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Numerical Model of Towing Dynamics of a Long Flexible Liferaft in Irregular Waves

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Abstract

The equations of motion for the coupled dynamics of a long flexible liferaft and fast rescue craft in an irregular ocean wave are formulated in two dimensions using the methods of Kane and Levinson (1985). The flexible raft is modeled as spring-connected lumped masses and it is assumed that the motion normal to the wave surface is small and can be neglected, i.e. the bodies move along the propagating wave profile. The wave forces are applied using Morison's equation for bodies in accelerated flow. Wind loads are similarly modeled using drag coefficients. The equations are solved numerically using the Runge-Kutta routine "ode45" of MATLAB®. The numerical model provides guidelines for predicting the tow loads and motions in severe sea states.

Keywords :Towing, flexible raft, irregular wave, numerical model

1 Introduction

Long flexible liferafts are being used as a means of evacuation from many sea going vessels and petroleum installations. Large cruise ships and passenger ferries may be equipped with such liferafts that are capable of holding up to 150 people each. Even though inflatable liferafts are considered a mandatory piece of survival equipment on any sea-going vessel, their operational performance in varying sea states is largely unknown. Current regulations by the International Maritime Organisation require liferafts to be towed in calm water conditions to achieve certification. Since it is difficult and dangerous to perform tests in storm conditions, it is useful to develop numerical models which can provide guidelines to the behaviour of marine systems in severe sea states. The two-dimensional problem of a single small body in waves was addressed by Marchenko (1999) using a vectorial approach and by Grotmaack and Meylan (2006) using Hamilton's Principle. These works are based on a slope sliding model and lead to the same equation of motion. Here we consider the coupled motions of the bodies on an irregular wave. The wave profile is determined from a standard Pierson-Moskowitz spectrum. The liferaft is modeled as n spring-connected lumped masses P_k $(k = 1, \ldots, n)$ and the FRC (Fast Rescue Craft) is modeled by mass P_{n+1}. For towing in following seas, the tow line connects particles P_n and P_{n+1}, and for towing in head seas the tow line connects masses P_1 and P_{n+1}. It is assumed that the dimensions of all masses are small relative to the wavelength corresponding to the centroidal period of the spectrum (less than one-fifth of the wavelength) so that wave reflection and diffraction are negligible.We also assume that the motion of the bodies normal to the wave surface is small and can be neglected. The governing equations are derived in two dimensions using Kane's equations of motion (Kane and Levinson, 1985) and solved numerically.

2 Kinematics

The problem is illustrated in Fig 1. Point O is the origin of a fixed inertial

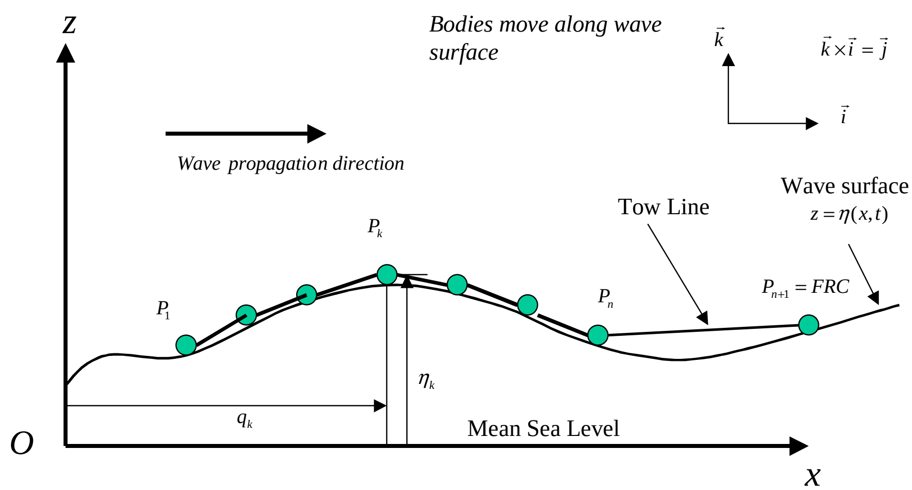

Figure 1: Configuration

coordinate system with x axis at the mean sea level , z axis pointing vertically upwards with unit vectors $\overrightarrow{i}, \overrightarrow{k}$ in x, z directions respectively. The flexible liferaft (P_1 to P_n) is being towed by a Fast Rescue Craft (P_{n+1}), both constrained to move on the surface of an irregular wave which is propagating in the positive x direction. The wave profile $z = \eta\left(x, t\right)$ is represented as the sum of p

sinusoidal components and written in the form

$$\eta(x,t) = \sum_{j=1}^{p} A_j \cos\left(k_j x - \omega_j t + \phi_j\right) \tag{1}$$

