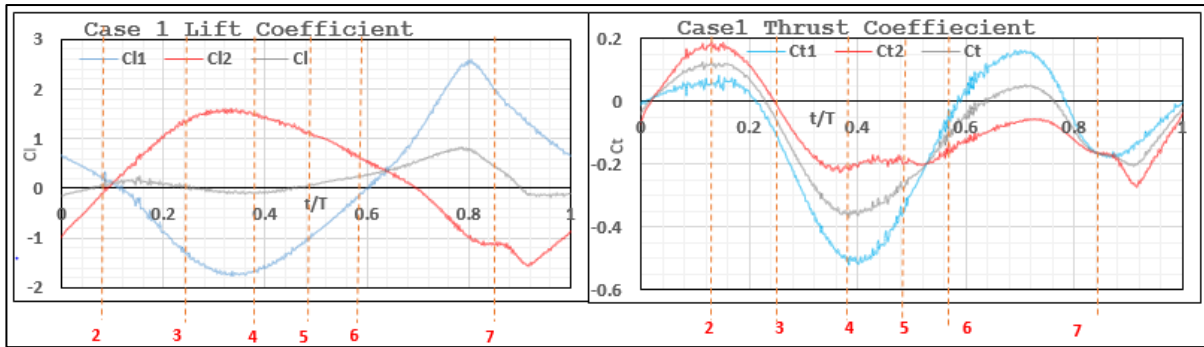


Figure 5-18: Case 1 Lift and thrust coefficients time plot

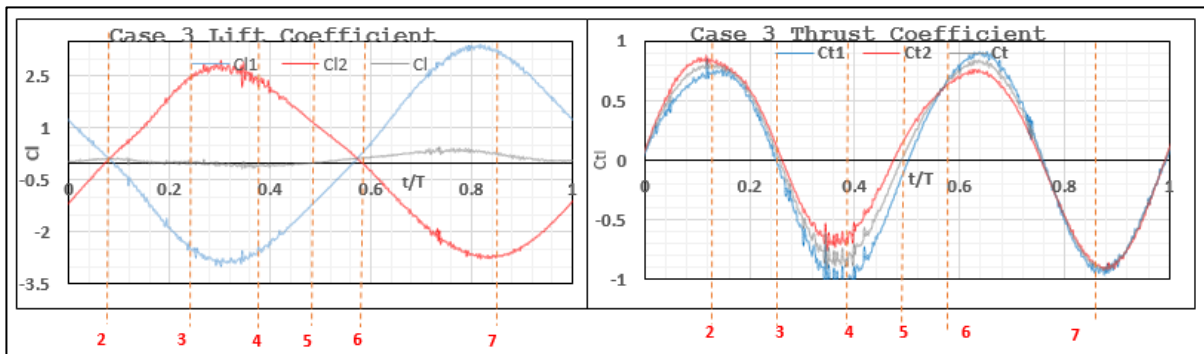


Figure 5-19: Case 3 lift and thrust coefficients time plots

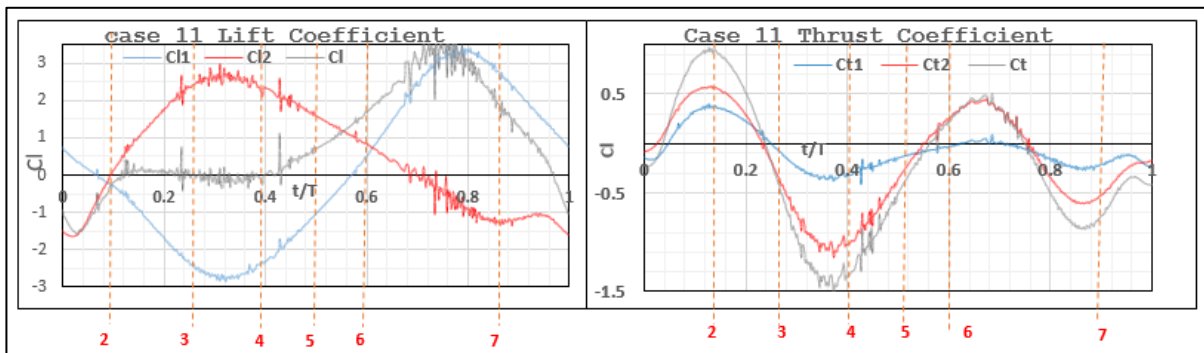


Figure 5-20: Case 11 lift and thrust time plots

Deriving from the size of A1 is larger in Case1 and Case 3 than Case 11 it can be deduced that small stagger values enhance the formation and growth of F1 top LE features. For all the cases negative feature B2 is always in contact with F2 bottom surface as it rolls downstream leading to further drop in F2 lift.

Between $t=0.25T$ and $t=0.375T$, lowest lift values are recorded for F1 in all the cases. F1 TE positive feature, C1, are shed near the middle of F2 upper surface in Case 1 and near the F2 LE in case11. This results in F2 being affected differently for both cases producing 75% of the total thrust in case 1 compared to 28% in case 11. In Case 3 C1 has little interaction with F2 because of the large gap resulting in F1 and F2 producing almost equal thrust with F2 producing 55% of the total thrust. It is noted that equal dipole features develop with F1 shedding the positive ones and F2 the negative. The stagger and gap

counter-flapping effect is evident with both foils producing opposite but equal lift values, thus resulting in close to zero total lift.

In cases 1 and 11, A2 start to grow at $t=0.5T$ and this is marked by Cl_1 and Cl_2 crossing over each other. A2 has much more momentum in Case 1 compared to Case 11. However, for case 3 it is much weaker. At this moment for cases 1 and 13 the lamina separation bubble burst as the pressure gradient increases. This is leading edge stall. For both cases as the low pressure LEV grows lift and thrust increase up to a stall point, after which they fall dramatically. For case 1 the separated shear layers do not re-attach to the airfoil surface however they roll up into bigger E1. The two separated bubbles are similar in structure and progression to those observed by Gharali and Johnson [47] and Lee and Gerantakos [16]. It is also important to note that in case 3 A2 doesn't separate from F2 surface as it rolls downstream. This confirms absence of stall in Case 3 F2. Theoretically the most effective stagger would be the one which suppress flow separation as shown in Figure 5-21 below as this increases the lift of the aft airfoil.

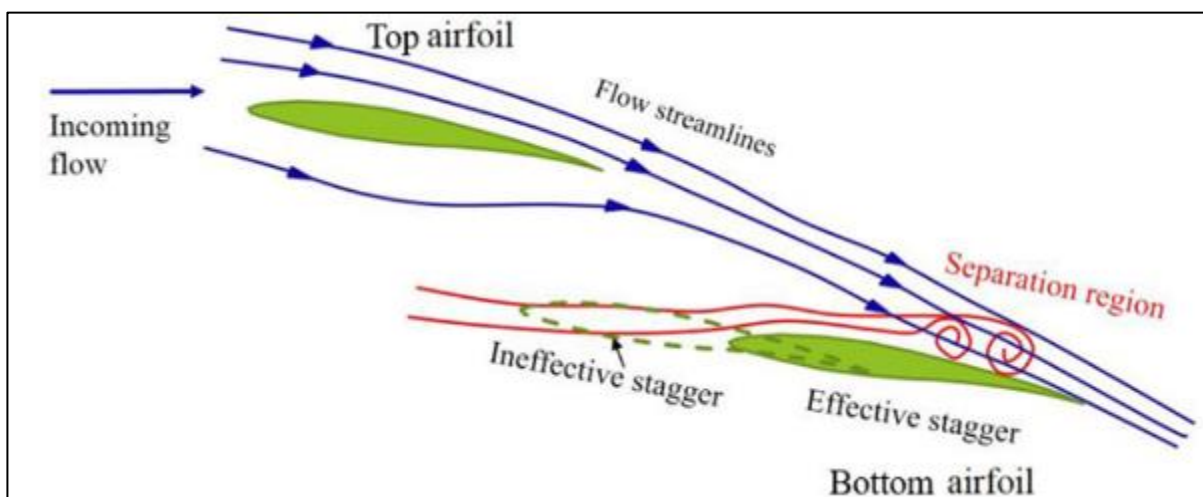


Figure 5-21: Suppression of flow separation hypothesis

Similar to observations by Shen & Cai [48] it is observed that due to the 180-phase flapping foils have better ability to recapture LE vortices from the previous stroke. As F2 is pitching downwards a positive feature detached from the top lamina sheet progresses downstream where it joins with C1 to form a larger E1. Together with G1 these roll up into a greater momentum feature K1 resulting in a large suction region near the TE. However, an E1-like feature is absent in cases 3 and 11 and subsequently F1 produces only 32% of the drag produced during in-stroke. In case 11 the separated feature is further from F1 surface compared to Case 1 and it therefore has little interaction with F1 shed vortices as it does in Case 1 where it bounces on F2 resulting in a momentarily thrust drop. For both Case 1 and Case 11 the maximum thrust is less than the maximum drag magnitude. The same

trend is observed for tandem foils by Broering & Lian [49], Krige [1] and in dragonfly-inspired corrugated airfoil [7].

5.4. EFFECT OF PHASE DIFFERENCE

The selected stagger and gap cases are further run on varying phase difference. Each case begins with F1 LE at the highest position from the horizontal (down-stroke). For the sake of simplicity up-stroke is taken to commence when F1 LE is at the lowest position from the horizontal. Phase angle is positive when F1 is in the lead and is varied from -45° to 135° whilst stagger and gap are held constant.

The cases are listed in Table 5-1 below. The instantaneous force plots for all the cases are shown in Appendix I to Appendix M.

Table 5-1: Case setup & parameters for variable ϕ

CASE	STAGGER	GAP	ϕ
16	0.5	0.5	-45
17	0.5	0.5	0
18	0.5	0.5	45
19	0.5	0.5	90
20	0.5	0.5	135
21	0.5	1	-45
22	0.5	1	0
23	0.5	1	45
24	0.5	1	90
25	0.5	1	135
26	1	0.5	-45
27	1	0.5	0
28	1	0.5	45
29	1	0.5	90
30	1	0.5	135

Figure 5-22 to Figure 5-24 below illustrate the effects of phase difference between the airfoils on thrust generation. Similarly to findings by Broering et al [49], thrust production is highly sensitive to changes in phase angle and maximum force generation occurs at different phase angles, for different spacing. Case 26 and 30 have highest and lowest performance respectively.

ΔCt_1 and ΔCt_2 show similar trend with change in phase difference. As phase angle is increased they generally both drop to a minimum. For all the phase angles F1 outperformed the tandem airfoils. Stagger and gap arrangement proved to benefit the fore airfoil thrust performance only at $\phi = 180^\circ$ where it produced between 1.2 to 1.6 times more thrust than a single airfoil. For the smallest spacing ($X=0.5C$; $Y=0.5C$) F1 thrust performance was found to be the same as a single airfoil between $\phi = -45^\circ$ and $\phi = 0^\circ$. The least ΔCt_1 was observed at $\phi = 90^\circ$ where F1 produced 83-88% thrust less than a single airfoil. At $\phi = 45^\circ$ and $\phi = 135^\circ$ for all the cases F1 tend to produce almost half the thrust produced by a single airfoil ($\Delta Ct_1 \approx -0.5C$) in contrast to the rest of the cases where an increase in spacing leads to drop in ΔCt_1 .

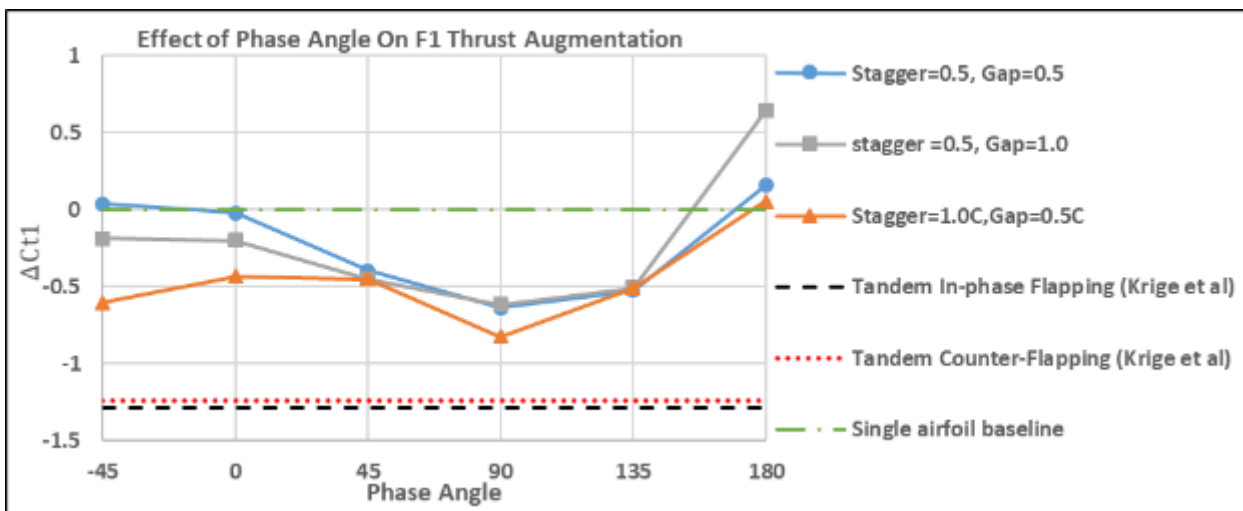
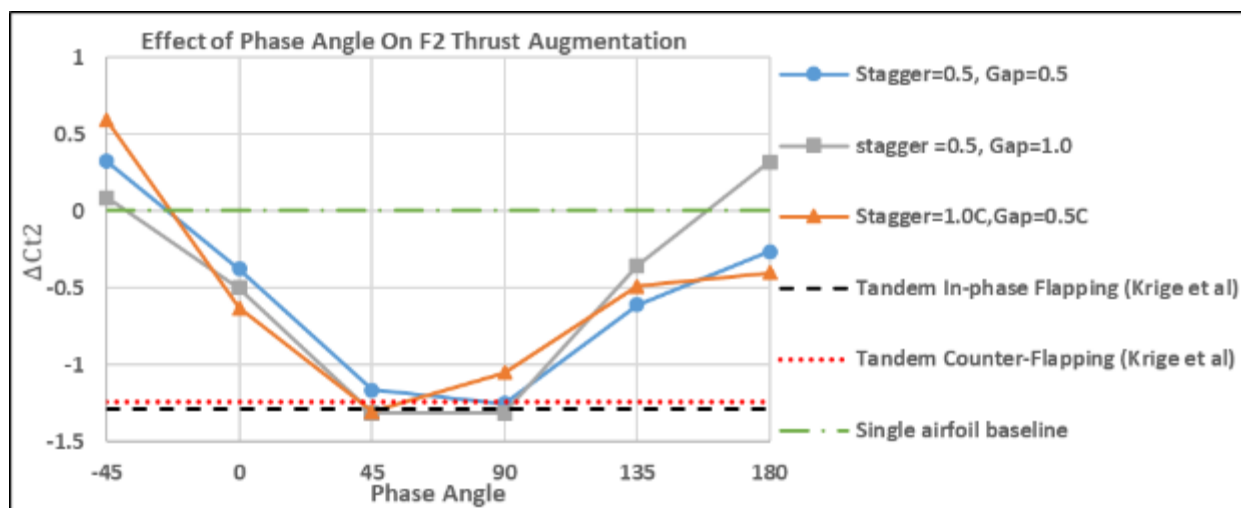
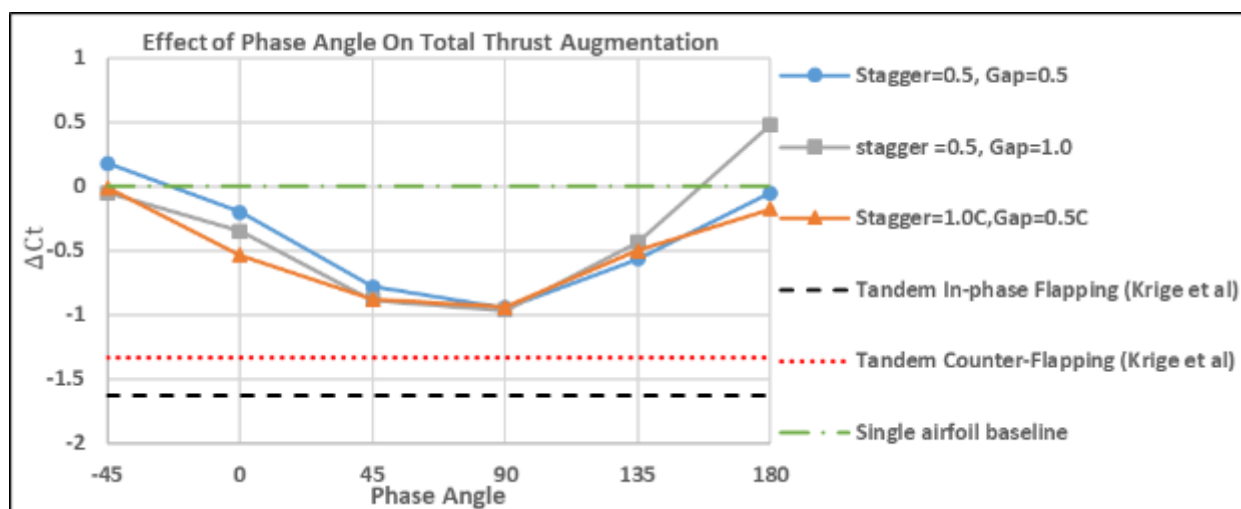


Figure 5-22: Effect of ϕ on Ct_1

Figure 5-23 below shows that at the worst F2 thrust performance is almost equal to that of tandem airfoils at $\phi = 45^\circ$ and $\phi = 90^\circ$. Optimal thrust performance is obtained at $\phi = -45^\circ$ for $Y=0.5C$. However, for $Y=1.0C$ the counter-flapping case produces the most ΔCt_1 , 13% more than a single airfoil. For in-phase flapping increasing spacing leads to drop in F2 thrust performance.

