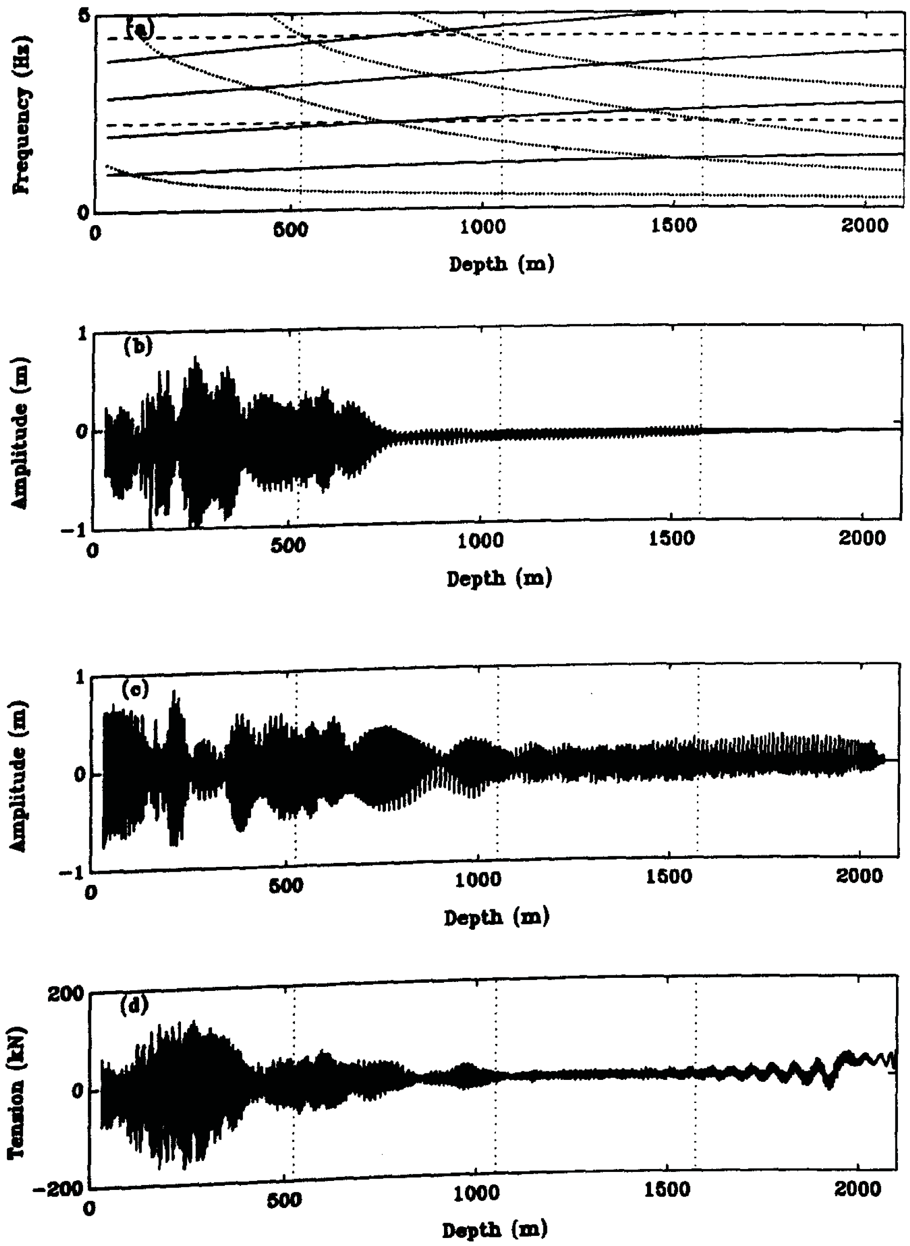

Figure L.9: Ascending cycle - Kloof Mine hoist system: 14.8 m/s
a) Linear Frequency Map.
b) In-Plane Motion - $s = l_c/4$.
c) Out-of-Plane Motion - $s = l_c/4$.
d) Dynamic Catenary Tension.

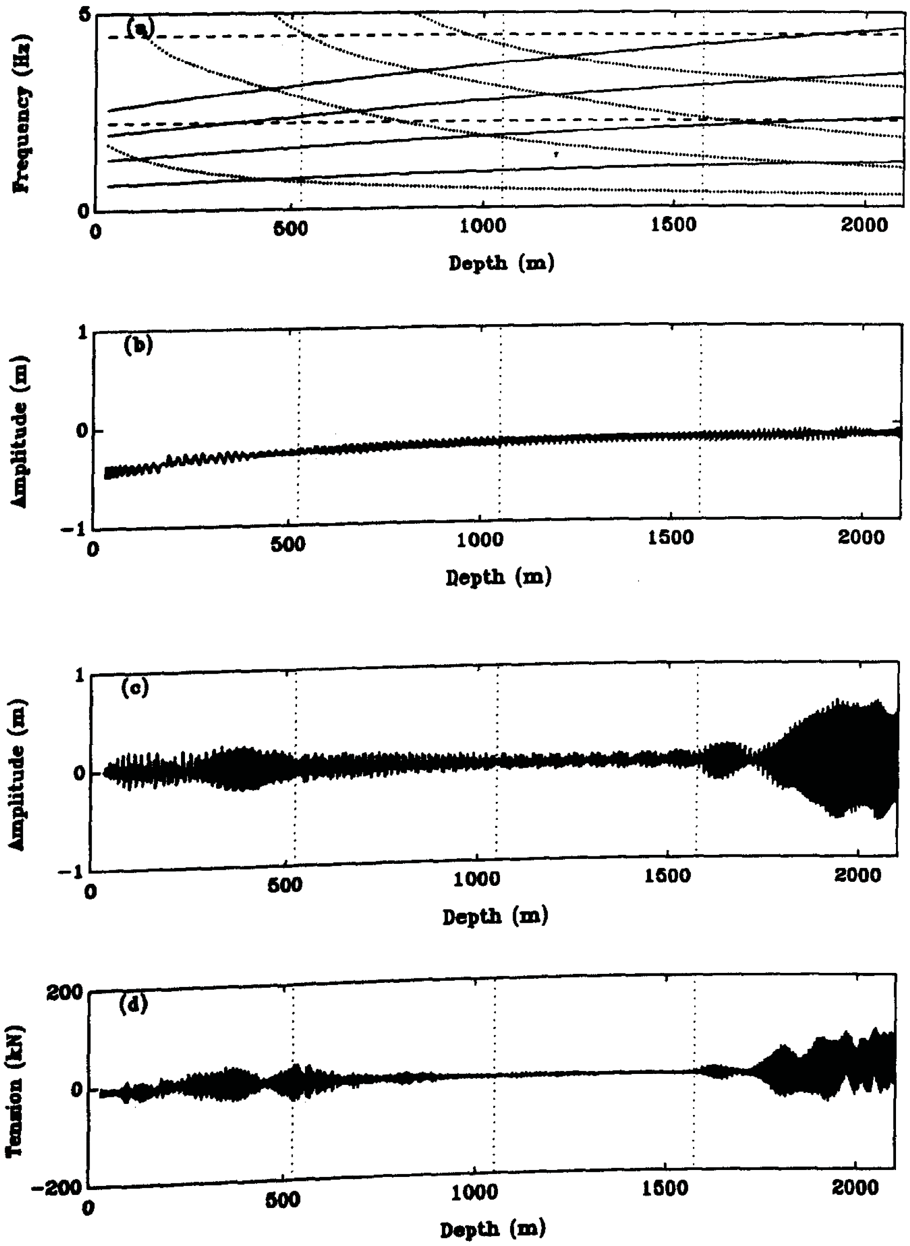

Figure L.10: Descending cycle - Kloof Mine hoist system: 14.8 m/s

a) Linear Frequency Map.

b) In-Plane Motion - $s = l_c/4$.

c) Out-of-Plane Motion - $s = l_c/4$.

d) Dynamic Catenary Tension.