where t is time. The amplitudes A_j and frequencies ω_j are determined from a typical wave spectrum and the phase angles ϕ_j are chosen randomly. At time t, the position of body k is (q_k, η_k) where $\eta_k = \eta(q_k, t)$, $k = 1, \ldots m$ and $m = n + 1$. The generalised coordinates are q_r and we define the generalised speeds as $u_r = \dot{q}_r$ $(r = 1, \ldots, m)$, where the dot indicates differentiation with respect to time. The unit tangential vector to the wave surface at body k is denoted by $\overrightarrow{t_k}$ and is given by

$$\overrightarrow{t_k} = \left(\overrightarrow{i} + \eta_k' \overrightarrow{k}\right) Z_k^{-\frac{1}{2}} \tag{2}$$

where $Z_k = 1 + \left(\eta_k'\right)^2$, $\eta_k' = \frac{\partial}{\partial q_k}(\eta_k)$, $k = 1, \ldots, m$.

The position vector $\overrightarrow{r_k}$, velocity $\overrightarrow{v_k}$ and acceleration $\overrightarrow{a_k}$ of body k are given by (for $k = 1, \ldots, m$)

$$\overrightarrow{r_k} = q_k \overrightarrow{i} + \eta_k \overrightarrow{k} \tag{3}$$

$$\overrightarrow{v_k} = Z_k^{\frac{1}{2}} u_k \overrightarrow{t_k} + \frac{\partial}{\partial t}(\eta_k) \overrightarrow{k} \tag{4}$$

$$\overrightarrow{a_k} = Z_k^{\frac{1}{2}} \dot{u}_k \overrightarrow{t_k} + f_k \overrightarrow{k} \tag{5}$$

where

$$f_k = u_k \frac{d}{dt}(\eta_k') + \frac{d}{dt}\left(\frac{\partial \eta_k}{\partial t}\right) \tag{6}$$

The partial velocities $\overrightarrow{v}_{kr}$ of body k are written by inspection as (Kane and Levinson, 1985)

$$\overrightarrow{v}_{kr} = \delta_{kr}\left(\overrightarrow{i} + \eta_k' \overrightarrow{k}\right) = Z_k^{\frac{1}{2}} \delta_{kr} \overrightarrow{t_k} \quad (k, r = 1, \ldots, m) \tag{7}$$

where δ_{kr} is the Kronecker delta.

3 Forces

3.1 Inertia and Environmental Forces

Let the mass of body k be m_k. The generalised inertia force (non-hydrodynamic) on body k is $G_{kr}^* = \overrightarrow{v}_{kr} \cdot (-m_k \overrightarrow{a}_k)$. This is evaluated as

$$G_{kr}^* = \left(A_k \dot{u}_k + B_k\right) \delta_{kr} \quad , \quad (k, r = 1, \ldots, m) \tag{8}$$

where

$$\begin{array}{l} A_k = -m_k Z_k \\ B_k = -m_k f_k \eta'_k \end{array} \qquad (k = 1, \ldots, m) \tag{9}$$

The generalised inertia force (non-hydrodynamic) on the system is $F_r^* = \sum_{k=1}^{n+1} G_{kr}^*$ which gives

$$F_r^* = A_r \dot{u}_r + B_r \qquad (r = 1, \ldots, m) \tag{10}$$

We write the external force $\overrightarrow{F_k}^E$ on body k as the sum of forces due to gravity ($\overrightarrow{F}_k^G$), waves ($\overrightarrow{F_k}^{\text{wave}}$), wind ($\overrightarrow{F}_k^{\text{wind}}$) and propulsion ($\overrightarrow{F_k}^P$). The associated generalised force is $G_{kr}^E = \overrightarrow{v}_{kr} \cdot \overrightarrow{F_k}^E$ which can be written as

$$G_{kr}^E = Z_k^{\frac{1}{2}} \overrightarrow{t}_k \cdot \overrightarrow{F_k}^E \delta_{kr} \ , \ (k, r = 1, \ldots, m) \tag{11}$$