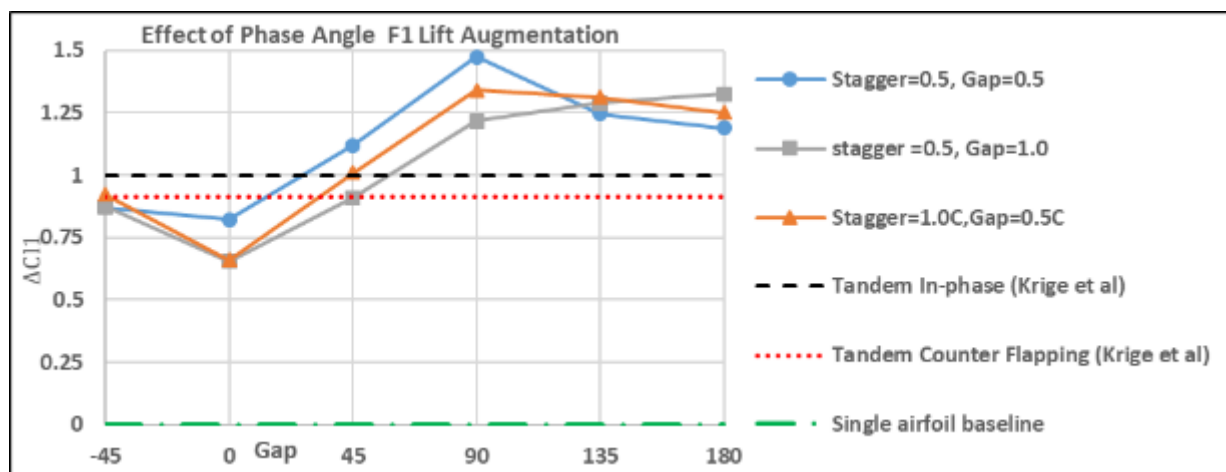
Figure 5-23: Effects of ϕ on Ct_2

A closer look at Figure 5-23 and Figure 5-24 further shows that the phase leading airfoil has more influence on the total thrust than the follower. F2 produced 57-84% of the total thrust at $\phi = -45^\circ$. For in phase flapping it produced 38-39% for all the cases. Between $\phi = -45^\circ$ and $\phi = 90^\circ$ it contributes 20% to the overall thrust. This increases to 47-58% at $\phi = 135^\circ$. For the cases under consideration F2 produces 37-45% of the overall thrust during counter-flapping ($\phi = 180^\circ$).

Figure 5-24: Effects of ϕ on ΔCt

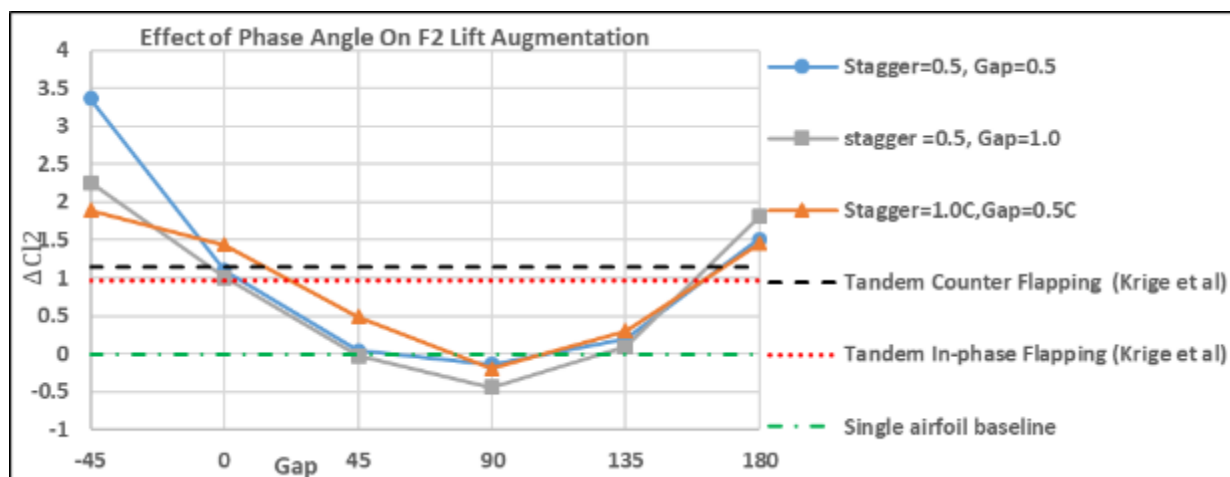
Even at low Strouhal number counter-flapping remains the most effective for thrust production especially at smaller staggers and gaps compared to tandem in-phase and counter-flapping. 90 degrees' phase angle is the worst for overall thrust production.

Figure 5-25 below shows that in stagger and gap F1 produces between 1.6 and 2.4 times more lift than a single airfoil. When phase angle is increased from -45° Cl_1 drops to a minimum at $\phi = 0^\circ$.

Figure 5-25: Effects of ϕ on ΔCl_1

In-phase flapping produces 1.6-1.8 times more lift than a single airfoil. Change in phase angle from $\phi = 0^\circ$ leads to Cl_1 sharply increases to a maximum at $\phi = 90^\circ$. F1 lift tend to decrease with gap for $\phi \leq 90^\circ$, further galvanizing the findings that the introduction of the lower airfoil does have great influence on the top airfoil. At $\phi = 135^\circ$ F1 lift tend to converge to the same value ($\Delta Cl_1 \approx 1.25$) for all the cases.

Figure 5-26 below shows that the aft airfoil produces the most lift when it is leading. At $\phi = -45^\circ$ the airfoil produces ΔCl_2 between 1.8 to 3.4. When phase angle is increased ΔCl_1 drops to a minimum at $\phi = 90^\circ$ where it produces almost half the lift produced by a single airfoil. It is also notable that F2 out-performed the tandem airfoils only at $\phi = -45^\circ$ and at $\phi = 180^\circ$.

Figure 5-26: Effects of ϕ on ΔCl_2

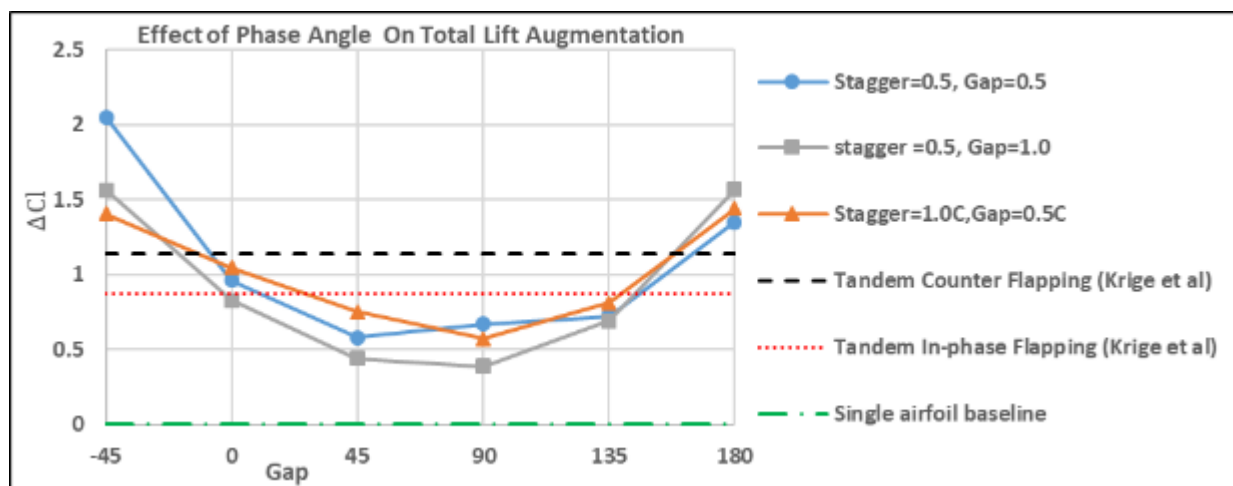


Figure 5-27: Effects of ϕ on ΔCl

Figure 5-27 shows that F2 influences total lift more than F1 does. The cases with the hind-foil in the lead produced more lift with an augmentation of 1.4-2.2 times more than twice the lift produced by a single airfoil. For all the phase angles the stagger and gap produced more lift than a single airfoil, however it only $\phi = -45^\circ$ and at $\phi = 180^\circ$ out-performed the tandem airfoils.

To analyze the flow, it is vital to first visualize the variation of each airfoils position with time. The F2 LE instantaneous position for each case with reference to the horizontal is shown in Figure 5-28 below.

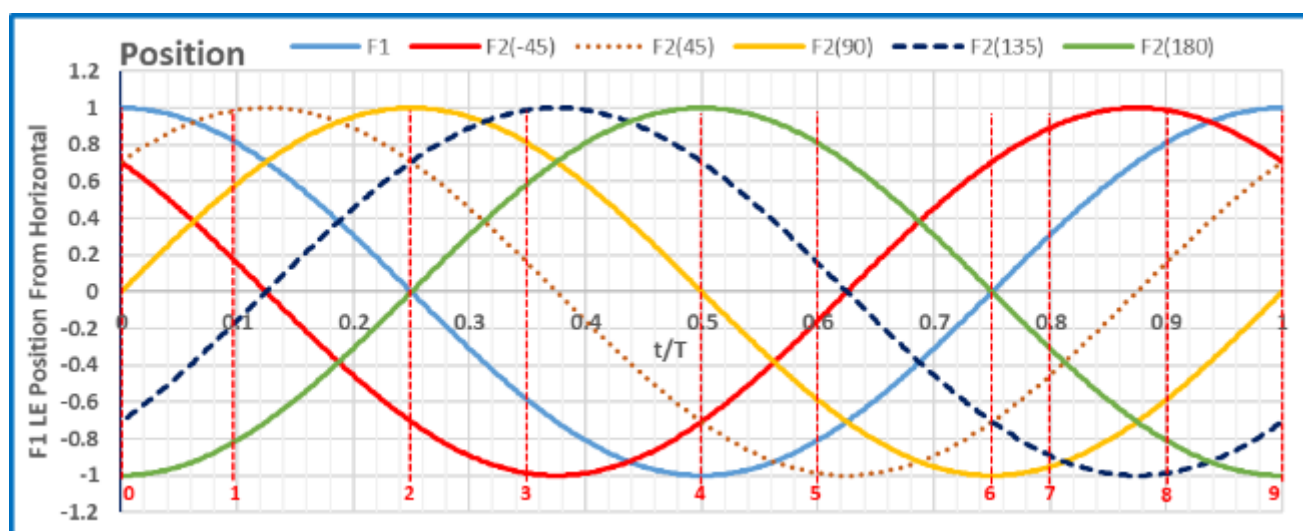


Figure 5-28:LE positions from the horizontal:

Each case begins with F1 LE at the maximum position above the horizontal. For in-phase flapping F2 LE and F1 LE positions are identical (both represented by the blue line). The differences in position and direction between two aft airfoils at any given time determines the timing and nature of interaction with shed features from upstream.

The depicted flow phenomena during downstroke and upstroke, as represented in Figure 5-29 and Figure 5-30 **Error! Reference source not found.** respectively, are intricately influenced by the phase angle parameter. Phase angle significantly impacts the turbulence characteristics upstream by influencing the effective gap between the leading edges (LE) of the airfoils at the initiation of the downstroke phase. This is evidenced by differences in leading edge (LE) features for cases with phase angles of $\phi = -45^\circ$ and $\phi = 90^\circ$. Figure 5-29 provides a snapshot of this phenomenon at $t=0.0T$ (the beginning of a cycle). In this context, it is evident that the cases with a phase angle of $\phi = 90^\circ$ (Cases 19 and 29) exhibit a larger gap between their leading edges in comparison to the cases with a phase angle of $\phi = -45^\circ$ (Cases 16 and 26). This implies that the fluid located between the airfoils experiences a more pronounced acceleration for cases with $\phi = -45^\circ$ than for those with $\phi = 90^\circ$ ultimately leading to the development of more extensive suction regions in the $\phi = -45^\circ$ configuration hence the early presence of A1 and A2 features. The positioning of A2 is such that greater suction region is on F1 TE and F2 LE hence resulting in C_{t2} increase as F1 momentarily shift into drag production.

For $\phi = -45^\circ$, At $t = 0.1T$ as A2 encounters the negative vortex stream shed from F1 TE it reduces in size and vertical structure B2 separates. This separation phenomenon is shows greater prominence in Case 16 ($X=0.5C$; $Y=0.5C$), occurring between $t=0.2T$ and $t=0.375T$. In contrast, for Case 26 ($X=0.5C$; $Y=1.0C$) due to the stagger, F2 LE proximity from the F1 TE shed vertical feature C1, plays a crucial role in preventing a complete detachment of B2 from A2. In this case, B2 remains consistently attached to the upper surface of airfoil F2. Additionally, the upward motion of airfoil F2 during this phase of the stroke effectively suppresses the tendency of B2 to break away from the top surface of F2. Consequently, B2 does not fully separate from A2, as observed in counter-flapping foils. This unique interaction results in a consistently positive ΔCl in Case 26, whereas in Case 16, there is a momentary drop in ΔCl , causing it to briefly fall below zero. Furthermore, F2 in Case 26 demonstrates superior lift and thrust production compared to F1. This performance disparity is attributed to the effective suppression of vortical separation and the presence of a positively oriented shed vortex sheet C1 from airfoil F1, which significantly extends the duration of a positive change in ΔCl over time. For Case 16, B2 encounters a negative vortical feature labeled as E1 near the TE of airfoil F2, spanning from $t = 0.375T$ to $t = 0.5T$. This interaction leads to a drop thrust.

For $\phi = 90^\circ$ cases A1 start to grow at $t=0.2T$ and A2 develop at $t=0.375T$ for Case 19 and during stroke reversal for Case 29. For this part of the stroke F2 TE is moving downwards away from the vicinity of C1 therefore avoiding interaction. Simultaneously, a negative feature D2 on the bottom surface of airfoil F2 induces suction pressure.

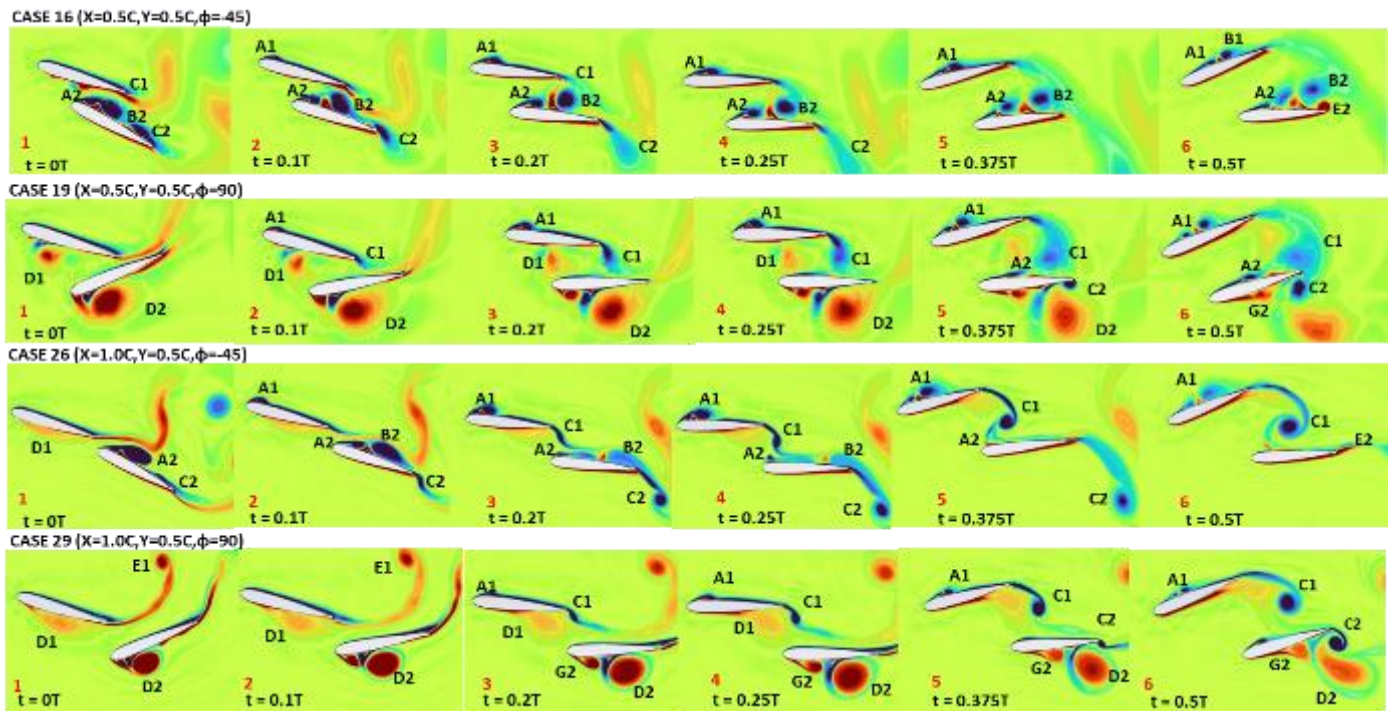


Figure 5-29: Effect of phase angle on vorticity during downstroke

This pressure gradient leads to a rapid reduction in the lift augmentation ΔCl_2 , which experiences a sharp drop. Notably, during this phase, thrust initially experiences an increase. However, this initial thrust increase is gradually mitigated starting from $t = 0.2T$ as the low-pressure region propagates toward the trailing edge.