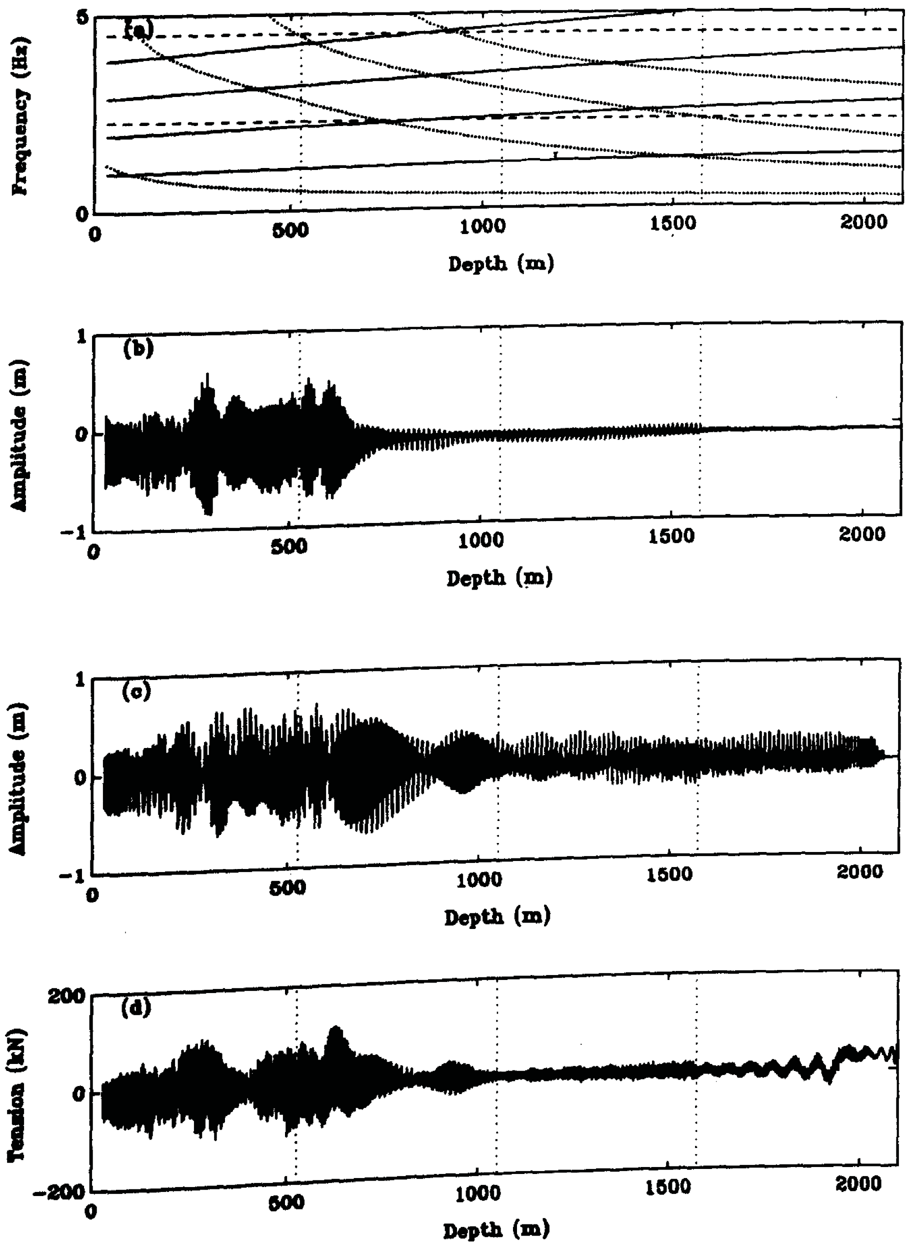

Figure L.11: Ascending cycle - Kloof Mine hoist system: 15 m/s

a) Linear Frequency Map.

b) In-Plane Motion - $s = l_c/4$.

c) Out-of-Plane Motion - $s = l_c/4$.

d) Dynamic Catenary Tension.

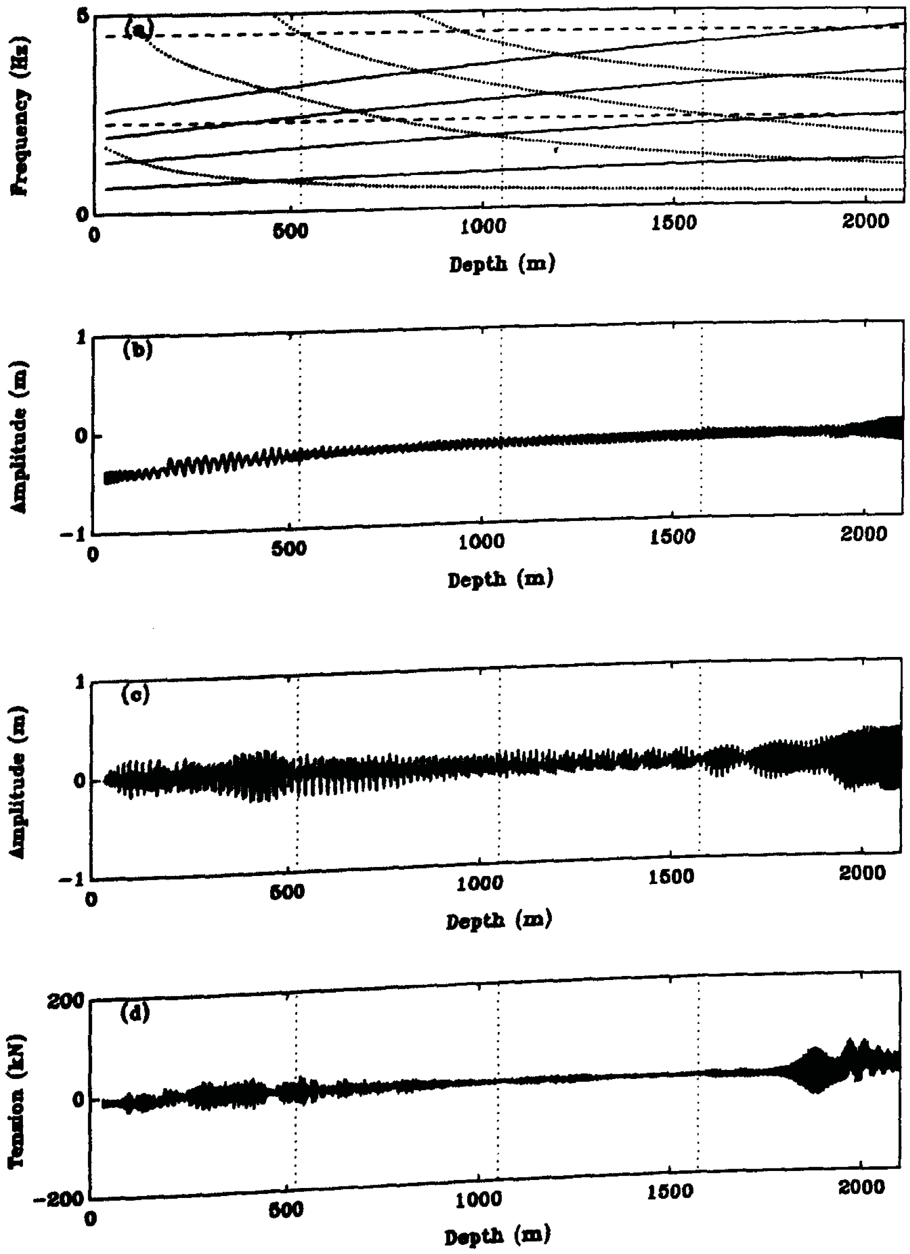

Figure L.12: Descending cycle - Kloof Mine hoist system: 15 m/s
a) Linear Frequency Map.
b) In-Plane Motion - $s = l_c/4$.
c) Out-of-Plane Motion - $s = l_c/4$.
d) Dynamic Catenary Tension.