The gravitational force is $\overrightarrow{F}_k^G = -m_k g \overrightarrow{k}$ where g is the acceleration due to gravity. The wave force $\overrightarrow{F_k}^{\text{wave}}$ on body k is written using the Morison equation as (Sumer and Fredsoe, 1997)

$$\overrightarrow{F_k}^{\text{wave}} = \overrightarrow{F_k}^{FK} + \overrightarrow{F_k}^A + \overrightarrow{F_k}^D \tag{12}$$

where $\overrightarrow{F_k}^{FK}$ is the Froude-Krylov force, $\overrightarrow{F_k}^A$ is the inertial force due to added-mass and $\overrightarrow{F_k}^D$ is the wave drag force. Let $\overrightarrow{v}_k^F$, $\overrightarrow{a}_k^F$ be the water particle velocity and acceleration respectively at body k. The x and z components of $\overrightarrow{v}_k^F$, $\overrightarrow{a}_k^F$ are denoted by $\left(u_k^F, w_k^F\right)$ and $\left(a_{x,k}^F, a_{z,k}^F\right)$ respectively. We use linear wave theory to estimate the water particle kinematics above the mean water level (Grue et al., 2003). From (1) and the standard formulae of linear wave theory, these quantities are evaluated as

$$u_k^F = \sum_{j=1}^{p} \omega_j A_j D_{jk} R_{jk} \ ; \quad w_k^F = \sum_{j=1}^{p} \omega_j A_j Q_{jk} S_{jk} \tag{13}$$

and

$$\begin{array}{l} a_{x,k}^F = \frac{\partial}{\partial t}\left(u^F\right) + u^F \frac{\partial}{\partial x}\left(u^F\right) + w^F \frac{\partial}{\partial z}\left(u^F\right) \\ a_{z,k}^F = \frac{\partial}{\partial t}\left(w^F\right) + u^F \frac{\partial}{\partial x}\left(w^F\right) + w^F \frac{\partial}{\partial z}\left(w^F\right) \end{array} \quad \text{at } P_k \tag{14}$$

where, for $k = 1, \ldots, n+1 \ ; \ j = 1, \ldots, p$

$$\begin{array}{ll} R_{jk}\left(q_k, t\right) = \cos\left(k_j q_k - \omega_j t + \phi_j\right) \ ; & S_{jk}\left(q_k, t\right) = \sin\left(k_j q_k - \omega_j t + \phi_j\right) \\ D_{jk} = \frac{\cosh(k_j \eta_k + k_j d)}{\sinh(k_j d)} \ ; & Q_{jk} = \frac{\sinh(k_j \eta_k + k_j d)}{\sinh(k_j d)} \end{array} \tag{15}$$

and d is the water depth. The velocity and acceleration of body k relative to the water are, respectively $\overrightarrow{v}_k^R = \overrightarrow{v}_k - \overrightarrow{v}_k^F$ and $\overrightarrow{a}_k^R = \overrightarrow{a}_k - \overrightarrow{a}_k^F$. The Froude-Krylov force is $\overrightarrow{F_k}^{FK} = \rho V_k^F \overrightarrow{a}_k^F$, the added-mass force is $\overrightarrow{F_k}^A = -m_{a,k} \overrightarrow{a}_k^R$ and the drag force is $\overrightarrow{F_k}^D = -\frac{1}{2} \rho A_k^F C_{D,k}^F \left|\overrightarrow{v_k}^R\right| \overrightarrow{v}_k^R$, where ρ is the water density, V_k^F is the submerged volume of body k, A_k^F is the wetted area of body k, $C_{D,k}^F$ is the associated drag coefficient, and $m_{a,k}$ is the added-mass of body k for surge motion. To evaluate the wind force we write the velocity of P_k relative to the wind in direction $\overrightarrow{t}_k$ as $\overrightarrow{v}_k^{RW} = v_k^{RW}\overrightarrow{t}_k$. The wind drag force on P_k is written as $\overrightarrow{F_k}^{\text{wind}} = -\frac{1}{2}\rho_{\text{air}} A_k^{\text{wind}} C_{D,k}^{\text{wind}} \left|v_k^{RW}\right| v_k^{RW}\overrightarrow{t}_k$, where ρ_{air} is the air density, A_k^{wind} is the projected area of body k normal to $\overrightarrow{t}_k$ and $C_{D,k}^{\text{wind}}$ is the associated wind drag coefficient. The propulsive force on body k is assumed to be parallel to the wave surface and written as $\overrightarrow{F_k}^{P} = F_k^P\overrightarrow{t}_k$. We can then write equation (11) as

$$G_{kr}^E = \left(C_k\dot{u}_k + D_k\right)\delta_{kr} \quad , \quad (k, r = 1, \ldots, m) \tag{16}$$