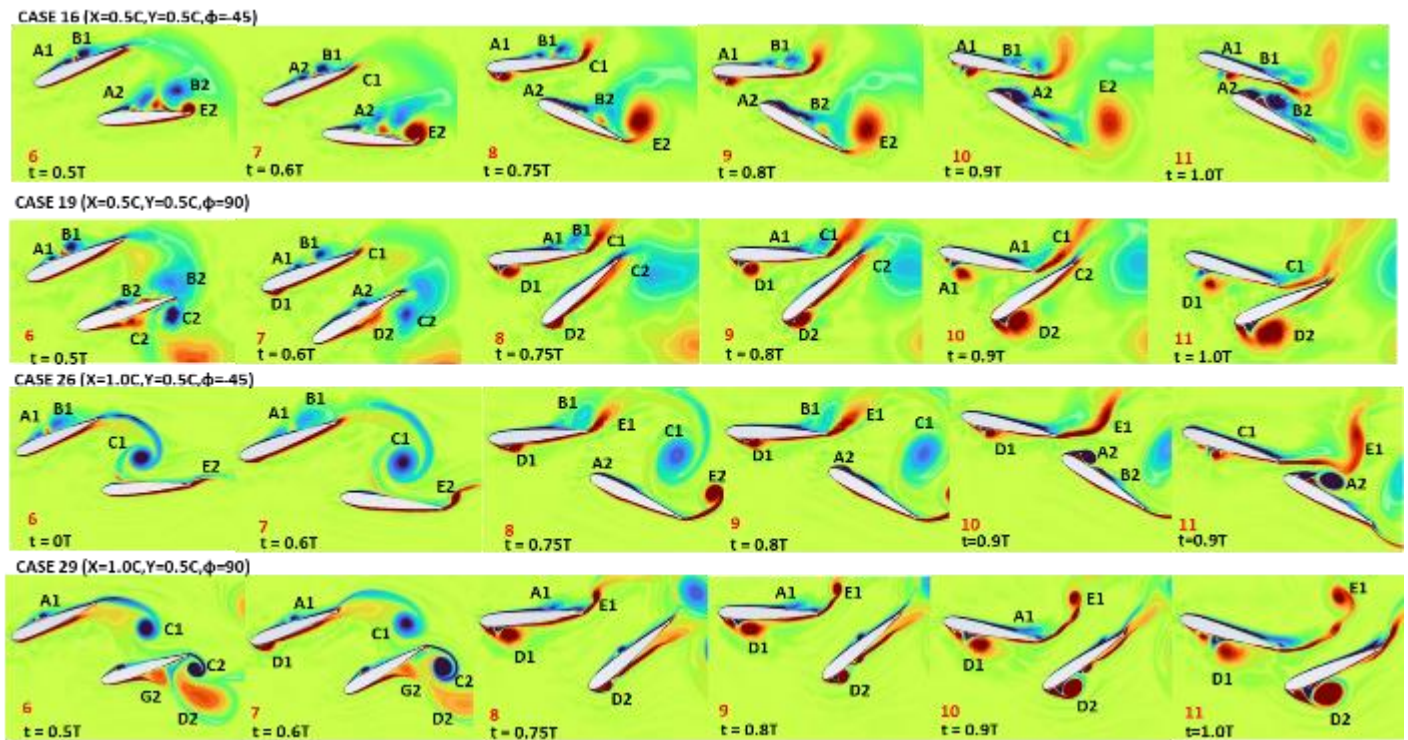


Figure 5-30: Effect of phase angle on vorticity during upstroke

For the $\phi = -45^\circ$ cases a suction region is present between the airfoils for a prolonged period. In Case 16, this phenomenon can be attributed to the presence of vortical feature A2, which was not completely shed during downstroke. In Case 26, a large C1 vortex is shed near the middle of the lower foil, F2. These vortices interact with the negative feature E2, which exhibits much greater momentum growth in Case 16 compared to Case 26.

The thrust produced by F2 continues to decrease up to $t = 0.8T$ in Case 16. However, in Case 26, the minimum thrust is shifted to $t = 0.6T$. The increase in thrust in Case 16 coincides with the shedding of E2, but this augmentation in F2 thrust does not turn positive before the end of the stroke. On the other hand, in Case 26, F2 only produces negative thrust augmentation from $t = 0.6T$ to $t = 0.85T$.

For the case with $\phi = 90^\circ$, positive features C1 and C2 are shed at the trailing edge (TE) of F1 and have greater momentum in Case 29 compared to Case 19. Negative leading-edge feature D1 begins to develop at $t = 0.6T$, followed by the emergence of D2. After shedding D2 from the previous stroke, a new D2 feature appears on the leading edge of F2 at $t = 0.75T$. ΔCl_2 and ΔCt_2 increases do not increase in Case 16 as much as they do in Case 26.

The 90° phase difference extends negative lift and thrust production periods whilst in the -45° case the positive augmentation periods are extended. The second airfoil benefits from the wake behavior upstream. The results are in agreement with Cai et al's [50] findings

who used Analysis of Variance (ANOVA) to investigate the significance of the correlations between various stagger and gap variations and aerodynamic coefficients for 2D NACA0012. It was concluded that as spacing increases the fore airfoil is hardly affected by stagger and gap whilst the aft foil is sensitive to changes in both stagger and gap.

5.5. EFFICIENCY

The efficiency characteristics for counter-flapping cases with varying gap and stagger are presented in Figure 5-31 and Figure 5-32 respectively. Additionally, Figure 5-33 depicts the variation of efficiency in relation to the phase difference between the fore airfoil (F1) and the aft airfoil (F2). Notably, it is worth mentioning that counter-flapping cases demonstrate superior efficiency compared to single and tandem airfoils. For a phase difference of 180° , as the gap is increased from $Y=0.5C$, the efficiency experiences a steady rise (between 25-34%), reaching its peak at $Y=0.75C$ for all stagger configurations. It is noteworthy to highlight the distinctive efficiency peaks observed: the lowest peak efficiency of 0.46 is observed at stagger= $0.75C$, while the highest peak efficiency of 0.49 occurs at stagger= $1.0C$. However, a notable transition occurs when the gap is further increased to $1.0C$, a subsequent decrease in efficiency by approximately 12.24% and 10.87% for $X=0.5C$ and $X=0.75C$ respectively occurs. In contrast for $X=1.0C$ the efficiency change is minimal, at approximately -1.08%. Nonetheless, when the gap is further increased from $1.0C$ to $1.25C$, efficiency experiences a sharp decline, averaging at a significant 33% reduction. When gap is increased from $1.0C$ to 1.25 efficiency sharply decreases by an average of 33%. This larger gaps are detrimental to efficiency primarily due to the attenuation of wake-wake. Beyond this, the efficiency remains relatively constant, suggesting that incremental increases in gap size no longer yield substantial improvements in aerodynamic efficiency.

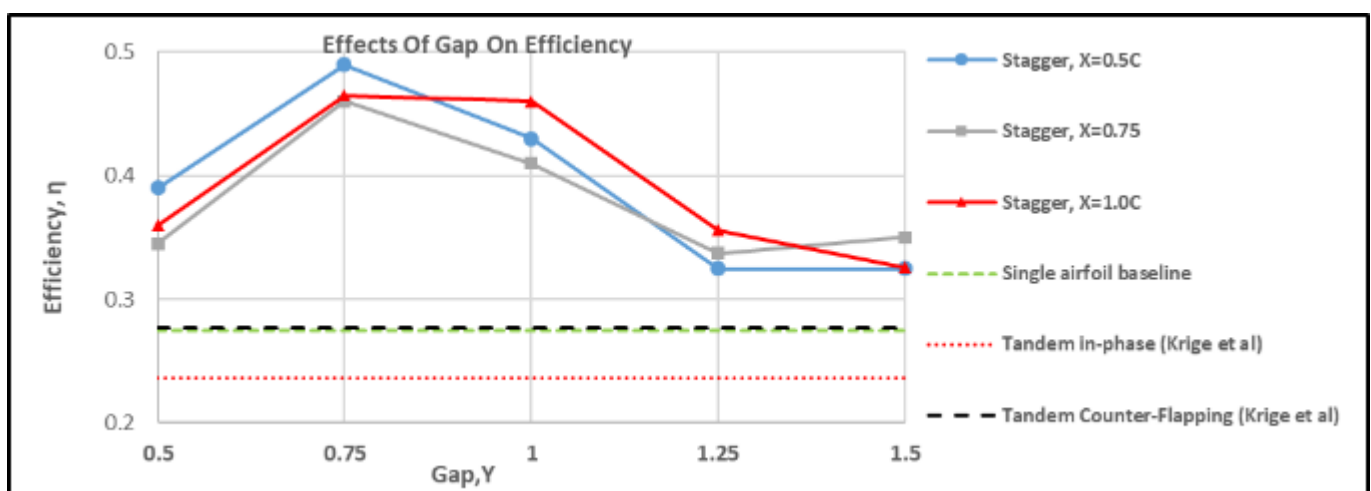


Figure 5-31: Efficiency variation with gap.

Figure 5-32 below illustrates the relationship between efficiency and stagger configurations. Within the range of stagger values spanning from $0.5C$ to $0.75C$, it becomes apparent that efficiency experiences a notable decrement, with reductions of 43%, 26%, and 47% observed for respective gaps of $0.5C$, $0.75C$, and $1.0C$. Conversely, when stagger is increased from $0.75C$ to $1.0C$, efficiency change is minimal for $Y=0.5C$ and $Y=0.75$, increasing 1.1% and 4.3% respectively. However, for $Y=1.0C$ efficiency registers and increase of 12%.

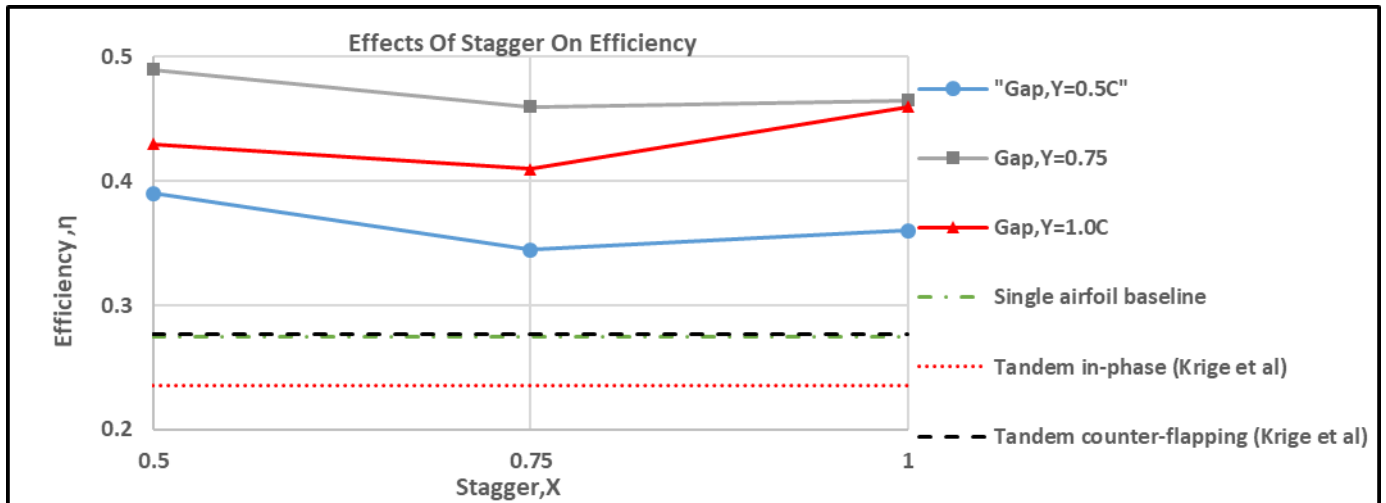


Figure 5-32: Efficiency variation with stagger.

As shown in Figure 5-33 below it is observed that for the given Strouhal number and spacing parameters considered in this study, stagger and gap counter-flapping exhibits superior efficiency compared to both single and tandem airfoils. This is particularly notable for in-phase flapping, counter-flapping cases and when the aft airfoil is leading in phase ($\phi = -45^\circ$). The highest efficiency is recorded for $\phi = -45^\circ$. While the $\phi = 45^\circ$ and $\phi = 90^\circ$ cases comparatively the least efficient.

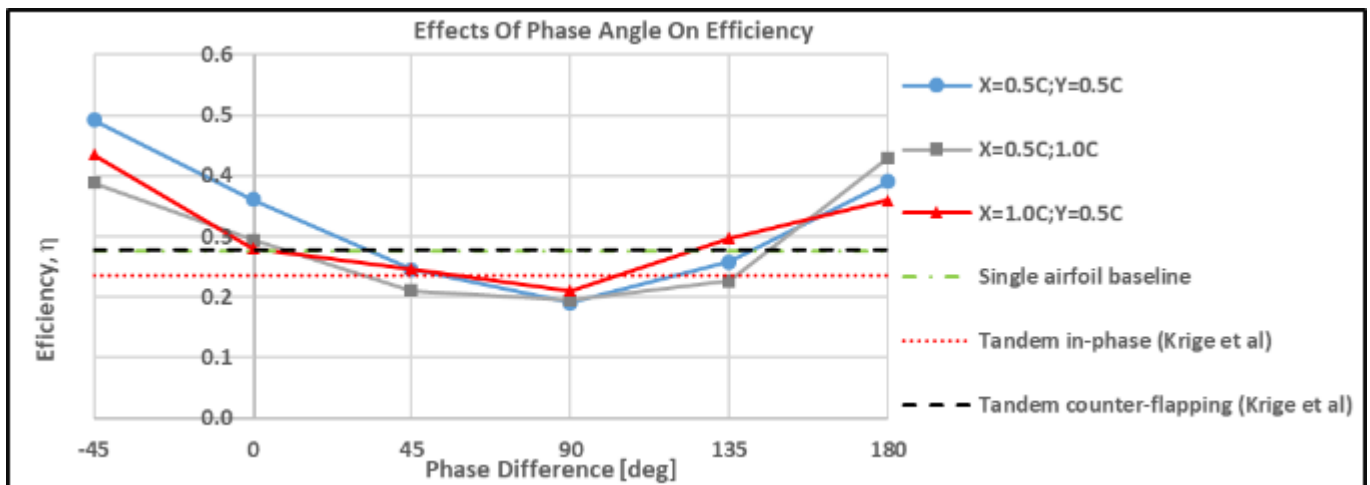


Figure 5-33: Efficiency variation with ϕ .

It is worth noting, in accordance with Lai et al.'s research [18], that there is no universally optimal wing phase applicable to all damselfly species. Alexandra's work further illustrates this by revealing that certain primitive insect species such as locusts, maintain a constant ϕ with the hindwings slightly leading. In contrast, dragonflies exhibit a broad spectrum of phase angles, with their choice depending on the flight mode required during a specific situation [17].

5.6. FOUR AIRFOIL CASES

In this section the number of airfoils was increased to incorporate four airfoils, while keeping phase difference fixed at 180° . The cases were derived from cases 1 and 11 with the stagger between F2 and F3 maintained at 1.0C (i.e F3 LE aligns with F2 TE). It's noteworthy that F1 and F4 operate in-phase, whereas F2 and F3 also maintain an in-phase relationship.

To evaluate the performance, the force and efficiency coefficients are presented in Table 5-2 below. These are compared with single and double airfoil cases. The augmentation ratios are calculated from equations below.

$$dPr(N = 2) = \frac{P_{N=4} - P_{N=2}}{P_{N=2}} \dots \dots \dots [8]$$

$$dPr(single) = \frac{P_{case31} - P_{single}}{P_{single}} \dots \dots \dots [9]$$

Where

$dPr(N = 2)$ – – Parameter augmentation ratio with reference to double airfoil case .

$dPr(N = 1)$ – – Parameter augmentation with reference to single airfoil case.

$P_{N=4}$ – – – – – Parameter in 4 airfoil case. eg $Cl1$, $Ct1$ or eff in Case 31.

$P_{N=2}$ – – – – – Parameter in double airfoil case eg $Cl1$, $Ct1$ or eff in case1.