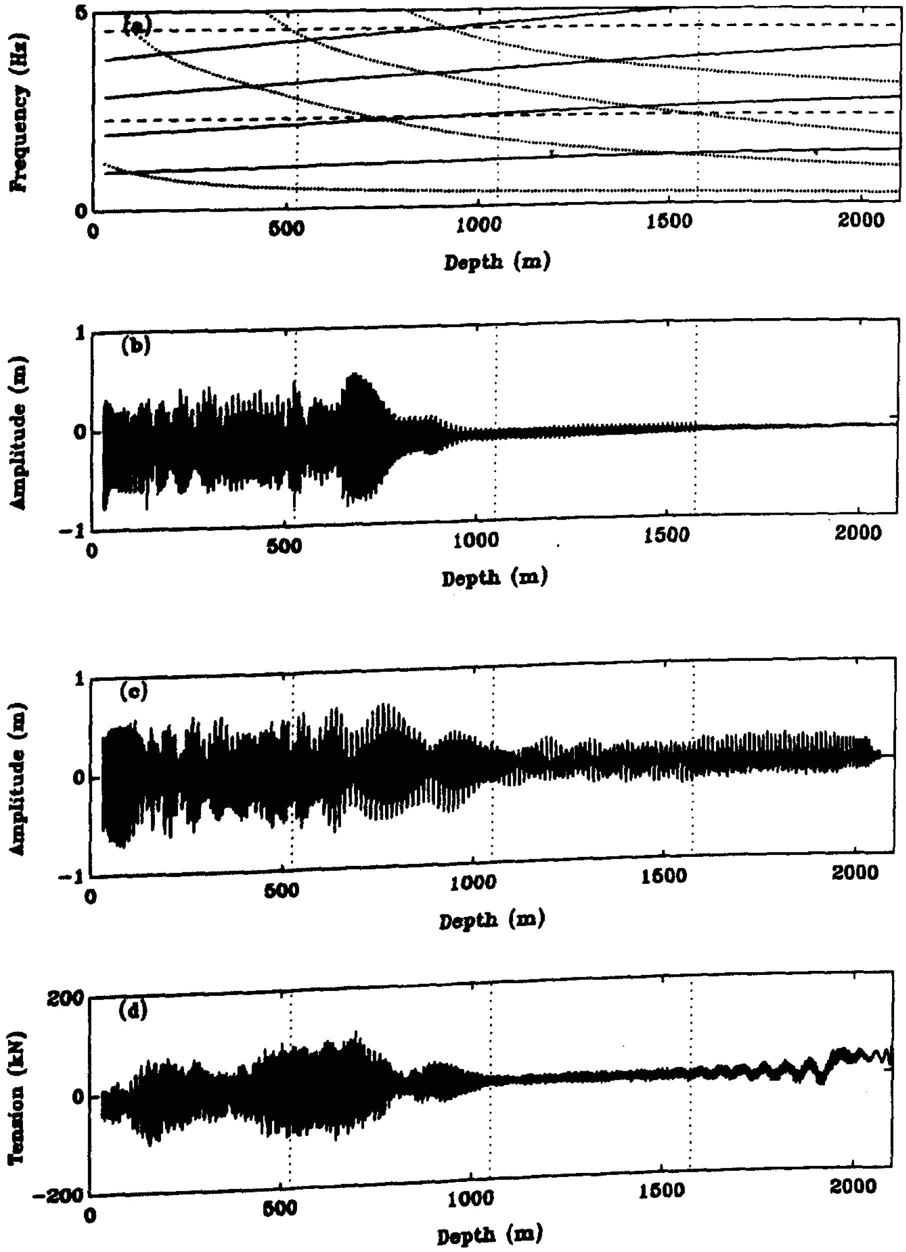

Figure L.13: Ascending cycle - Kloof Mine hoist system: 15.2 m/s

a) Linear Frequency Map.

b) In-Plane Motion - $s = l_c/4$.

c) Out-of-Plane Motion - $s = l_c/4$.

d) Dynamic Catenary Tension.

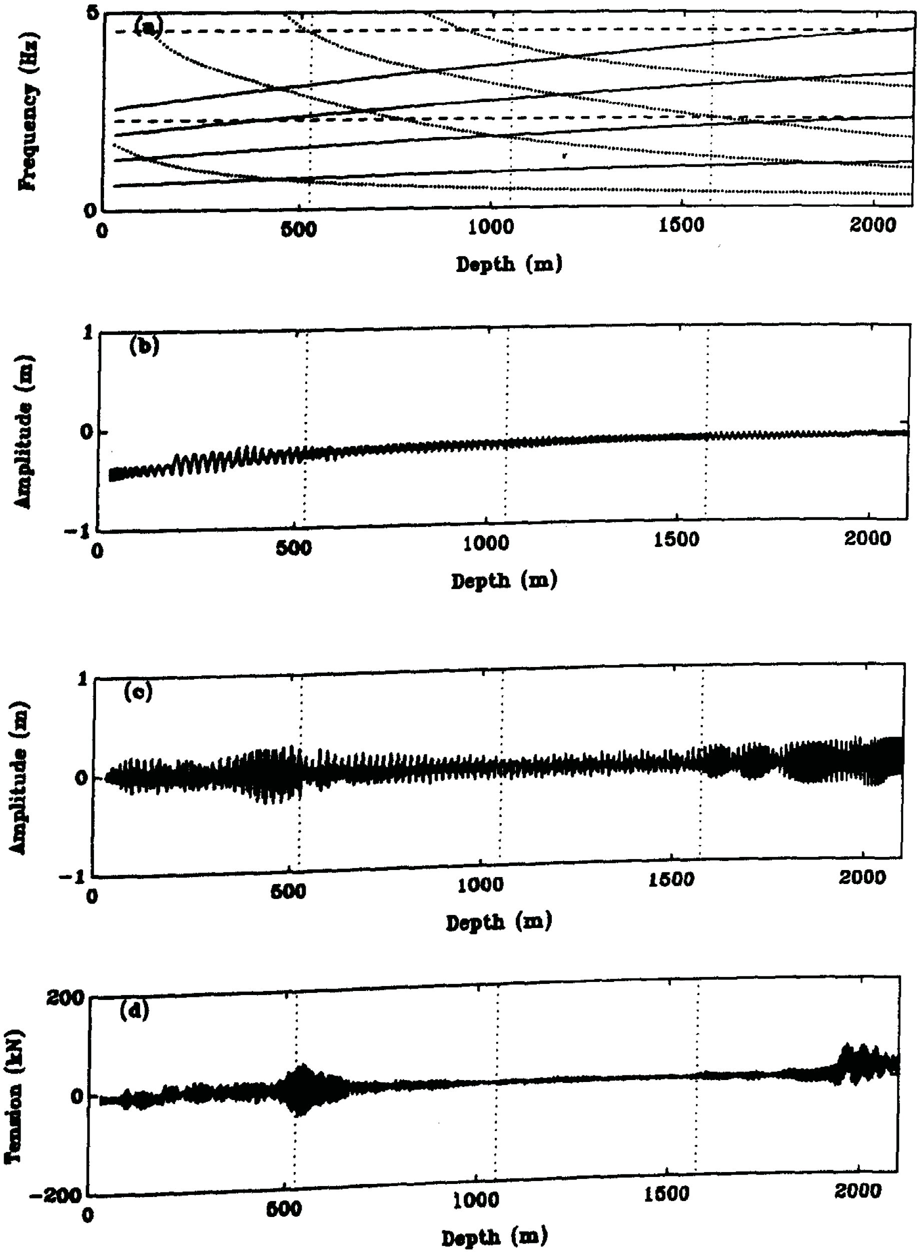

Figure L.14: Descending cycle - Kloof Mine hoist system: 15.2 m/s
a) Linear Frequency Map.
b) In-Plane Motion - $s = l_c/4$.
c) Out-of-Plane Motion - $s = l_c/4$.
d) Dynamic Catenary Tension.