P_{single} – – – Cl , $Ct2$ or ef for single airfoil case .

N – – number of airfoils.

As Table 5-2 reveals that the four-airfoil case generated higher lift than the single airfoil. In fact, across all airfoils the lift augmentation was at least 1.1 times the single airfoil lift. It is observed that compared to case 1 F1 lift improved by 1.1 times, but Cl_2 experienced an 81% reduction. However, it is important to note that the introduction of additional airfoils did not result in an enhancement of thrust production when compared to both single and double airfoil cases. Specifically, F1 shed 43% thrust due to the introduction of the additional airfoils, although Ct_2 remained largely unchanged.

Table 5-2: Four airfoils (case31) comparison with double and single airfoils.

	Cl_1	Cl_2	Cl_3	Cl_4	Cl	Ct_1	Ct_2	Ct_3	Ct_4	Ct	eff
Case 1	0.108	0.249	-	-	0.178	-0.106	-0.0870	-	-	-0.096	0.247
Case 31	0.283	0.048	0.077	0.073	0.120	-0.151	-0.091	-0.105	0.018	-0.082	0.133
dFr (N=2)	1.621	-0.808	-	-	-0.327	-0.427	-0.043	-	-	-0.148	-0.462
dFr (N=1)	1.189	1.437	1.135	1.128	1.312	-1.724	-1.434	-1.502	-0.913	-1.393	-0.518

Moreover, the four-airfoil configuration exhibited an efficiency level approximately half that of the single and double airfoil cases. This indicates that while the four-airfoil setup for Case 31 ($X=0.5C$; $Y=0.5C$) excelled in terms of lift, it did so at the expense of overall efficiency when compared to the other configurations.

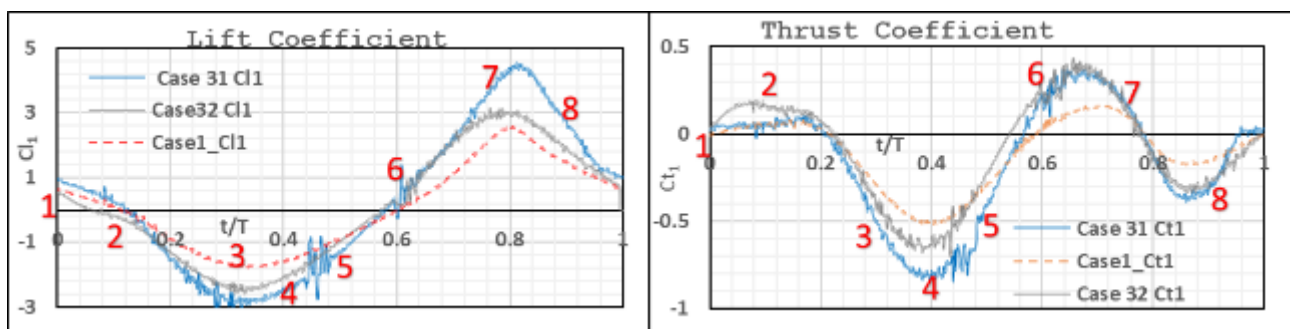
Results presented in Table 5-3 below indicate highlight a notable trend where the efficiency of the four airfoil cases efficiency improves with increased stagger. Case 32 ($X=1.0C$; $Y=0.5C$) produced 77.5% more lift than case 31. However, it is essential to delve into the individual airfoil performance to gain a comprehensive understanding of the effects of spacing. F1 produced 62% more lift than the double airfoil case (Case 1). However, in Case 32 experiences a significant adverse impact on lift production, yielding 66% lift less than the correspondent double airfoil case (Case 11). In contrast, to Case 31 F2 shows a substantial boost in lift production, with an increase of up to 98%, and also achieves a 10% gain in thrust. F3 undergoes a remarkable transformation, shifting from net drag production to net thrust generation and producing 4.6 times more lift than in Case 31.

Table 5-3: Four airfoils (Case 32) comparison with double and single airfoils.

	Cl1	Cl2	Cl3	Cl4	Cl	Ct1	Ct2	Ct3	Ct4	Ct	eff
Case 11	0.286	1.122	-	-	0.704	-0.131	-0.336	-	-	-0.234	0.200
Case 32	0.096	0.095	0.354	0.305	0.213	-0.080	-0.083	0.025	-0.069	-0.052	0.205
dFr (N=2)	-0.664	-0.915	-	-	-0.698	0.390	0.752	-	-	-0.778	0.023
dFr (N=1)	1.169	1.166	1.622	1.536	1.373	-1.383	-1.399	-0.881	-1.332	-1.249	-0.256

Furthermore, it's worth noting that in Case 31, the fore pair contributes to 69% and 57% of the net lift and thrust, respectively. However, in Case 32, the aft pair performs better, contributing 77% to both lift and thrust. This shift in performance between the fore and aft pairs underscores the significant impact of spacing alterations on the distribution of lift and thrust across the airfoils in the four-airfoil configuration.

Force-normalized time plots for case 31 are illustrated in Figure 5-34 to Figure 5-38 below. Additionally, lift and thrust curves for case 1 have been incorporated to facilitate a comparative analysis.

**Figure 5-34: N=4 cases F1 lift and thrust plots.**

The lift and thrust plots for F1 in Case 31 exhibit a strikingly similar pattern to those observed in the double airfoil case. However, it's crucial to note that there are significant changes in performance metrics. Specifically, the minimum lift decreased by a substantial 78%, while the minimum thrust dropped by 45%. On the positive side, there is an improvement in terms of average performance, with lift increasing by approximately 0.73 times and thrust increasing by approximately 1.4 times when compared to the double airfoil configuration. These changes highlight the nuanced impact of the modified spacing on F1's lift and thrust characteristics.

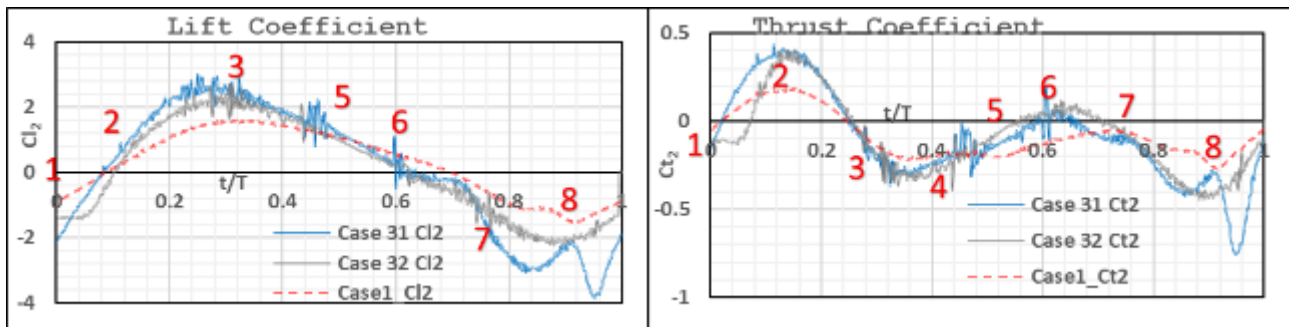


Figure 5-35: N=4 cases F2 lift and thrust plots.

As depicted in Figure 5-34 shows F2 lift and thrust plots closely mirror those observed in Case 1. Remarkably, the maximum, minimum, cross-over, and cross-under points align precisely with those of the double airfoil case. This alignment is points to a consistent performance pattern between the two configurations. Notably, there are significant improvements in F2's performance metrics compared to the double airfoil case. The maximum lift increases by an impressive 84%, while thrust more than doubles. However, the minimum lift and thrust experience a decrease, falling to 1.5 times less than that of the double airfoil case.

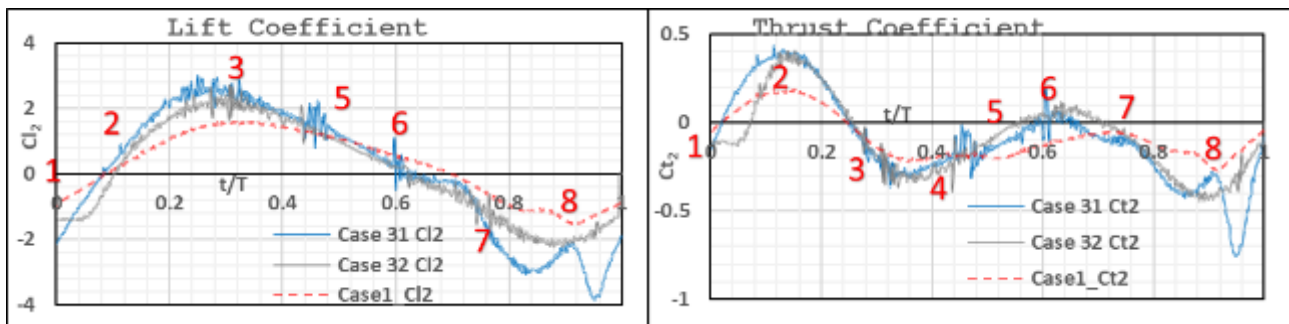


Figure 5-36: N=4 F3 lift and thrust plots.

Lift and thrust values for F3 are shown in Figure 5-36. During the pitch-up phase, the lift coefficient, Cl_3 experiences an increase and its peak value surpasses Cl_2 by 25%. Remarkably, during the pitch-down phase Cl_3 doesn't decrease significantly, maintaining a minimum value that is 8% higher than Cl_2 minimum. This results in F3 producing 52% more lift than F2.

However, compared to F1, Cl_2 maximum value is 17% lower, and its minimum value is 15% lower, leading to F3 producing 73% less lift than F1. Regarding thrust, F3 achieves a 43% increase in maximum thrust but experiences a 27% reduction in minimum thrust compared to F1. Ultimately, F3 produces 30% less thrust than F1. When juxtaposed with F2, F3's maximum thrust is augmented by 21%. However, its minimum thrust is 2.4 times less than that of F2, resulting in F3 producing 14% less thrust than F2.

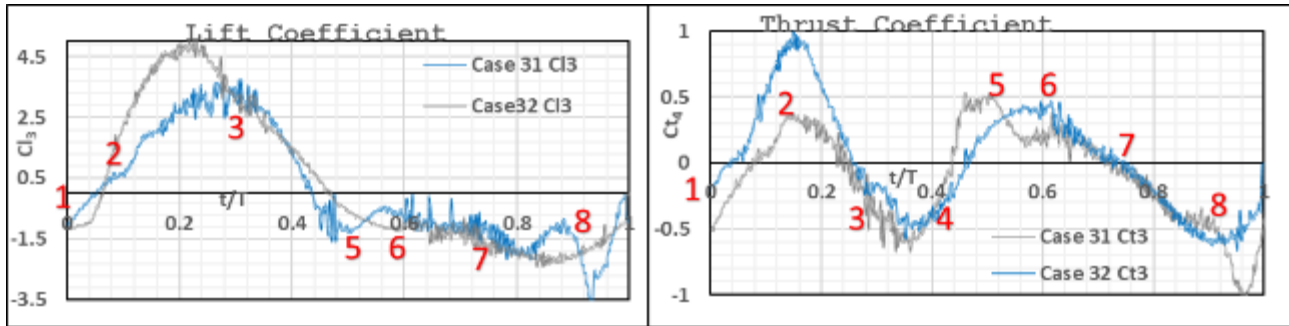


Figure 5-37: N=4 F4 lift and thrust plots.

Figure 5-38 shows the F4 lift and thrust plots against normalized time. The peak lift for F4 is nearly equivalent to Cl_2 maximum value, while its minimum is roughly 17% greater than Cl_2 minimum. When compared to F1 and F3, F4 experiences a reduction in peak lift by 34% and 20%, respectively. However, it has the highest peak thrust value among all the airfoils. Conversely, its minimum thrust value is nearly equivalent to Ct_1 , approximately 17% more than Ct_2 , and about 29% less than Ct_3 . Furthermore, when considering average thrust, F4 registers a value that is almost equal to that of F3, but notably, it is quite low, almost approaching zero. This suggests that F4's thrust production varies significantly throughout its operational cycle, with a pronounced peak but reduced thrust during other phases.

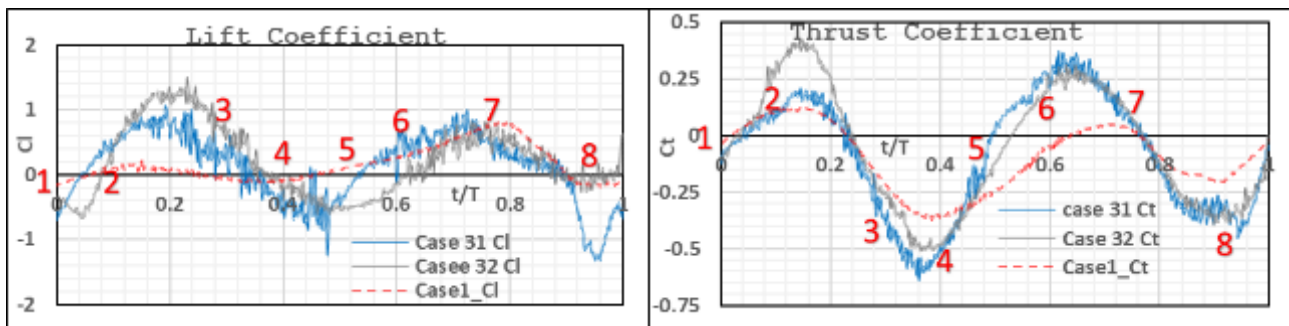


Figure 5-38: N=4 total lift and thrust plots.

As illustrated in Figure 5-38, the maximum lift is equal for both strokes, in contrast to the double airfoil case where the maximum lift is higher during the outstroke than during the instroke where maximum lift is higher during outstroke than during instroke. Additionally, the thrust plots exhibit similar patterns to those observed in the double airfoil case. Initially, the thrust in the four-airfoil case matches that produced by the double airfoil case up to $t=0.25T$ (25% of the cycle). However, it subsequently experiences a notable drop, decreasing by 43% when compared to Case 1. Furthermore, the maximum thrust in the four-airfoil case exceeds that produced during the instroke phase.

Figure 5-39 and Figure 5-40 below are meant to facilitate a comprehensive understanding of the flow characteristics in Case 31 and Case 32 respectively by valuable information

through vorticity and pressure contours. These contours allow for an in-depth examination of the fluid dynamics and pressure distribution, offering insights into the aerodynamic behavior of the airfoils.

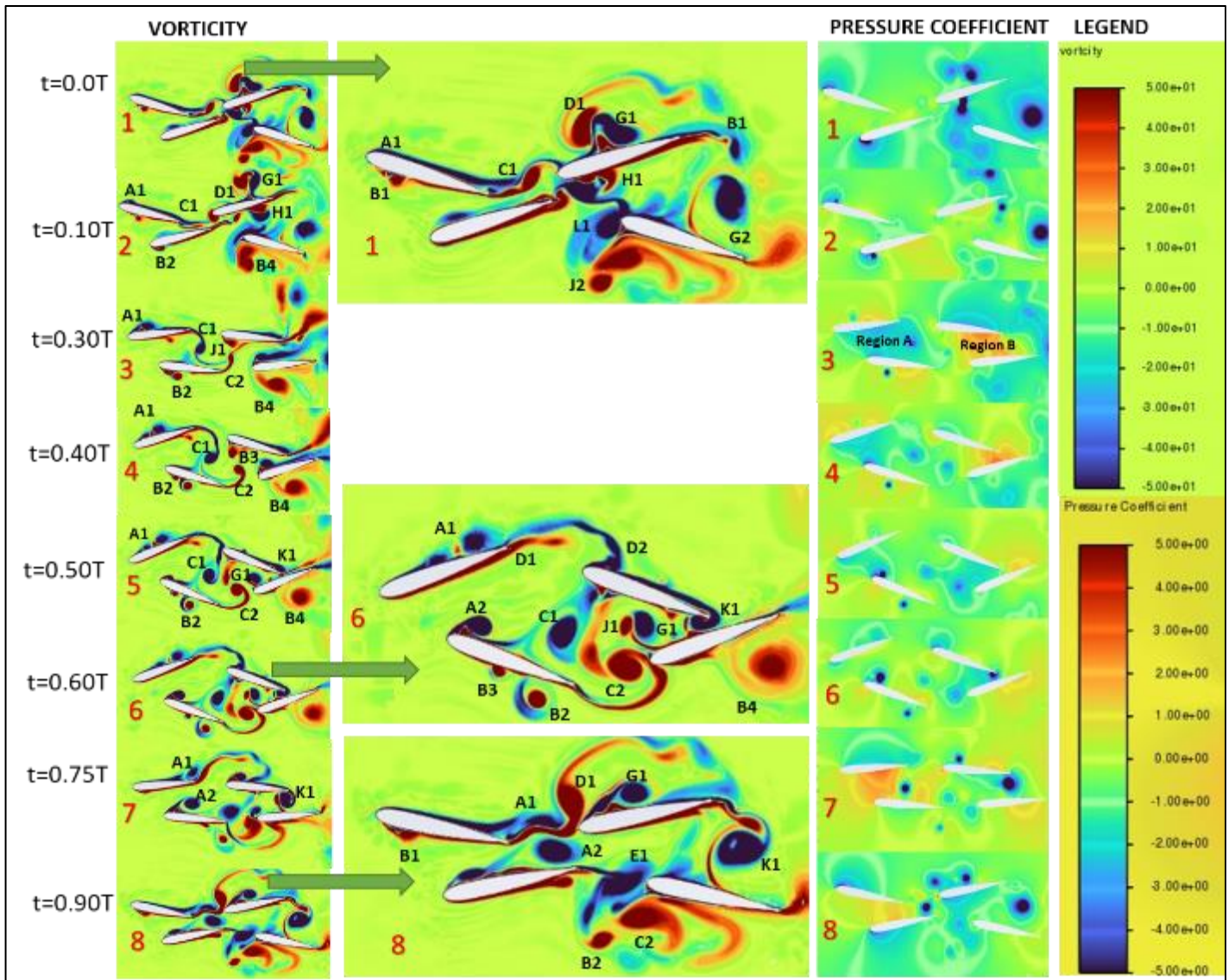


Figure 5-39: Vorticity and pressure contours for 4-airfoil case (Case31).

The characteristics observed for F1 and F2 in the four-airfoil case closely resemble those seen in the double airfoil configuration. However, a lot of interaction between the rear shed vortices and the rear airfoils is observed. Moreover, the presence of features from the previous cycle, such as D1, G1, and L1, at the beginning of the current cycle can significantly impact the formation of leading edge (LE) features for F3 and F4. This suggests that the behavior of the shed vortices from the prior cycle plays a crucial role in shaping the aerodynamic characteristics of the rear airfoils in the current cycle. This observation highlights the complex and interconnected nature of flow phenomena in the

four-airfoil case, where the interactions between vortices and airfoils from previous cycles have a significant influence on the aerodynamic behavior of the subsequent airfoils.

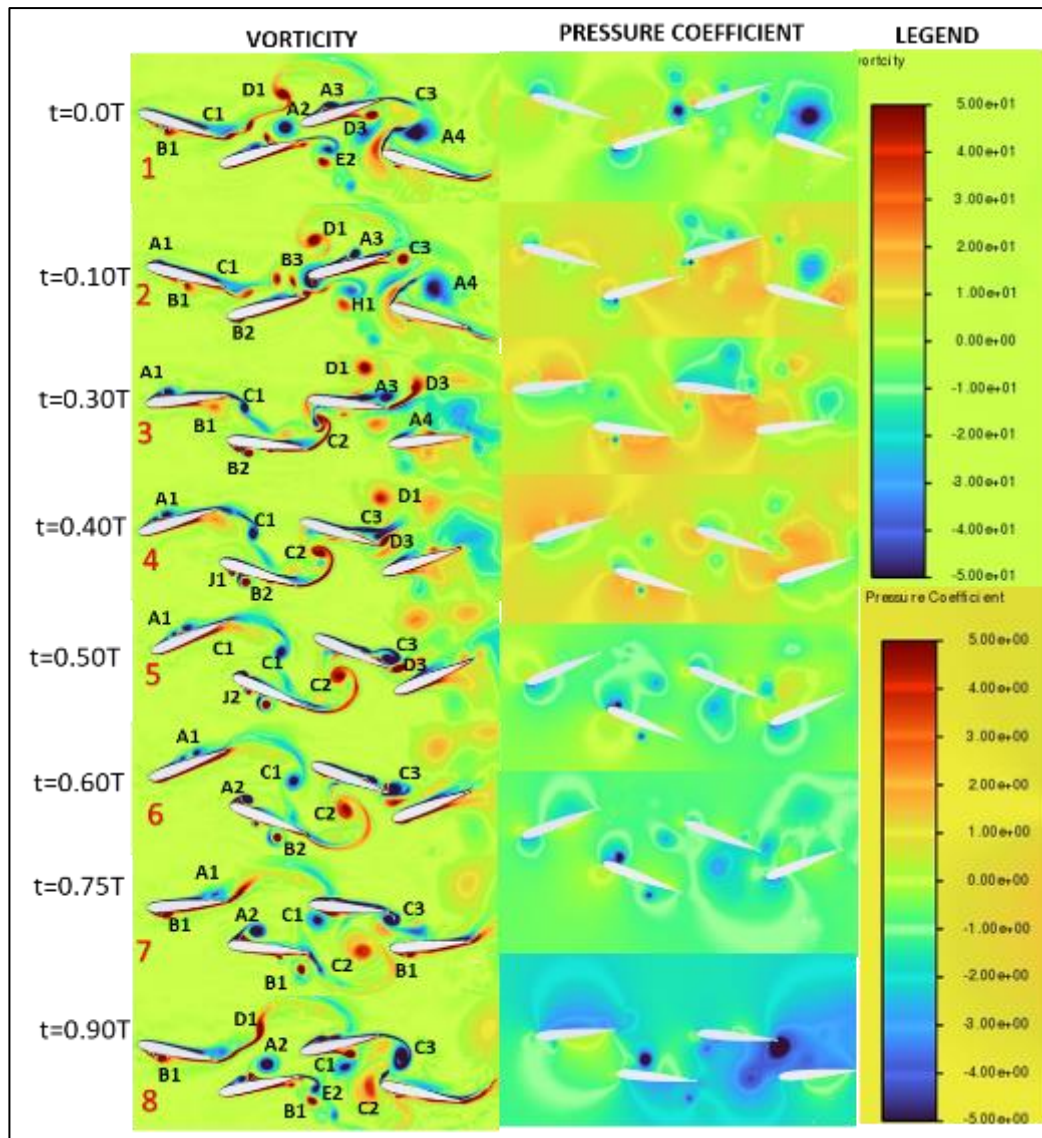


Figure 5-40: Vorticity and pressure contours for 4-airfoil case (Case32).

The interference effects between the airfoils and vortices are more pronounced in Case 31 compared to Case 32, as depicted in Figure 5-40 above shows. In Case 31, with smaller spacing, these vortices are recaptured and remain closer to or within the wake of F1-F2, enhancing the performance of F1 and F2. Consequently, they produce more lift and thrust compared to both the double airfoil case and Case 32. During the instroke phase, there is an interesting pressure dynamic between regions A and B (as marked in Figure 5-39 ,point 3). As F3 and F4 leading edges move away from each other, the fluid in region B decelerates, causing an increase in pressure in region B and a decrease in region A. This pressure change leads to an increase in F2 and F3 lift while F1 and F4 experience a drop in lift.

Between $t=0.1T$ and $t=0.3T$, in Case 31, it becomes evident that F3's leading edge develops a negative feature, B3, which comes into contact with F2's shed vortex, C2. This interaction coincides with the peak in Cl_3 . Similarly, in Case 32, F3 and F4 leading edges are further from F1 and F2 trailing edges, resulting in less interruption between D1 and E2. A3 develops earlier and more prominently, creating a greater low-pressure region in F3's leading edge compared to Case 31, thereby leading to F3 producing more lift and thrust. Between $t=0.4T$ and $t=0.5T$, C1 and C2 become closer to F3 and F4, respectively, in Case 31. In Case 32, only C2 interacts with F3. For Case 31, between $t=0.5T$ and $t=0.6T$, F3's leading edge collides with F1's shed vortex stream, splitting it into C1 and D2. This interaction enhances Cl_3 , preventing it from dropping significantly into the negative during the next stroke. However, Ct_3 drops, and D3 is shed near F3's middle, coupled with a high-pressure region at the trailing edge, resulting in a rise in Cl_4 . In Case 32, after the shedding A4 between $t=0.1T$ and $t=0.1T$, no significant features are produced by F4. However, its lift and thrust are enhanced through interactions with F3 features, mainly C3 and D3. F4, which is pitching up, delays the shedding of D3, leading to destructive interference with C3 at F3's trailing edge (which is F4's leading edge). Both F3 and F4 thrust rise, although Ct_4 is greater than Ct_3 . Between $t=0.75T$ and the stroke reversal, C1 hits F2 at the trailing edge in Case 31, resulting in Cl_2 not rising as much as it does in the double airfoil case. The resultant feature E1 interferes with F4's leading edge features at $t=0.9T$, augmenting Cl_4 , which increases from its minimum. In Case 32, C3 grows bigger right at F4's leading edge, further augmenting F4's lift and thrust.

5.7. PERFORMANCE INDEX

Wing-wing interaction produces a compromise between thrust & lift production [18]. A combination which produces more thrust might do so at the expense of lift production and vice-versa. This creates a complex interplay between these two critical performance parameters. Therefore, it is imperative to exercise caution when comparing and ranking cases based on their aerodynamic performance. To provide a comprehensive assessment, the performance index, which has been adapted from previous work by Lim and Tay [51] is employed. This index accounts for lift, thrust, and efficiency, offering a balanced measure of overall performance. The formula for calculating the performance index is provided in Equations 1 to 4. It takes into account the lift, thrust and efficiency.

These performance index values, Table 5-4 below, serve as a valuable tool for ranking and comparing the various cases, considering the intricate balance between lift and thrust production, as well as efficiency. They provide a holistic perspective on the overall aerodynamic performance of each configuration.

Table 5-4: Propulsive performance index and ranking.

Case	X	Y	ϕ	Ct	CL	η	I_p	Rank
Single	1.3	0	0	0.209	-0.570	0.275	0.392	26
K4	1.3	0	0	-0.130	-0.070	0.236	-0.049	33
K6	1.3	0	180	-0.070	0.080	0.277	0.448	24
1	0.5	0.5	180	0.198	0.199	0.390	1.718	13
2	0.5	0.75	180	0.185	0.213	0.490	1.896	8
3	0.5	1	180	0.309	0.323	0.430	2.340	1
4	0.5	1.25	180	0.276	0.184	0.325	1.819	11
5	0.5	1.5	180	0.247	0.177	0.325	1.712	14
6	0.75	0.5	180	0.181	0.171	0.345	1.533	18
7	0.75	0.75	180	0.178	0.225	0.460	1.832	10
8	0.75	1	180	0.277	0.281	0.410	2.132	4
9	0.75	1.25	180	0.247	0.196	0.337	1.766	12
10	0.75	1.5	180	0.224	0.167	0.350	1.673	15
11	1	0.5	180	0.173	0.251	0.360	1.651	16
12	1	0.75	180	0.179	0.219	0.465	1.836	9
13	1	1	180	0.271	0.291	0.460	2.230	2
14	1	1.25	180	0.276	0.201	0.356	1.905	7
15	1	1.5	180	0.216	0.179	0.326	1.619	17
16	0.5	0.5	-45	0.247	0.281	0.485	2.186	3
17	0	0.5	0	0.167	-0.022	0.360	1.233	20
18	0.5	0.5	45	0.046	-0.239	0.245	0.290	28
19	0.5	0.5	90	0.046	-0.189	0.190	0.252	29
20	0.5	0.5	135	0.012	-0.158	0.259	0.326	27
21	0.5	1	-45	0.249	0.681	0.388	2.074	6
22	0.5	1	0	0.198	-0.098	0.294	1.090	21
23	0.5	1	45	0.135	-0.319	0.210	0.393	25
24	0.5	1	90	0.025	-0.350	0.195	-0.042	32
25	0.5	1	135	0.007	-0.176	0.227	0.221	30
26	1	0.5	-45	0.237	0.231	0.497	2.107	5
27	1	0.5	0	0.207	0.027	0.280	1.274	19
28	1	0.5	45	0.097	-0.142	0.247	0.602	22
29	1	0.5	90	0.025	-0.243	0.210	0.148	31
30	1	0.5	135	0.013	-0.109	0.297	0.480	23
Parameter Maximum				0.309	0.681	0.497	2.340	

The single airfoil case as well as Krige's counter-flapping (K4) and in-phase flapping (K6) cases are included in order to facilitate a comprehensive comparison. The maximum thrust, lift and efficiency values are highlighted in green.

Although the stagger and gap configuration has some instances where its thrust or lift production is lower than that of a single or tandem airfoils generally demonstrates a superior performance index. Specifically, Case 11 ($X=1.0C$; $Y=0.5C$; $\phi=180^\circ$) emerges as the worst performing configuration. However, with a shift in phase to 45° with the aft foil it becomes the overall best performing among all non-counter-flapping cases. The tandem counter-flapping airfoil outperforms both the tandem in-phase and single airfoil setups in terms of overall performance.

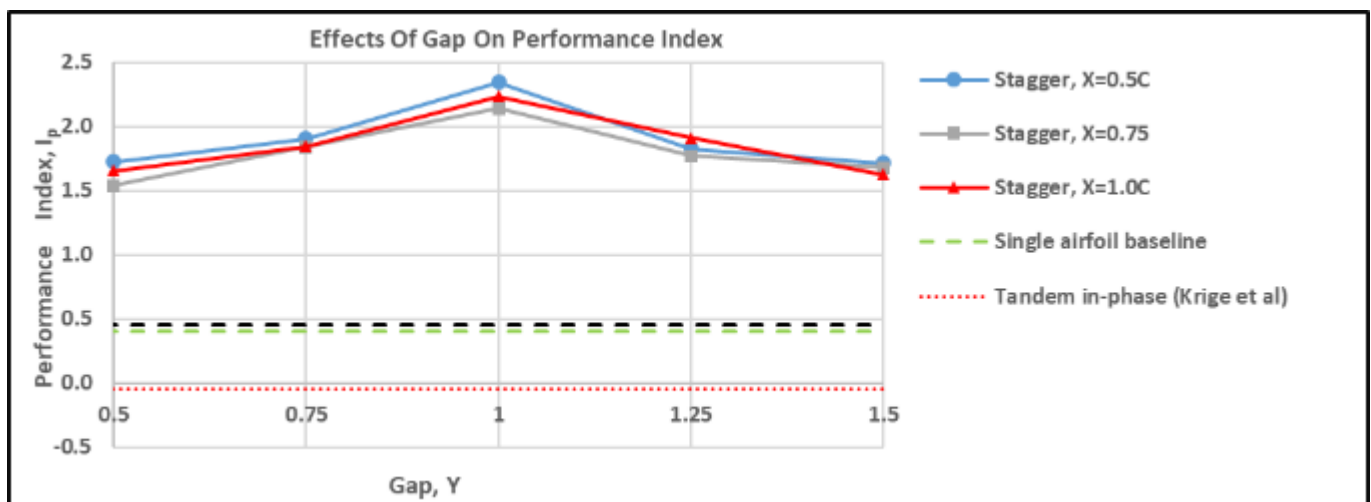


Figure 5-41: I_p variation with gap.

In Figure 5-41, it is evident that performance index increases with gap, reaching a maximum point before declining at larger gap values. The peak I_p is observed at $Y=1.0C$ for all stagger values. All the cases have an I_p greater than single and tandem airfoils. Moreover, it's worth highlighting that in all the cases, the I_p values surpass those of both single and tandem airfoil configurations.

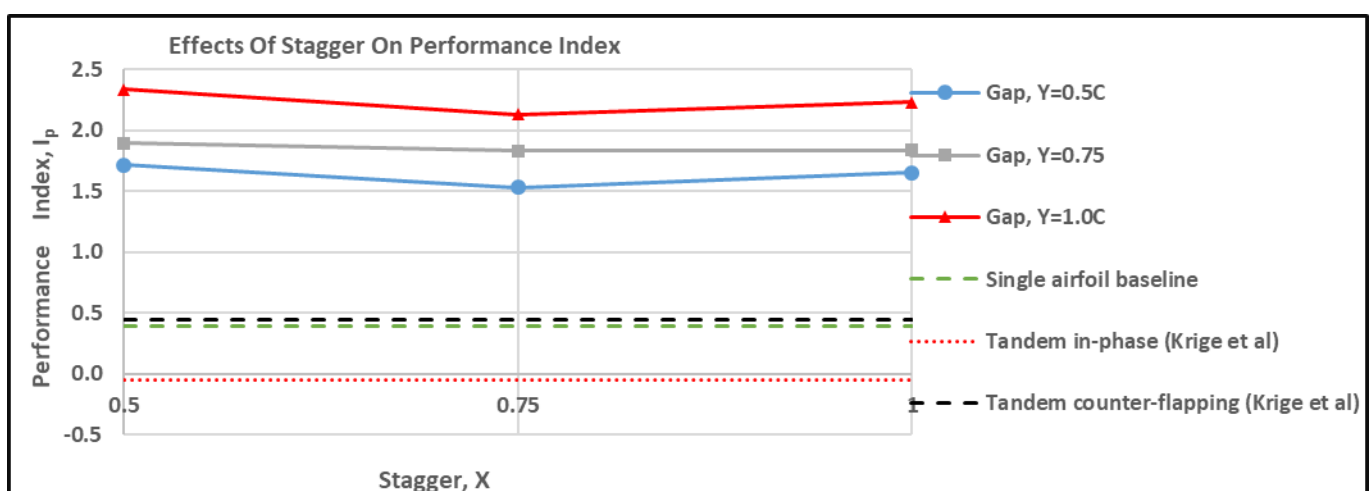


Figure 5-42: I_p variation with stagger.

Stagger has an opposite effect on performance index to gap as shown in Figure 5-42 above. For stagger $< 0.75C$ I_p decreases before it rises between stagger $= 0.75C$ and $1.0C$. Generally small stagger enhances performance index. It is evident that the stagger has less significant impact on the performance index compared to gap.