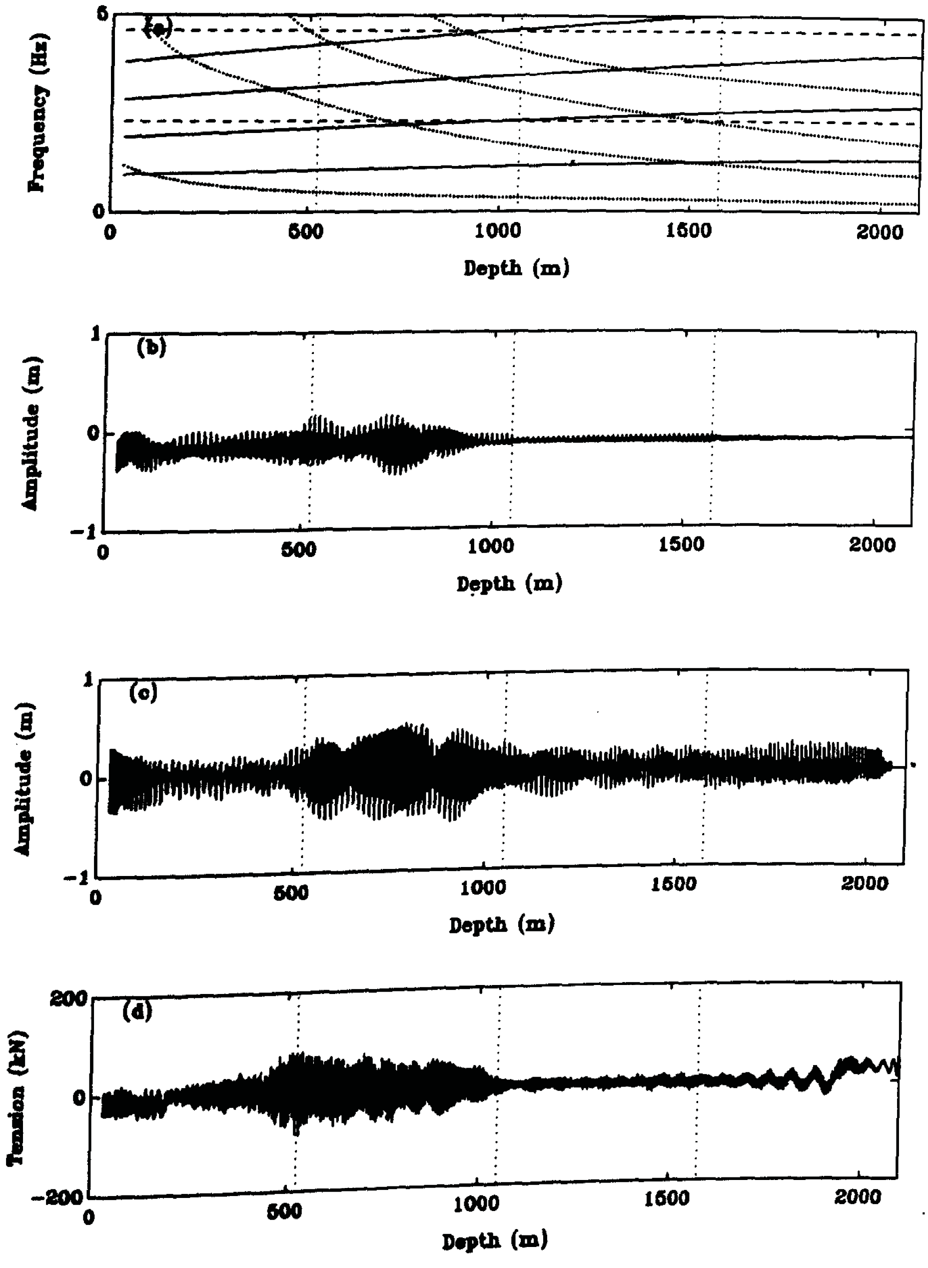

Figure L.15: Ascending cycle - Kloof Mine hoist system: 15.4 m/s

a) Linear Frequency Map.
b) In-Plane Motion - $s = l_c/4$.
c) Out-of-Plane Motion - $s = l_c/4$.
d) Dynamic Catenary Tension.

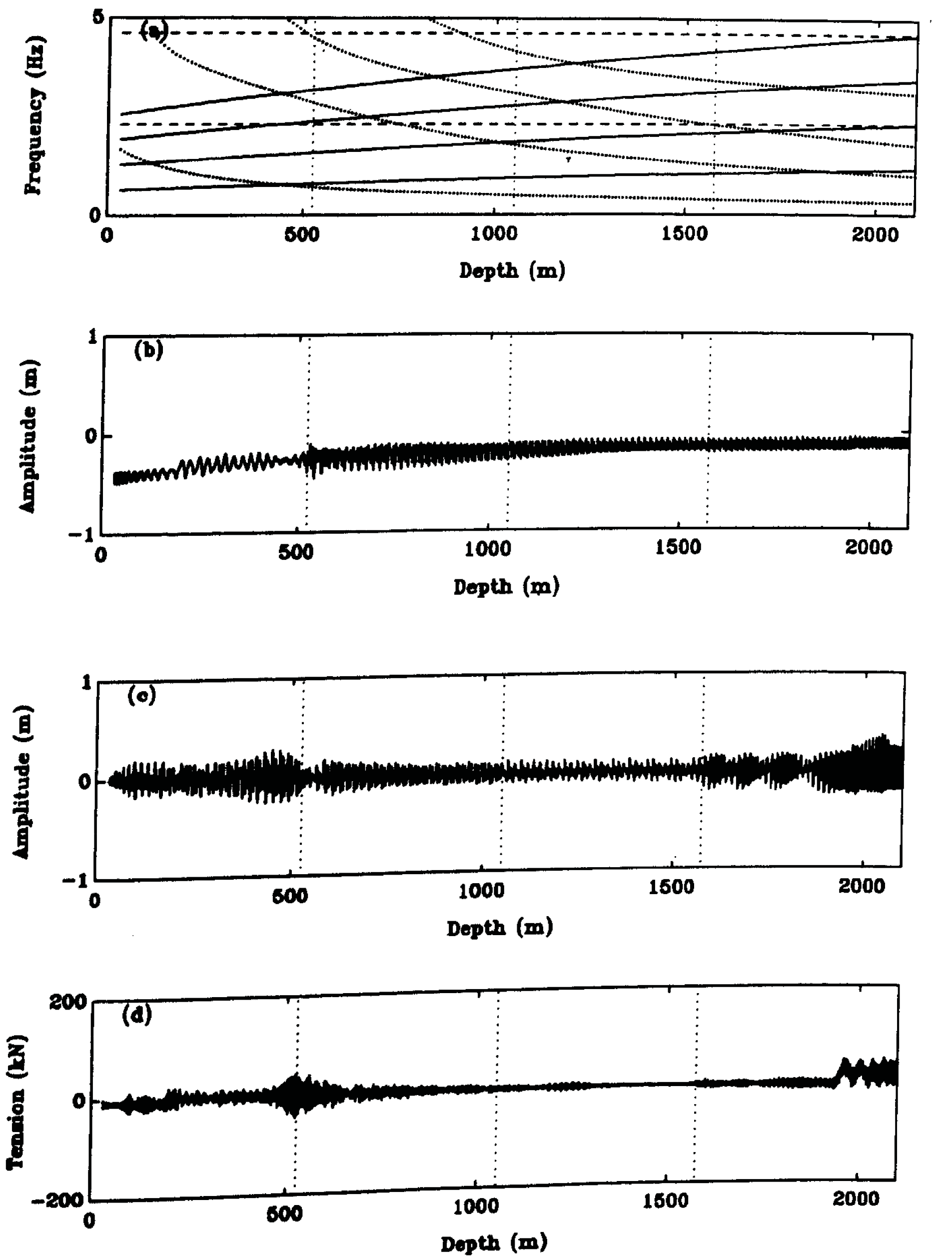

Figure L.16: Descending cycle - Kloof Mine hoist system: 15.4 m/s
a) Linear Frequency Map.
b) In-Plane Motion - $s = l_c/4$.
c) Out-of-Plane Motion - $s = l_c/4$.
d) Dynamic Catenary Tension.

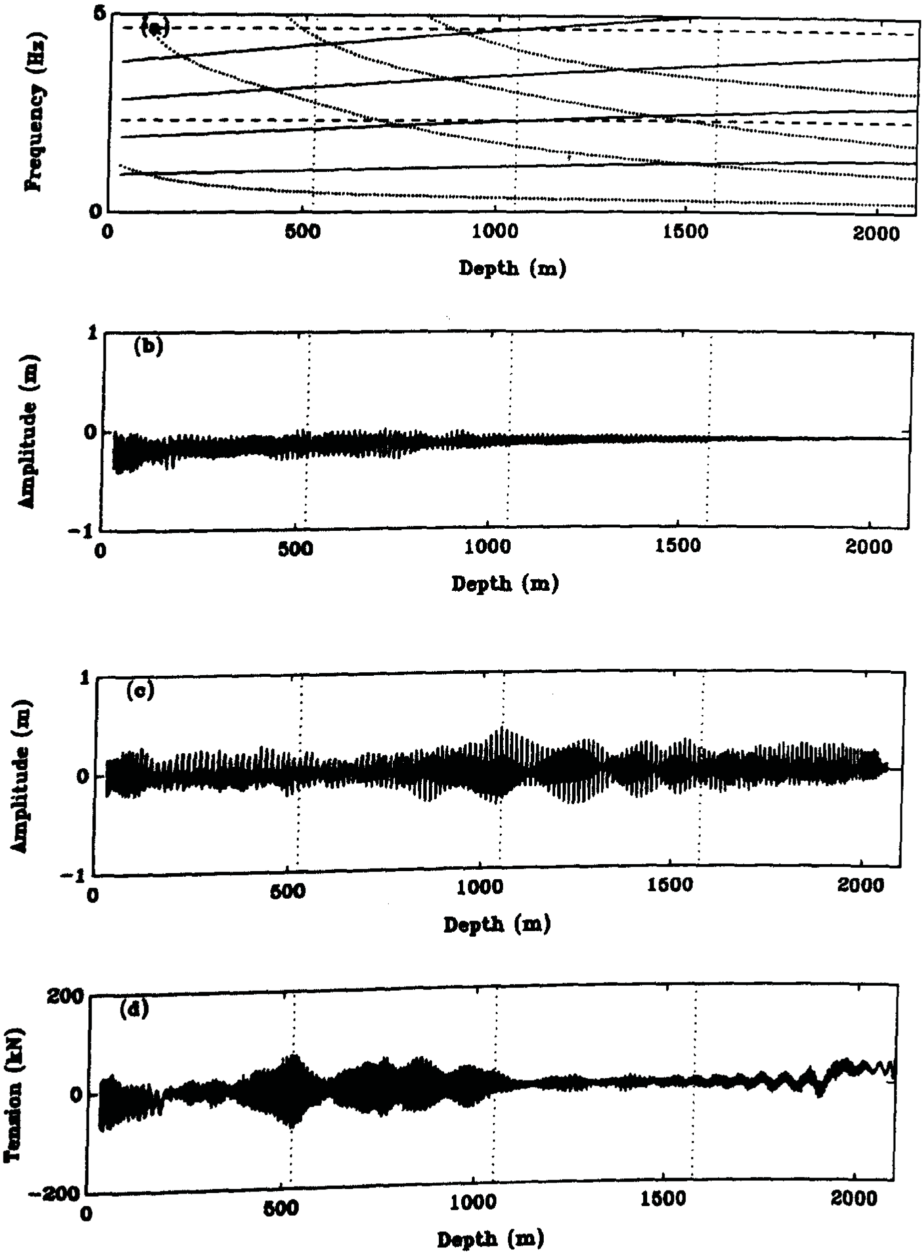

Figure L.17: Ascending cycle - Kloof Mine hoist system: 15.6 m/s
a) Linear Frequency Map.
b) In-Plane Motion - $s = l_c/4$.
c) Out-of-Plane Motion - $s = l_c/4$.
d) Dynamic Catenary Tension.

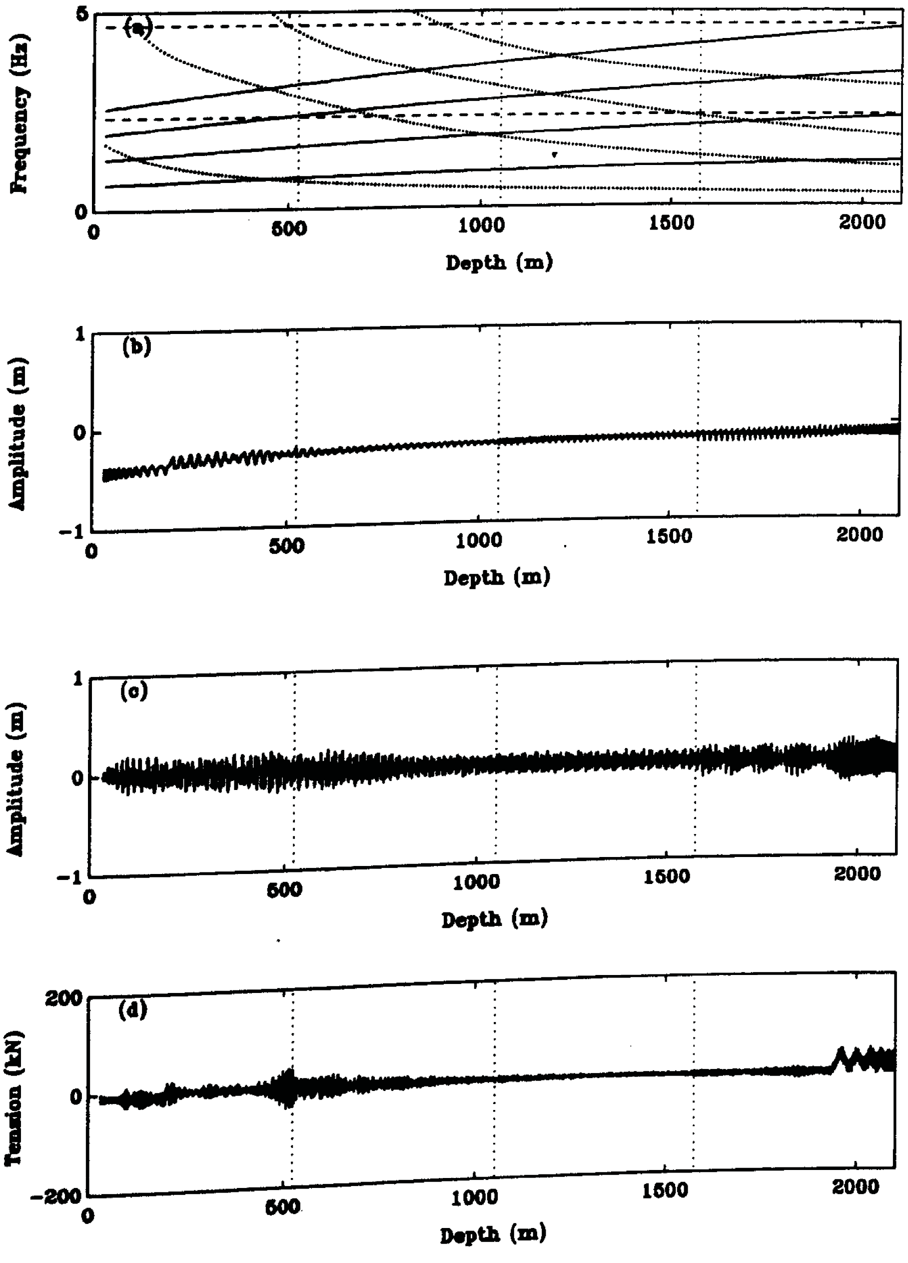

Figure L.18: Descending cycle - Kloof Mine hoist system: 15.6 m/s
a) Linear Frequency Map.
b) In-Plane Motion - $s = l_c/4$.
c) Out-of-Plane Motion - $s = l_c/4$.
d) Dynamic Catenary Tension.

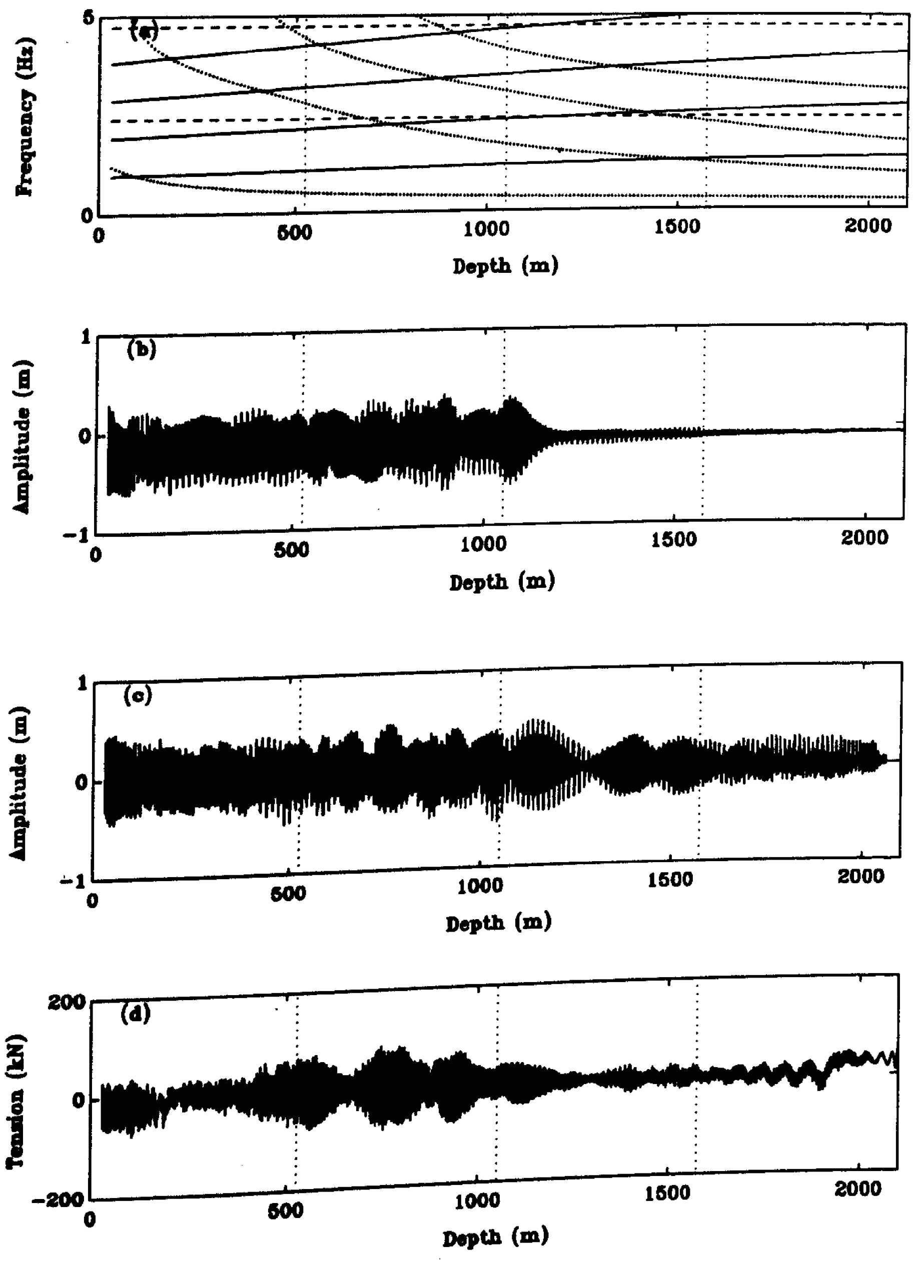

Figure L.19: Ascending cycle - Kloof Mine hoist system: 15.8 m/s
a) Linear Frequency Map.
b) In-Plane Motion - $s = l_c/4$.
c) Out-of-Plane Motion - $s = l_c/4$.
d) Dynamic Catenary Tension.