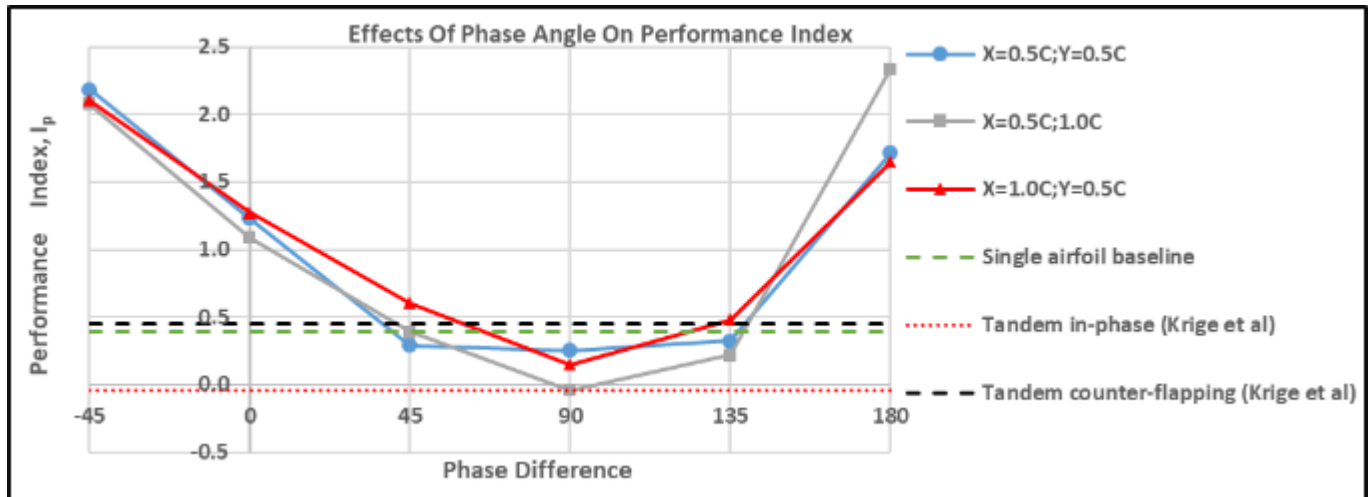


Figure 5-43: I_p variation with ϕ .

For all the cases performance index showed similar response to variation in phase angle as indicated in Figure 5-43 above. Phase angles between 45° - 135° have the worst performance indices. The $\phi = -45^\circ$ proved to have the highest performance index.

6. CONCLUSION

This research has provided valuable insights into the aerodynamic performance of multiple airfoils in stagger and gap configurations. A key objective (objective 1) was to quantify the effects of stagger and gap on lift, thrust, and efficiency. Within the scope and results of the investigated cases in this research the findings clearly show that at $St = 0.2$, smaller stagger and gap, a phase angle of $\phi = 180^\circ$ resulted in diminished thrust. In fact, the airfoils in these cases generated less thrust than a single airfoil. However, the lift performance was consistently augmented across all cases, with an average increase (ΔCl_{av}) of 1.2 times compared to a single airfoil. Notably, smaller stagger and gap values enhanced efficiency, while larger gaps led to more stable ΔCt , ΔCl , and η values. Among these parameters, the gap had a more substantial influence on performance, with a specific stagger value ($X = 0.75C$) identified as optimal for maximizing Ct , Cl , and η . There however exists a particular stagger value ($X = 0.75C$) where Ct , Cl , and η reach their maximum and minimum values occur.

Generally small stagger and gap values are detrimental to thrust production however lift is mostly augmented. An increase in the second airfoil lift or thrust comes with a drop in the first airfoil lift or thrust and vice-versa. This trade-off becomes more pronounced as the gap between the airfoils increases. This phenomenon also holds true even for the four-airfoil ($N=4$) cases, where the fore pair performs better for small spacing but the aft pair outperforms for larger gaps.

The optimal values for each parameter (ΔCt , ΔCl , η) depend on the specific values of stagger, gap, and phase angle (ϕ). For instance, for $X = 0.5C$, the optimal gap for ΔCt is $1.0C$ at $\phi = 180^\circ$, while maximum efficiency is achieved at a gap of $0.75C$ for the same phase angle. Each X - Y - ϕ which produces a particular high aerodynamic force parameter usually does so at the expense of the other parameters. Comparing specific cases, Case 1 ($X = 0.5C$; $Y = 0.5C$; $\phi = 180^\circ$) with the smallest spacing produces low stagger and thrust. Increasing the gap by $0.5C$, Case 3 ($X = 0.5C$; $Y = 1.0C$; $\phi = 180^\circ$), generates the highest thrust, surpassing Case 1 by 57%, with minimal impact on lift and efficiency. This case had the highest ranking in terms of performance index. Case 11 ($X = 1.0C$; $Y = 0.5C$; $\phi = 180^\circ$), which has a larger stagger, produces the least thrust among $\phi = 180^\circ$. Notably, changing the phase angle can have a significant impact.

Additionally, the study explored the impact of phase differences between flapping airfoils, an important objective (objective 3) of this research. It was observed that while configurations with a phase angle of $\phi = 180^\circ$ generally performed worse in terms of thrust, altering the phase angle could significantly enhance performance. For example, spacing combination in Case 11 ($X = 1.0C$; $Y = 0.5C$; $\phi = 180^\circ$), which initially had poor thrust at,

became the best performer in terms of lift among all 30 cases, when the phase angle was changed to $\phi = -45^\circ$ (Case 26), demonstrating the critical influence of phase difference on performance outcomes. Case 26 ($X=1.0C$; $Y=0.5C$; $\phi = -45^\circ$) ranked 5th in the overall performance index and 2nd among $\phi \neq 180^\circ$. This concurs with Lai et al's findings who concluded that there is no overall optimal spacing, flapping frequency or phase difference for Damselfly single species. They also discovered that Damselflies with small spacing have $0.3T$ hindwing leading as more effective [18]. According to Alexander Dragonflies employ different phase angles in flapping depending on the situation and flight mode requirements [17].

The study also aimed to investigate whether increasing the number of airfoils beyond 2 could enhance performance (objective 2). The analysis of four-airfoil configurations revealed distinct trends, with smaller spacings improving lift but reducing overall efficiency. For instance, Case 31 demonstrated a 63% increase in lift for the first airfoil (F1) compared to its counterpart in a double airfoil setup. However, F2 experienced an 80% reduction in lift, resulting in an overall 33% decrease in lift performance. Thrust performance remained unchanged, and overall efficiency was reduced by 50%. In contrast, Case 32 showed improved thrust performance, with a 75% increase, despite a significant drop (66%) in lift for the aft pair. Consequently, the overall efficiency of the configuration saw a modest increase of 3%. This demonstrates that while adding more airfoils can improve specific performance metrics, it also introduces diverging effects between lift, thrust, and efficiency, depending on the configuration.

7. RECOMMENDATIONS FOR FUTURE WORK

In conclusion, this study underscores the complex trade-offs involved in configuring multiple airfoils for optimal aerodynamic performance. Future research should further explore a wider range of stagger and gap combinations for multi-airfoil configurations ($N > 2$) to identify layouts that maximize both lift and thrust while minimizing efficiency losses. Additionally, the potential for adaptive mechanisms that adjust gap and stagger dynamically during flapping should be investigated, as this could mirror the natural adaptability seen in species like damselflies and dragonflies, potentially leading to enhanced performance in varied flight conditions.

Student Name: Never Mabvuu

Signature: 

Date: October 24, 2024

Supervisor Name: Prof Weihua Ho

Signature:

Date:

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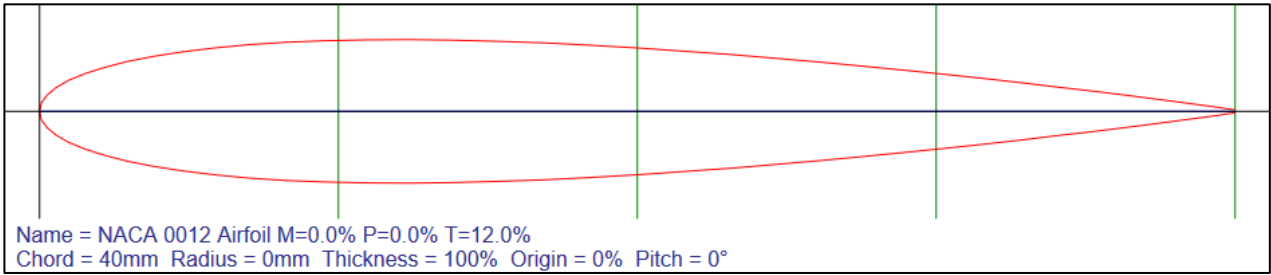
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APPENDIX A: NACA0012 AIRFOIL GEOMETRY AND COORDINATES



A-1 :NACA001airfoil geometry

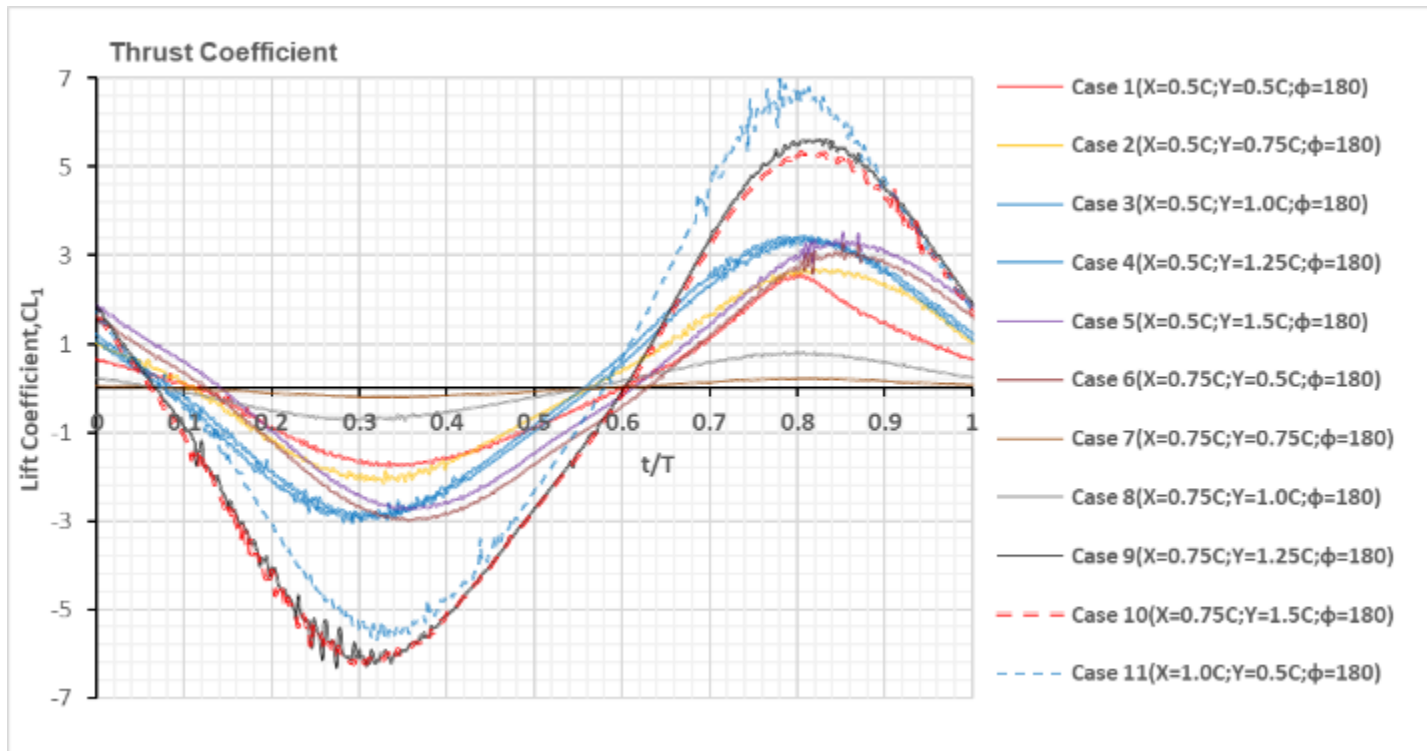
A-1:NACA0012 airfoil coordinates

Airfoil surface	
X(mm)	Y(mm)
40	0.0504
39.93836	0.05904
39.75376	0.0848
39.4474	0.12728
39.02112	0.18568
38.4776	0.25912
37.82012	0.34632
37.0528	0.44596
36.18032	0.55656
35.20812	0.67656
34.14212	0.80428
32.98896	0.93808
31.75572	1.0762
30.44996	1.21692
29.0798	1.35848
27.65368	1.49904
26.18032	1.63668
24.66892	1.76948
23.12868	1.89532
21.5692	2.01208
20	2.1176
18.4308	2.20964

16.87132	2.28592
15.33108	2.34436
13.81968	2.383
12.34632	2.4
10.9202	2.39392
9.55004	2.36368
8.24428	2.30856
7.01104	2.22836
5.85788	2.12332
4.79188	1.99416
3.81968	1.84196
2.9472	1.6682
2.17988	1.47468
1.5224	1.2632
0.97888	1.03572
0.5526	0.79416
0.24624	0.54012
0.06164	0.27508
0	0
0.06164	-0.27508
0.24624	-0.54012
0.5526	-0.79416
0.97888	-1.03572
1.5224	-1.2632
2.17988	-1.47468
2.9472	-1.6682
3.81968	-1.84196
4.79188	-1.99416
5.85788	-2.12332
7.01104	-2.22836
8.24428	-2.30856
9.55004	-2.36368
10.9202	-2.39392
12.34632	-2.4

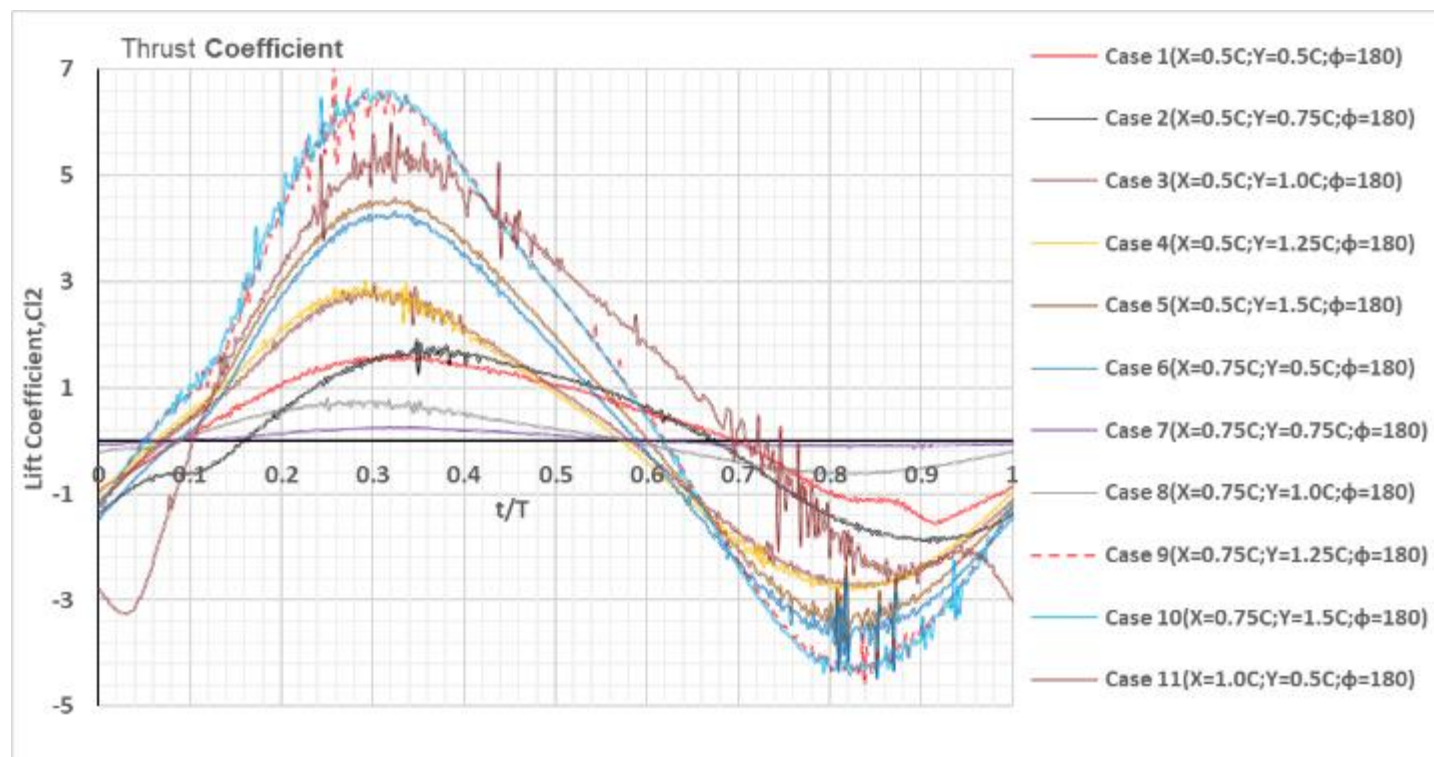
13.81968	-2.383
15.33108	-2.34436
16.87132	-2.28592
18.4308	-2.20964
20	-2.1176
21.5692	-2.01208
23.12868	-1.89532
24.66892	-1.76948
26.18032	-1.63668
27.65368	-1.49904
29.0798	-1.35848
30.44996	-1.21692
31.75572	-1.0762
32.98896	-0.93808
34.14212	-0.80428
35.20812	-0.67656
36.18032	-0.55656
37.0528	-0.44596
37.82012	-0.34632
38.4776	-0.25912
39.02112	-0.18568
39.4474	-0.12728
39.75376	-0.0848
39.93836	-0.05904
40	-0.0504