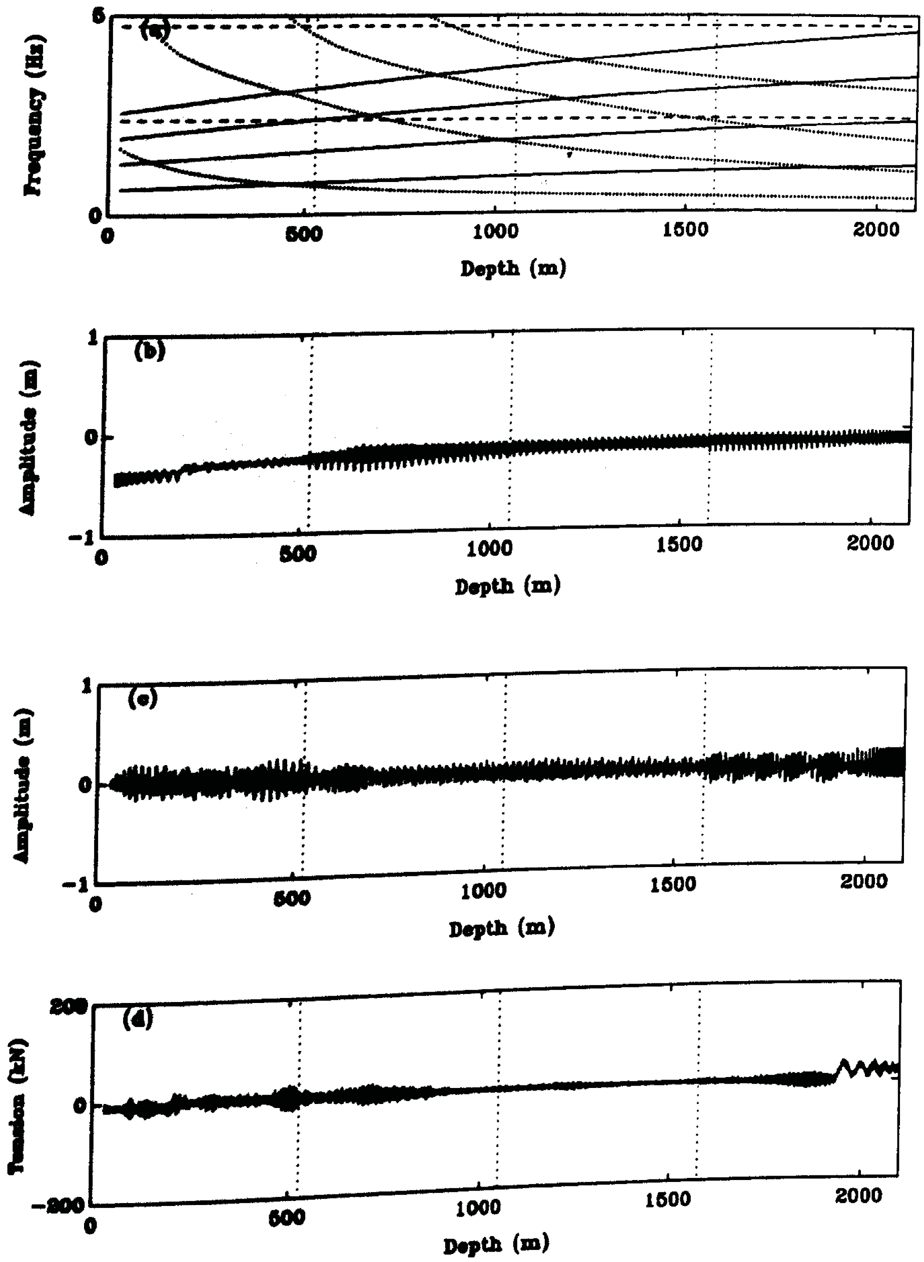

Figure L.20: Descending cycle - Kloof Mine hoist system: 15.8 m/s
a) Linear Frequency Map.
b) In-Plane Motion - $s = l_c/4$.
c) Out-of-Plane Motion - $s = l_c/4$.
d) Dynamic Catenary Tension.

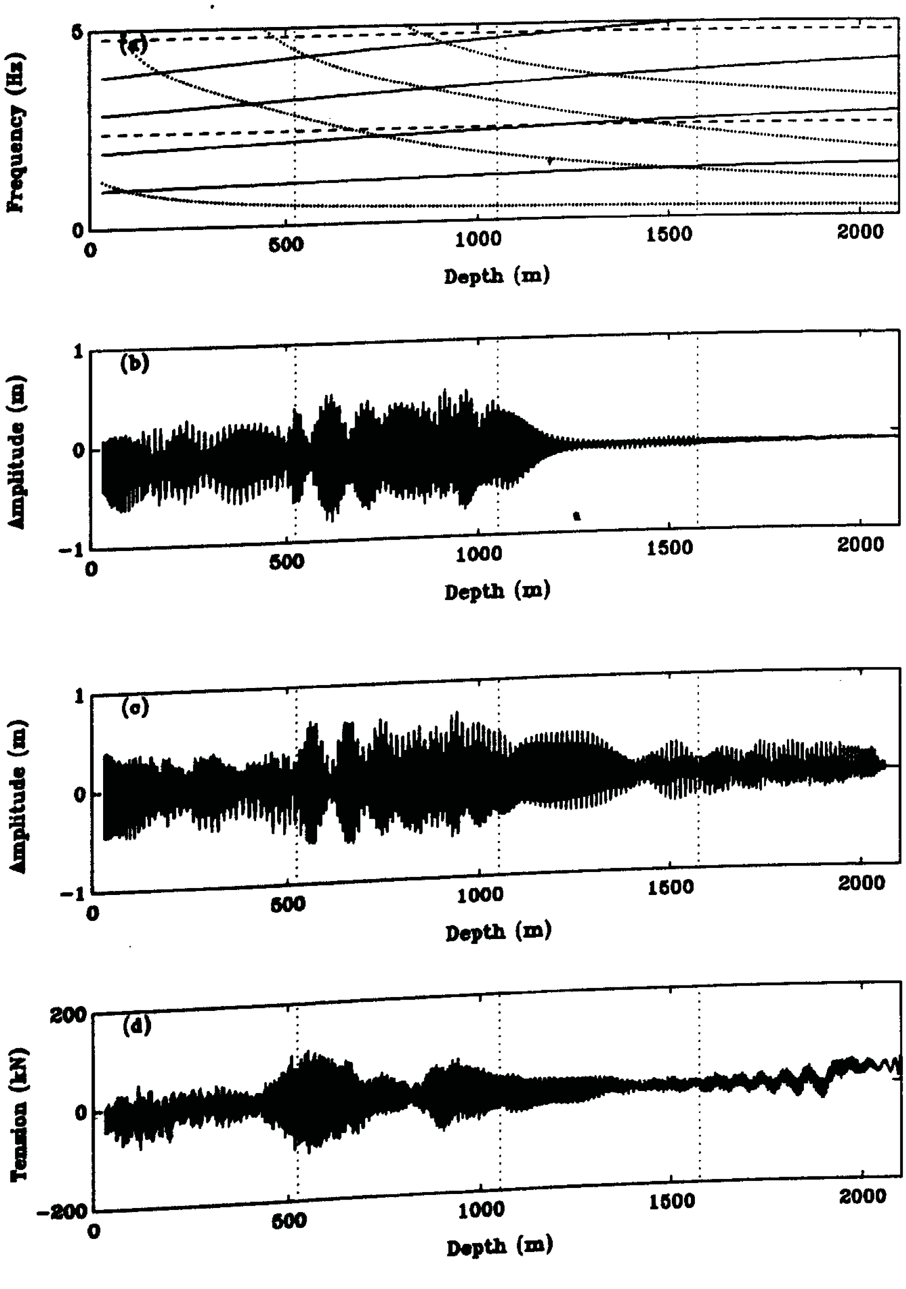

Figure L.21: Ascending cycle - Kloof Mine hoist system: 16 m/s
a) Linear Frequency Map.
b) In-Plane Motion - $s = l_c/4$.
c) Out-of-Plane Motion - $s = l_c/4$.
d) Dynamic Catenary Tension.