APPENDIX B: Cl_1 TIME PLOTS FOR $\Phi=180^\circ$



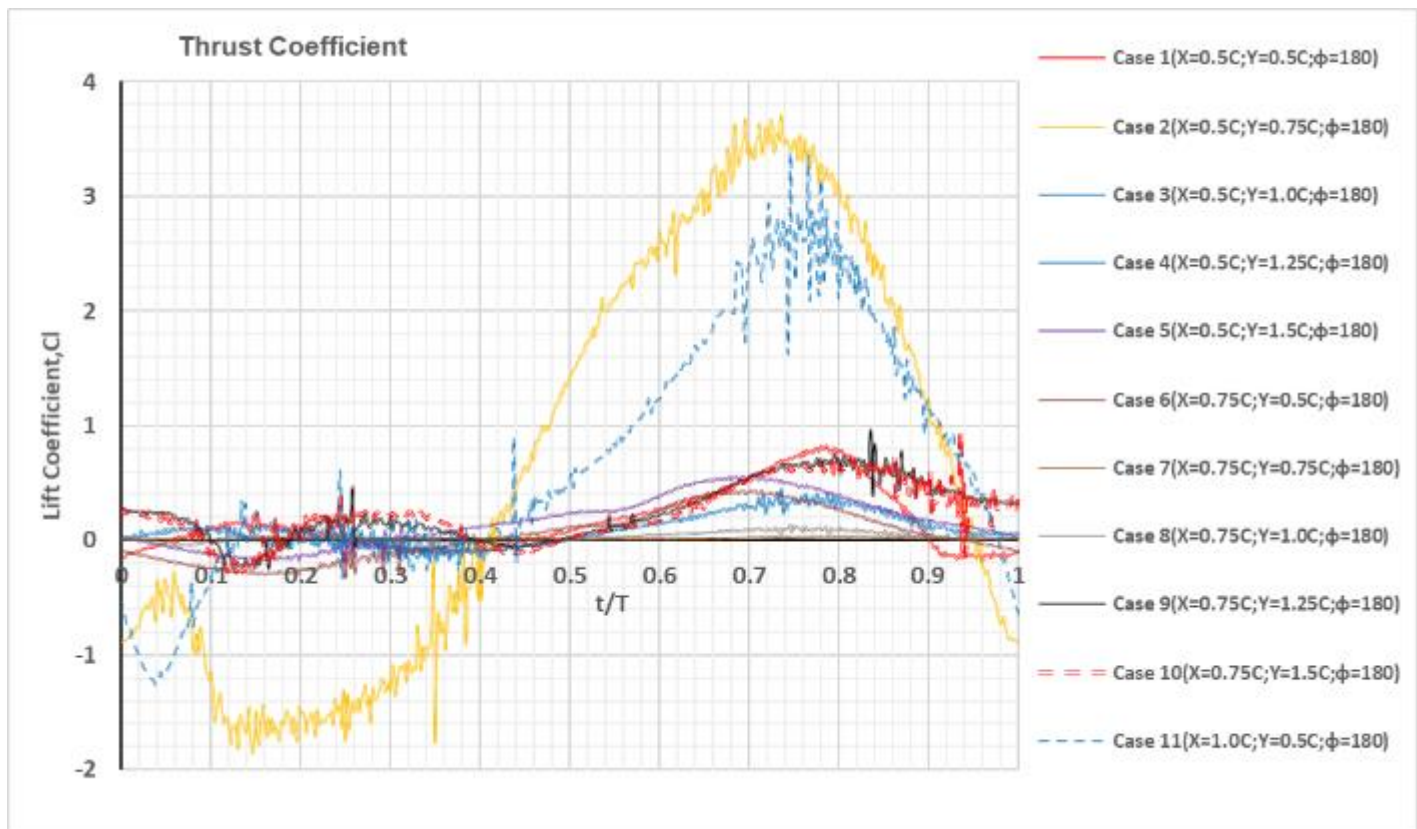
B-1: Cl_1 time plots for $\phi=180^\circ$

APPENDIX C: Cl_2 TIME PLOTS FOR $\phi=180^\circ$



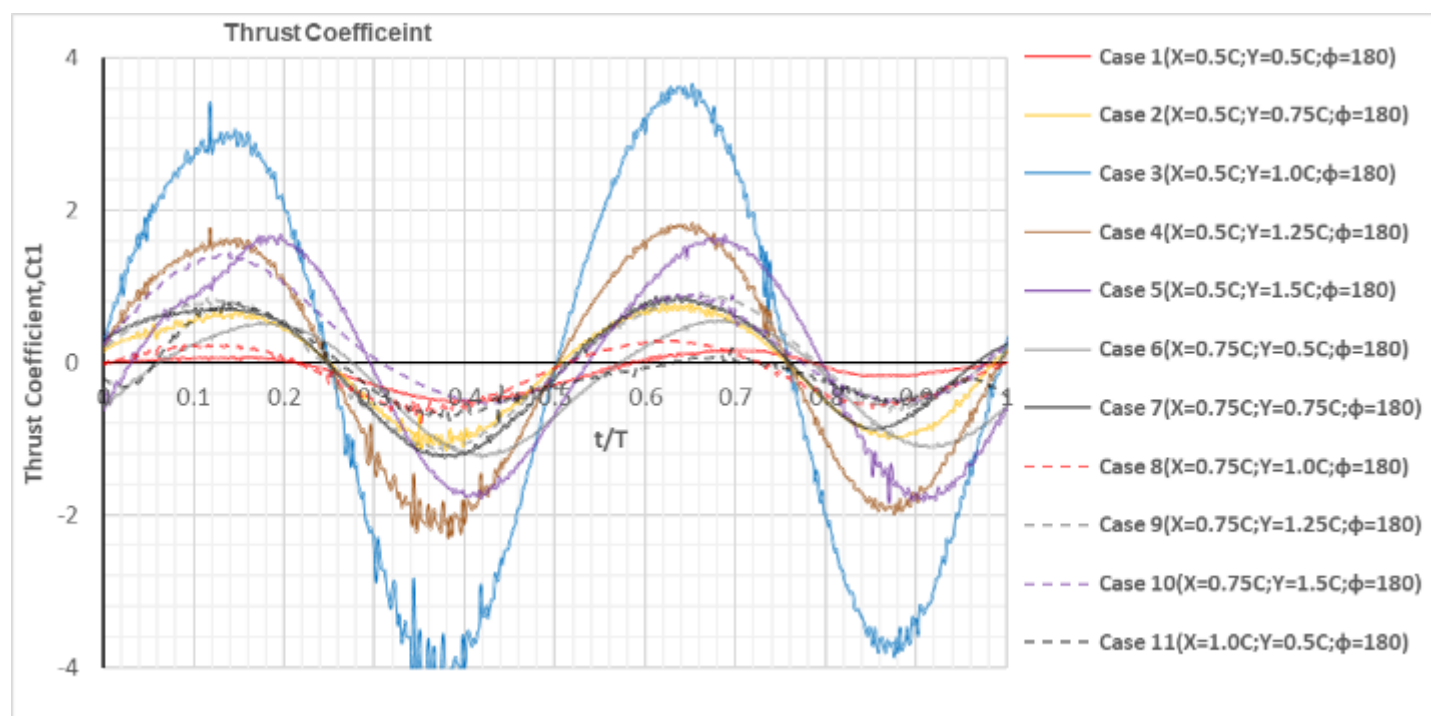
C-1 : Cl_2 time plots for $\phi=180^\circ$

APPENDIX D: APPENDIX D: CI TIME PLOTS FOR $\Phi=180^\circ$



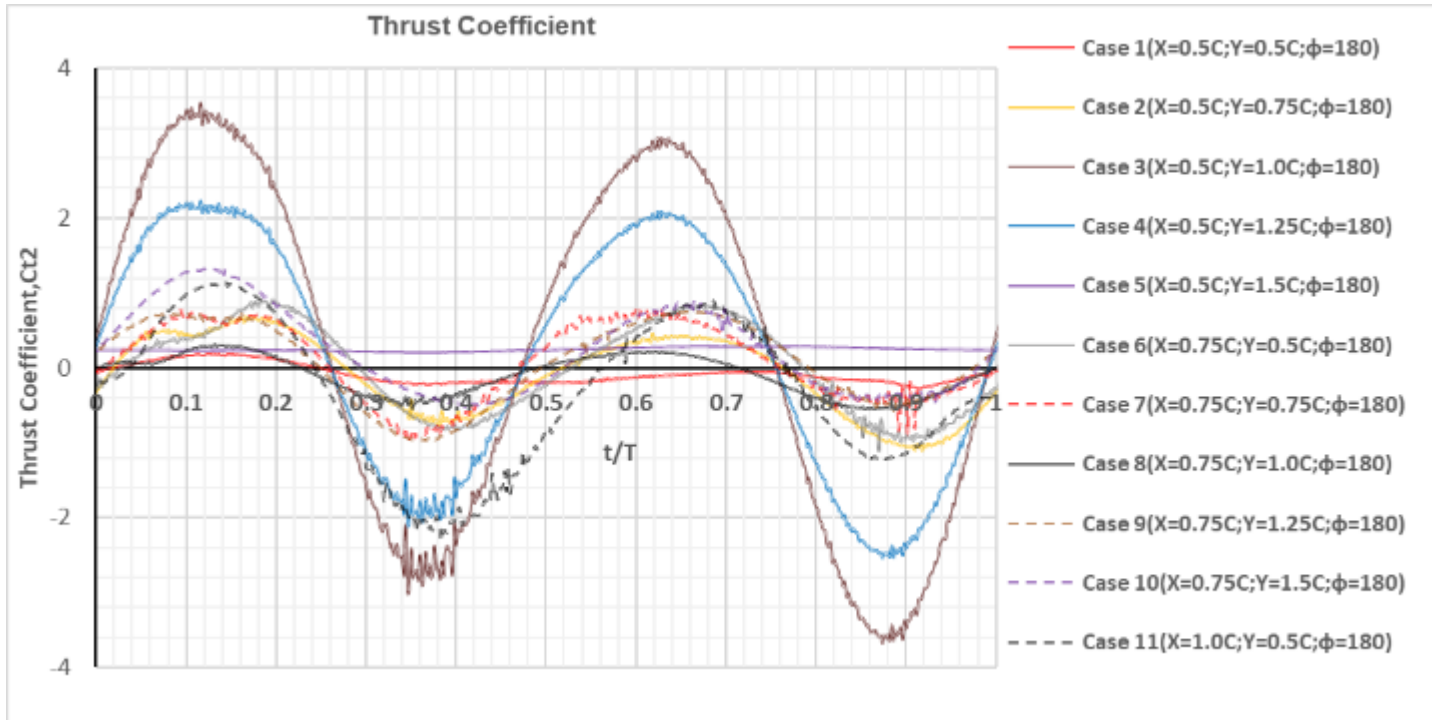
D-1: C_l time plots for $\phi=180^\circ$

APPENDIX E: C_{t1} - TIME PLOTS FOR $\Phi=180^\circ$



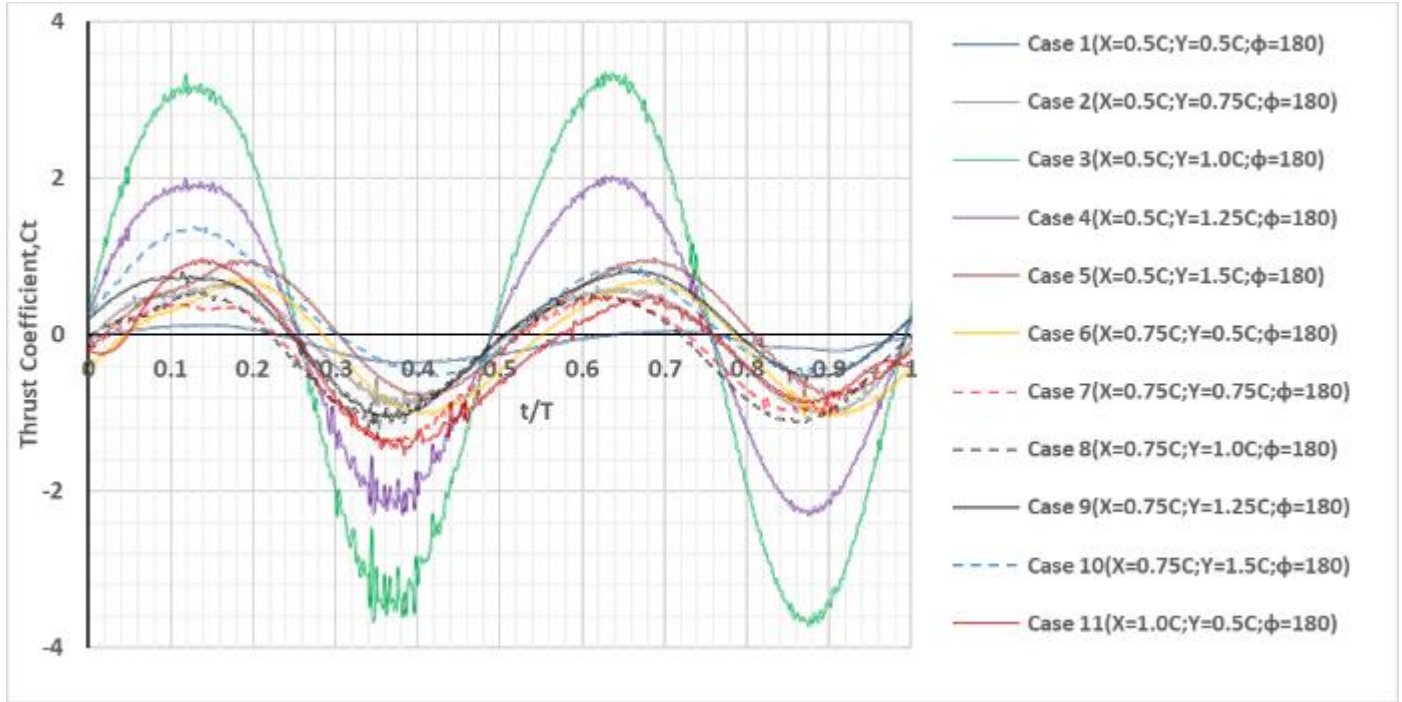
E-1: C_{t1} time plots for $\phi=180^\circ$

APPENDIX F: C_{t2} TIME PLOTS $\Phi=180^\circ$



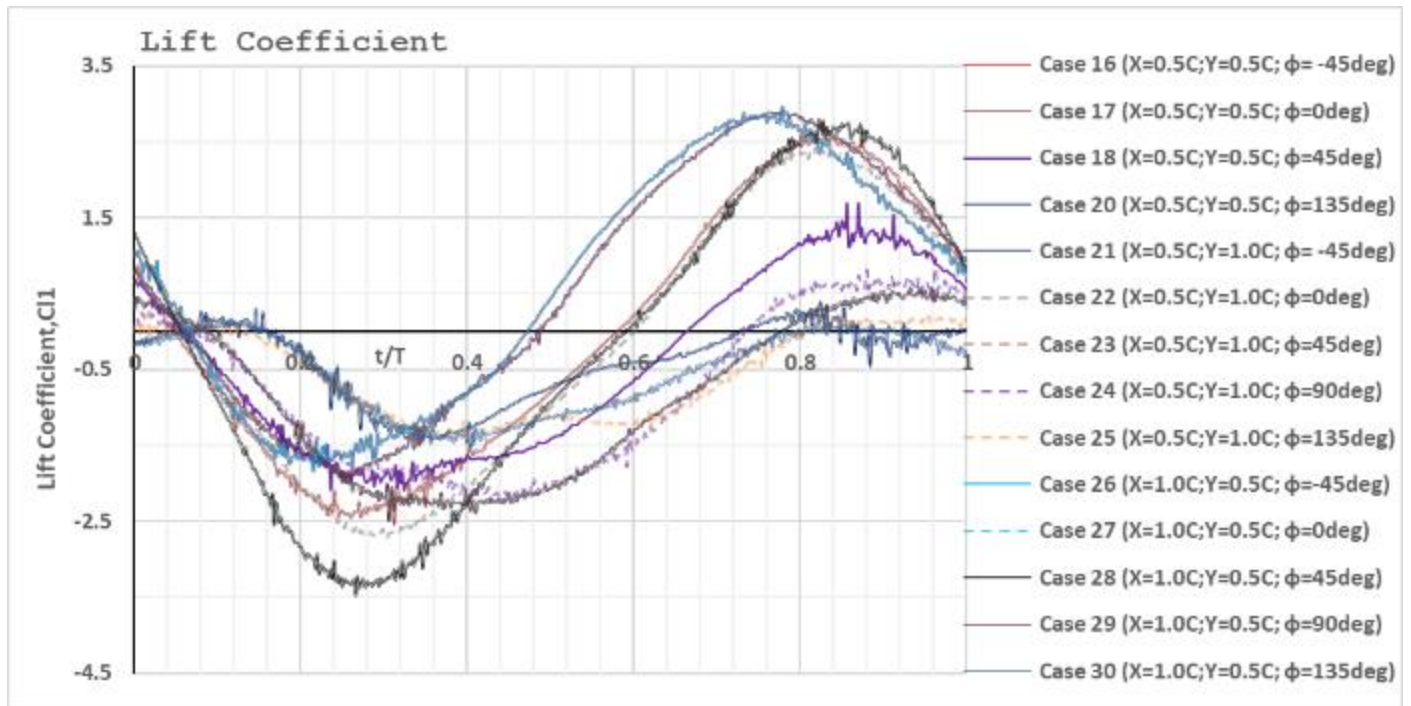
F-1: APPENDIX F- C_{t2} time plots for $\phi=180^\circ$