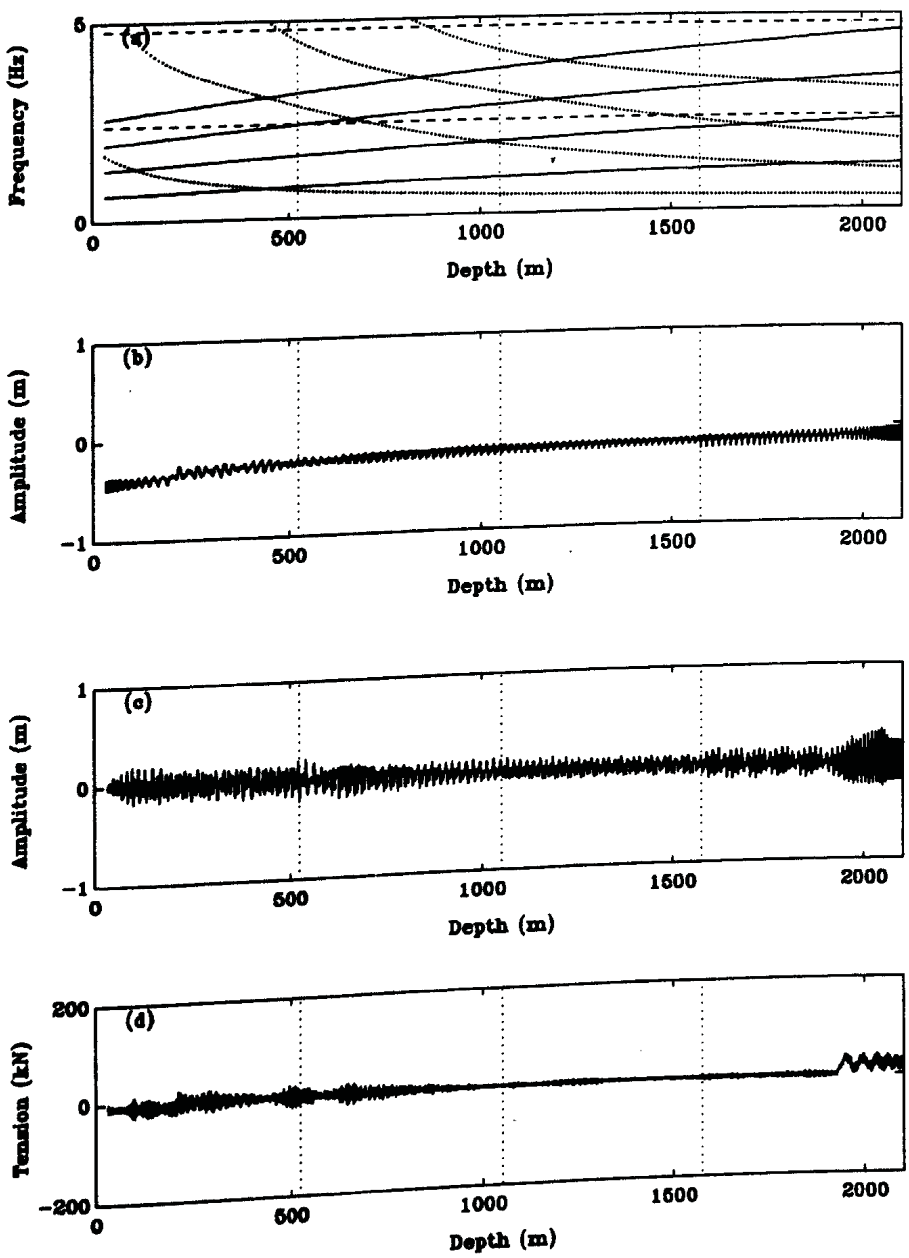

Figure L.22: Descending cycle - Kloof Mine hoist system: 16 m/s
a) Linear Frequency Map.
b) In-Plane Motion - $s = l_c/4$.
c) Out-of-Plane Motion - $s = l_c/4$.
d) Dynamic Catenary Tension.

Appendix M

Equations of Motion Including Sheave Wheel Constraints

The equations of motion developed in chapter 3 apply if the lateral motion of the rope at the sheave end of the catenary is constrained. This boundary condition is satisfied if a frictionless guide exists, which is aligned to the tangent of the equilibrium profile of the catenary at the sheave end. The rope is attached to this guide, such that motion in the tangential direction is admitted, whilst lateral motion is restrained. This constraint is a realistic approximation, since small longitudinal motion is generated at the sheave for realistic lateral deflections. Consequently the lateral movement which does exist in reality is not considered significant. However, the case where the geometry of the sheave is accounted for, and such an assumption is not made, is presented in this appendix. Since the curvature of the catenary, and the transport velocity of the rope add unnecessary complexity, they are neglected in the subsequent analysis. To further simplify the analysis, only the planar system is considered.

In order to develop the equations of motion without prescriptive boundary conditions at the sheave, the kinematic relationship between the movement of the rope and sheave requires consideration. Figure M.1 illustrates the equilibrium configuration of the rope, and the final configuration due to lateral and longitudinal motion of the station which was initially in contact with the sheave. Figure M.2 presents the geometric relationship between the rope and sheave rotation. A massless chord passes over the sheave wheel and attaches to the vertical rope. Thus the catenary, sheave and vertical rope are considered as separate sub-systems, which are combined via constraint equations developed to account for the kinematic relationships between the three subsystems.

Since the geometric relationship defining the interface between the end of the rope and sheave requires the definition of the displacements $u(l,t), v(l,t)$, the spatial derivative $v_{,x}(l,t)$, and the sheave rotation, three independent kinematic constraint equations involving these variables are required. An additional constraint relationship is required to couple the vertical subsystem to the sheave rotation. The constraint equations necessary to account for the sheave geometry are thus:

$$\begin{aligned} f_1 &= v_1 - (Rtan\frac{v_{x_1}}{2} + u_1)tanv_{x_1} \\ f_2 &= R\theta - (u_1^2 + v_1^2)^{1/2} \\ f_3 &= \int_0^{l_1}(1 + u_x + \frac{1}{2}v_x^2)sin(v_x - v_{x_1})dx + (l_1 - Rtan\frac{v_{x_1}}{2})sinv_{x_1} \\ f_4 &= \overline{u}_o - R\theta \end{aligned} \tag{M.1}$$

where u_1, v_1 represent the displacement at the interface between the rope and chord. v_{x_1} represents the slope of the rope at the interface between the rope and chord. θ, $\overline{u}_o$ represent the sheave rotation, and the displacement of upper boundary of the vertical system.

The first equation defines the constraint relationship ensuring that the chord between the end point of the rope and the point of contact with the sheave, is tangential to the rope and the sheave. The second equation relates the total displacement of the end point of the rope to the sheave rotation. The third equation requires that the profile of the catenary is geometrically related to the distance between the drum and sheave, l_1, and the slope v_{x_1}. The fourth equation couples the sheave rotation and the vertical system.

The equations of motion may be obtained by introducing Lagrange multipliers λ_i and applying Hamilton's principle[1]. Following Craig[1981], the potential energy V is modified to account for the constraint forces by utilising V^* where:

$$V^* = V - \sum_{i=1}^{C} \lambda_i f_i$$

and C represents the number of constraint equations f_i.

[1]The constraint equations are holonomic and thus the motion at t0 and t1 is considered defined, hence the variation of the motion at these times is zero (Meirovitch[1970]).

Following the development in chapter 3, and accounting the constraint via the potential energy of the rope, the Lagrangian is defined as:

$$\begin{aligned}
\mathcal{L} &= \int_0^{l_1} \left\{ \frac{1}{2} m(\dot{u}^2 + \dot{v}^2) - (P_1 + \frac{1}{2} AE\epsilon)\epsilon + \lambda_3 \overline{f}_3 \right\} dx \\
&+ \int_0^{l_2} \left\{ \frac{1}{2} m\dot{\overline{u}}^2 - (\overline{P} + \frac{1}{2} AE\overline{\epsilon})\overline{\epsilon} + mg\overline{u} \right\} dy \\
&+ \frac{1}{2} I\dot{\theta}^2 + \frac{1}{2} M\dot{\overline{u}}_2^2 + Mg\overline{u}_2 \\
&+ \lambda_1 f_1 + \lambda_2 f_2 + \lambda_3 \overline{\overline{f}}_3 + \lambda_4 f_4
\end{aligned}$$

where x, y refer to the spatial domain of the catenary and vertical rope; P_1, $\overline{P}(y)$ represent the static tension in the catenary (constant), and in the vertical rope respectively:

$$\overline{f}_3 = (1 + u_x + \frac{1}{2} v_x^2) sin(v_x - v_{x_1})$$

$$\overline{\overline{f}}_3 = (l_1 - R tan \frac{v_{x1}}{2}) sin v_{x_1}$$

$$\epsilon = u_x + \frac{1}{2} v_x^2$$

$$\overline{\epsilon} = \overline{u}_y$$

Hamilton's principle requires stationarity of the action integral, for arbitrary variations in the generalised co-ordinates, vanishing at the limits t_o, t_1.