APPENDIX G: C_t TIME PLOTS FOR $\Phi=180^\circ$



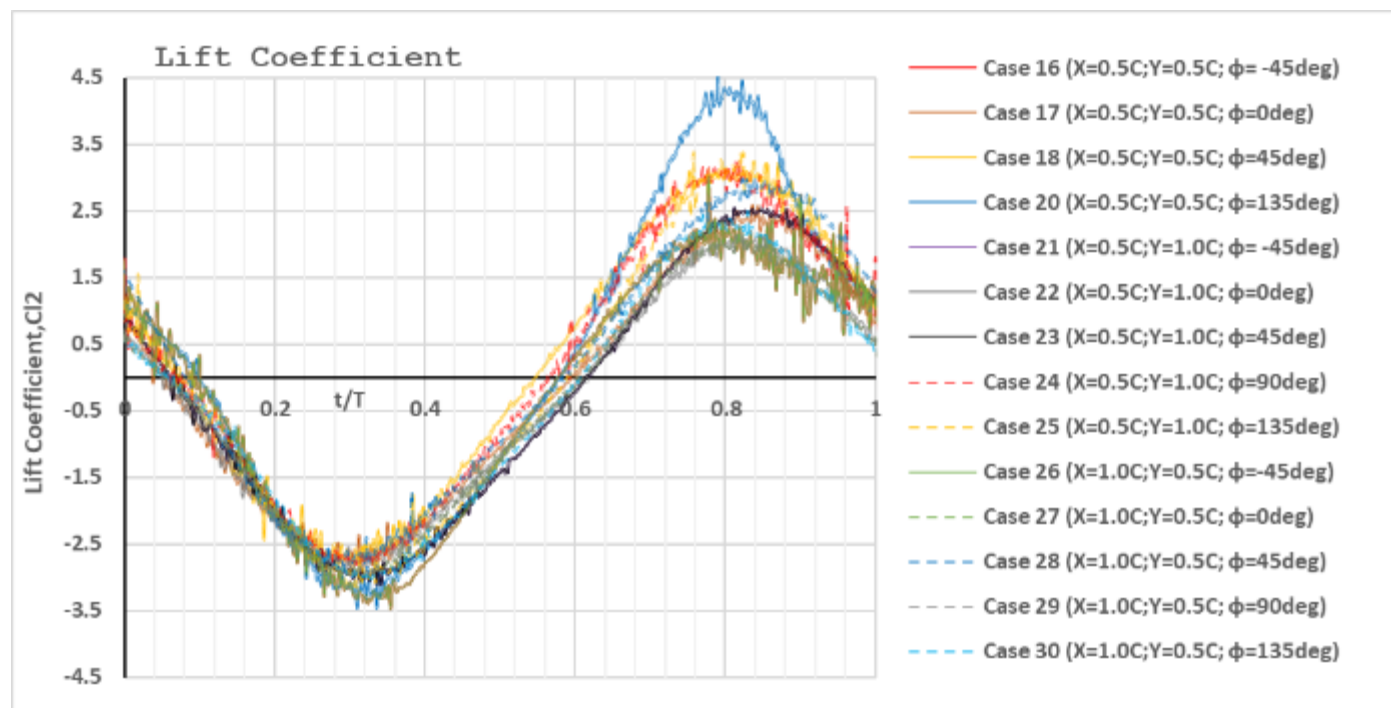
G-1: C_t time plots for $\phi=180^\circ$

APPENDIX H: Cl_1 TIME PLOTS FOR $\phi \neq 180^\circ$



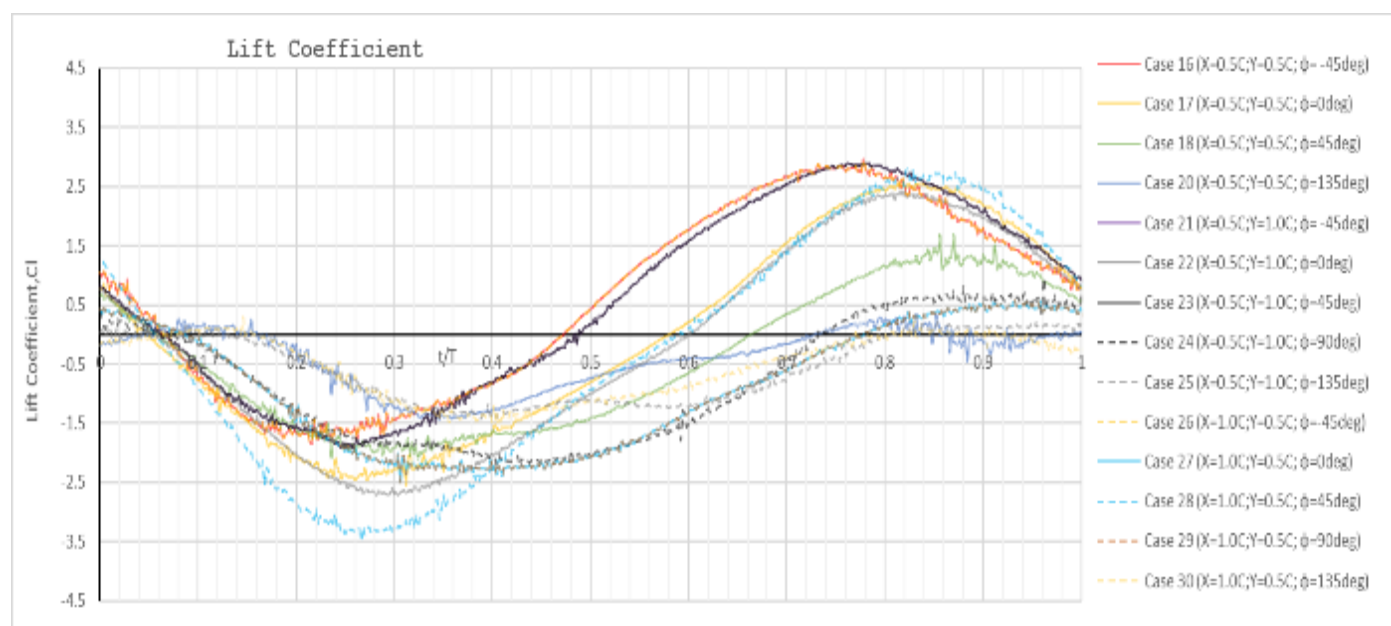
H-1: APPENDIX H- Cl_1 time plots for $\phi \neq 180^\circ$

APPENDIX I: Cl_2 TIME PLOTS FOR $\Phi \neq 180^\circ$



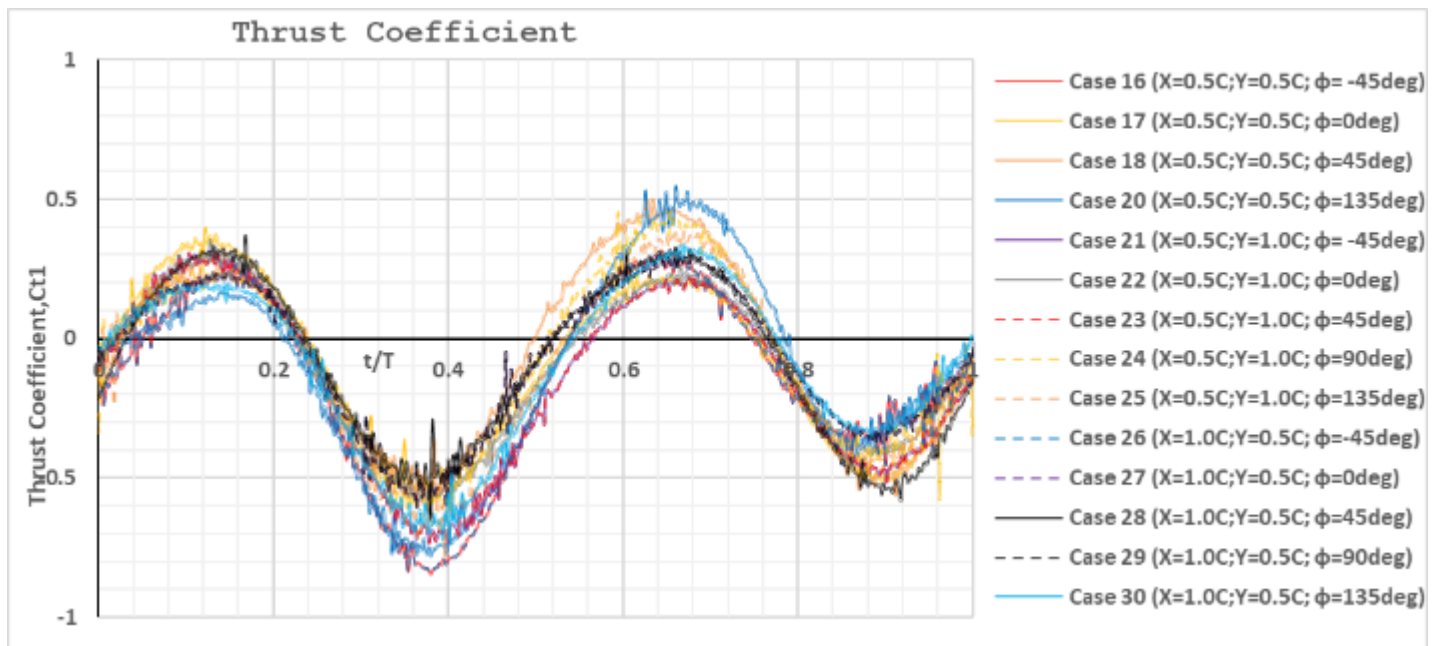
I-1: Cl_2 time plots for $\phi \neq 180^\circ$

APPENDIX J: C_I TIME PLOTS FOR $\phi \neq 180^\circ$



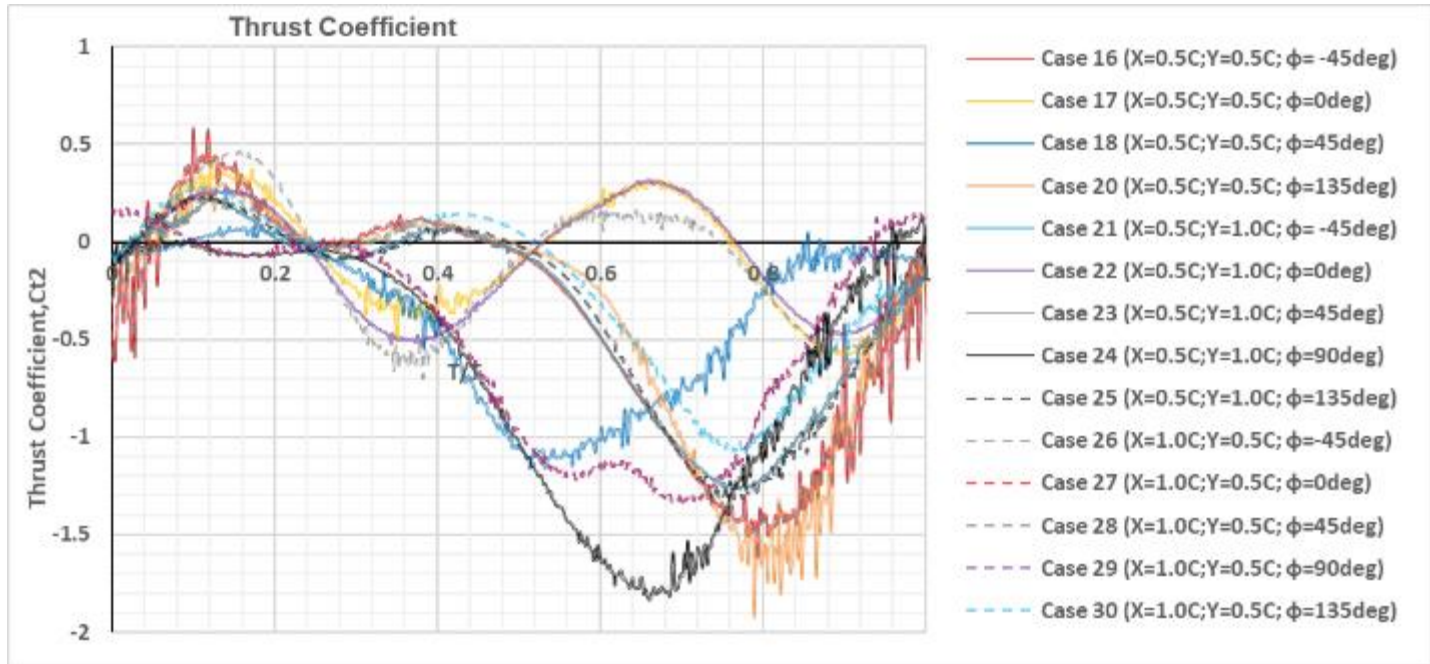
J-1: APPENDIX J- C_L time plots for $\phi \neq 180^\circ$

APPENDIX K: C_{t1} TIME PLOTS FOR $\Phi \neq 180^\circ$



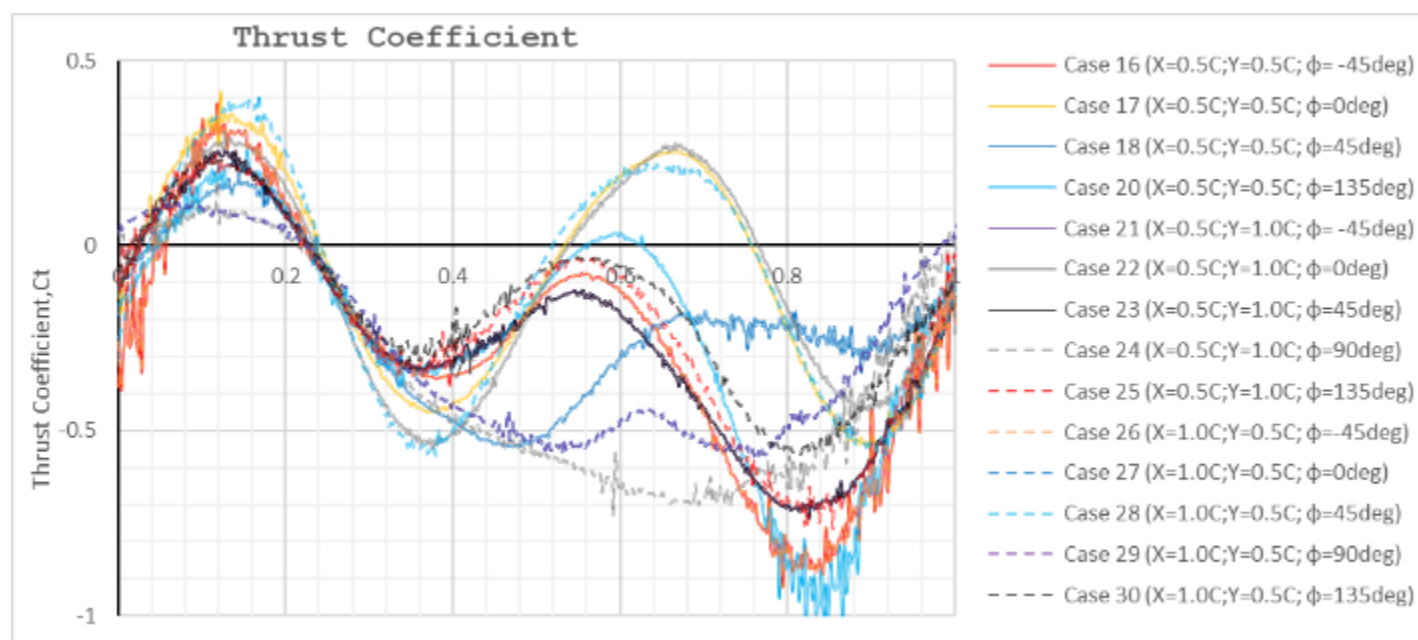
K-1: C_{t1} time plots for $\phi \neq 180^\circ$

APPENDIX L: C_{t2} TIME PLOTS FOR $\phi \neq 180^\circ$



L-1: C_{t2} time plots for $\phi \neq 180^\circ$

APPENDIX M: C_t TIME PLOTS FOR $\Phi \neq 180^\circ$



M-1: C_t time plots for $\Phi \neq 180^\circ$