$$\delta I = \delta \int_{t_0}^{t_1} \mathcal{L} dt = 0$$

The Lagrangian function contains continuous and discrete terms. Through appropriate integration by parts, and accounting for the equilibrium configuration, the resulting equations of motion are:

$$u_{,tt} = c^2 u_{,xx} + c^2\{v_{,x} v_{,xx}\} - \frac{1}{\rho A}\{\lambda_3 \frac{\partial}{\partial x}(\frac{\partial \overline{f}_3}{\partial u_x})\} \tag{M.2}$$

$$v_{,tt} = \overline{c}^2 v_{,xx} + c^2\{(u_{,x} v_{,x})_{,x} + \frac{3}{2} v_{,x}^2 v_{,xx}\} - \frac{1}{\rho A} \lambda_3 \frac{\partial}{\partial x}(\frac{\partial \overline{f}_3}{\partial v_x}) \tag{M.3}$$

$$I\ddot{\theta} = \lambda_2 \frac{\partial \overline{f}_2}{\partial \theta} + \lambda_4 \frac{\partial \overline{f}_4}{\partial \theta} \tag{M.4}$$

$$\overline{u}_{tt} = c^2 \overline{u}_{,yy} \tag{M.5}$$

$$M\ddot{\overline{u}}_2 = -AE \frac{\partial \overline{u}}{\partial y}|_{(l_2,t)} \tag{M.6}$$

$$\begin{bmatrix} \frac{\partial f_1}{\partial u_1} & \frac{\partial f_2}{\partial u_1} & \frac{\partial \overline{f}_3}{\partial \underline{u}}|_{(l_1,t)} & 0 \\ \frac{\partial f_1}{\partial v_1} & \frac{\partial f_2}{\partial v_1} & \frac{\partial \overline{f}_3}{\partial v_{\underline{x}}}|_{(l_1,t)} & 0 \\ \frac{\partial f_1}{\partial v_{x_1}} & \frac{\partial f_2}{\partial v_{x_1}} & \frac{\partial \overline{f}_3}{\partial v_{x_1}} & 0 \\ 0 & 0 & 0 & \frac{\partial f_4}{\partial \overline{u}_0} \end{bmatrix} \begin{Bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \end{Bmatrix} = \begin{Bmatrix} AE\epsilon_1 \\ (P_1 + AE\epsilon_1) v_{x_1} \\ 0 \\ AE\overline{\epsilon}_0 \end{Bmatrix} \tag{M.7}$$

Equations (M.7) are functions of the unknown variables $u(l,t), v(l,t), v_x(l,t)$. Thus equations (M.2)-(M.7) represent eight equations in twelve unknowns ie the variables $u(x,t), v(x,t), u(l,t), v(l,t), v_x(l,t), \theta, \overline{u}(0,t), \overline{u}(y,t), \lambda_1, \lambda_2, \lambda_3, \lambda_4$. The four additional equations required to define the system are provided by the four equations of constraint M.1. This results in a set of mixed ordinary and continuous differential and algebraic equations, which must be satisfied simultaneously. In addition, the constraints may be redundant at various times during the motion. The solution of these equations will present a difficult task. It may be possible to transform the equations into a mixed set of ordinary differential equations and nonlinear algebraic equations. This would require the application of an expansion for the continuous variables. If such a transformation is possible, then standard numerical techniques exist to integrate the equations with embedded nonlinear algebraic equations of constraint. Such methods are discussed by Amirouche[1992], Nikravesh[1988]. Further consideration was not given to the equations presented in this appendix, since the boundary condition assumed at the interface between the catenary and sheave, as implemented in chapter 3, was considered sufficiently accurate. An accurate representation of the sheave interface would be necessary if very large catenary motion and sheave rotation occurred. In the context of the mine hoist system the rotation of the sheave is of the order of $2v^2/l_cR \approx 0.01$.

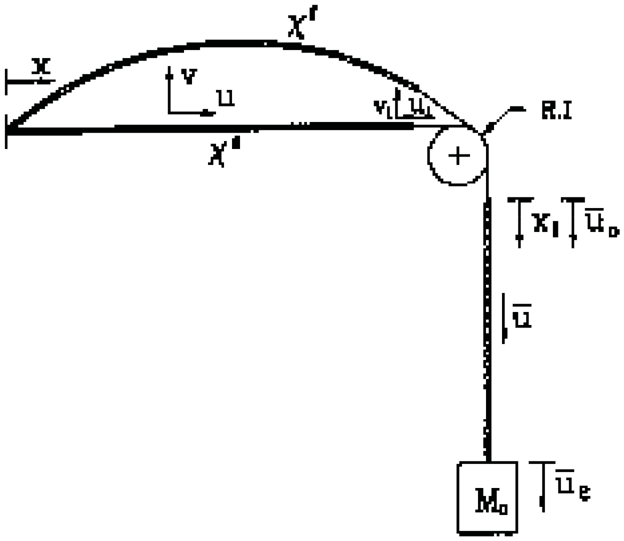

Figure M.1: System configuration with geometric constraints

χ^e Equilibrium configuration
χ^f Final configuration

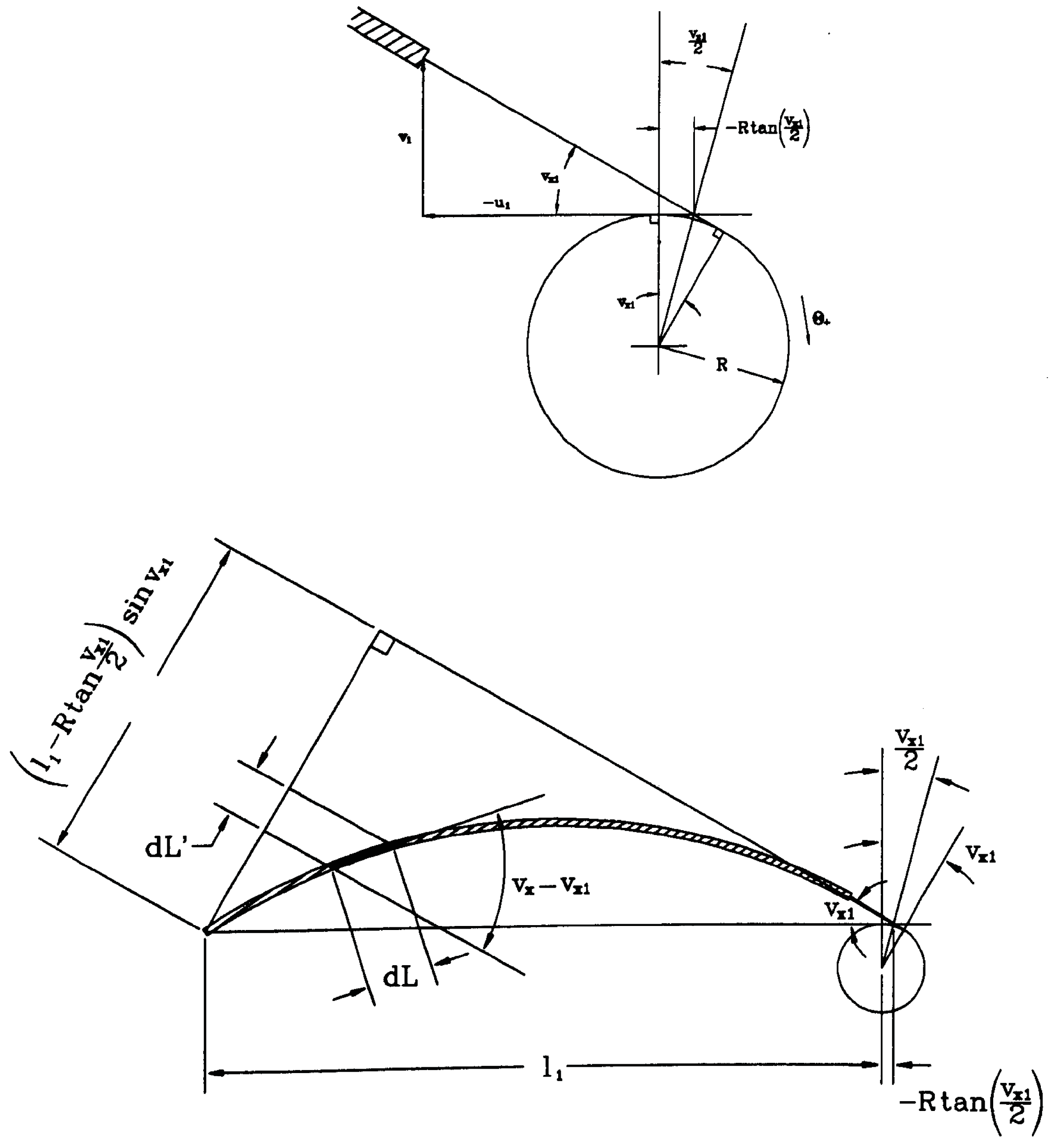

Figure M.2: Geometric constraint relationships

$$dL = \{1 + u_x + \frac{1}{2}v_x^2\}dx, \qquad dL' = dLsin(v_x - v_{x_1}) \qquad \int_0^{l_1} dL'dx = (l_1 - Rtan\frac{v_{x_1}}{2})sinv_{x_1}$$

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