where

$$\left.\begin{aligned}
C_k &= -m_{a,k} Z_k \\
D_k &= \alpha_k + Z_k^{\frac{1}{2}}\left(\beta_k + \gamma_k + F_k^P\right) - m_k g \eta_k' \\
\alpha_k &= -m_{a,k}\left\{\eta_k'\left(f_k - a_{z,k}^F\right) - a_{x,k}^F\right\} \\
\beta_k &= \rho V_k^F\left(a_{x,k}^F + \eta_k' a_{z,k}^F\right) Z_k^{-\frac{1}{2}} - \frac{1}{2}\rho A_k^F C_{D,k}^F \left|\overrightarrow{v_k}^R \cdot \overrightarrow{t}_k\right| \left(\overrightarrow{v}_k^R \cdot \overrightarrow{t}_k\right) \\
\gamma_k &= -\frac{1}{2}\rho_{\text{air}} A_k^{\text{wind}} C_{D,k}^{\text{wind}} \left|v_k^{RW}\right| v_k^{RW}
\end{aligned}\right\} \quad (k = 1, \ldots, m) \tag{17}$$

The quantities $\overrightarrow{v}_k^R \cdot \overrightarrow{t}_k$ and v_k^{RW} are given by

$$\overrightarrow{v}_k^R \cdot \overrightarrow{t}_k = Z_k^{\frac{1}{2}} u_k + Z_k^{-\frac{1}{2}}\left\{\eta_k'\left(\frac{\partial \eta_k}{\partial t} - w_k^F\right) - u_k^F\right\} \tag{18}$$

$$v_k^{RW} = Z_k^{\frac{1}{2}} u_k + Z_k^{-\frac{1}{2}}\left(\eta_k'\frac{\partial \eta_k}{\partial t} - v^{\text{wind}}\right) \tag{19}$$

where we assume that the wind velocity is $v^{\text{wind}}\overrightarrow{i}$. The generalised force on the system due to external influences is $F_r^E = \sum_{k=1}^{n+1} G_{kr}^E$ which gives

$$F_r^E = C_r\dot{u}_r + D_r \quad (r = 1, \ldots, m) \tag{20}$$

3.2 Interaction Forces

3.2.1 Tensile forces in flexible raft

The extension of the liferaft is modeled by springs and dampers. We assume that the raft has negligible bending stiffness and conforms to the wave profile. Segment P_kP_{k+1}, denoted by S_k, has length ℓ, stiffness λ and damping constant c, $(k = 1, \ldots, n-1)$. The instantaneous length of segment S_k is $Y_{1,k} = [(q_{k+1} - q_k)^2 + \left(\eta_{k+1} - \eta_k\right)^2]^{\frac{1}{2}}$ and its extension is $Y_{2,k} = Y_{1,k} - \ell$, ($k = 1, \ldots, n-1$). The strain energy due to tension in the liferaft is $V^T = \frac{1}{2}\lambda \sum_{k=1}^{n-1} Y_{2,k}^2$ and the associated generalised active force is $F_r^T = -\frac{\partial}{\partial q_r}\left(V^T\right)$, $r = 1, \ldots, m$. The dissipation function for the damping of extensional vibrations is $D^T = \frac{1}{2}c\sum_{k=1}^{n-1} \dot{Y}_{2,k}^2$ where $\dot{Y}_{2,k} = \frac{d}{dt}\left(Y_{2,k}\right)$, and the associated generalised active force is $F_r^{DT} = -\frac{\partial}{\partial \dot{q}_r}\left(D^T\right),\ r = 1, \ldots, m$. The quantities F_r^T and F_r^{DT} are evaluated as

$$F_r^T = -\lambda \sum_{k=1}^{n-1} H_{rk} Y_{2,k} \quad ; \quad F_r^{DT} = -c \sum_{k=1}^{n-1} H_{rk} \dot{Y}_{2,k} \qquad (r = 1, \ldots, m) \tag{21}$$

where

$$H_{rk} = \begin{cases} -Y_{3,k} & r = k \\ Y_{4,k} & r = k+1 \\ 0 & \text{otherwise} \end{cases} \qquad (k = 1, \ldots, n-1;\ r = 1, \ldots, m) \tag{22}$$

$$\dot{Y}_{2,k} = -Y_{3,k} u_k + Y_{4,k} u_{k+1} + Y_{5,k} \qquad (k = 1, \ldots, n-1) \tag{23}$$

and (for $k = 1, \ldots, n-1$)

$$Y_{3,k} = \frac{(q_{k+1} - q_k) + \eta_k' \left(\eta_{k+1} - \eta_k\right)}{Y_{1,k}} \tag{24}$$

$$Y_{4,k} = \frac{(q_{k+1} - q_k) + \eta_{k+1}' \left(\eta_{k+1} - \eta_k\right)}{Y_{1,k}} \tag{25}$$

$$Y_{5,k} = -\frac{1}{Y_{1,k}} \left\{ \frac{\partial}{\partial t}\left(\eta_{k+1}\right) + \frac{\partial}{\partial t}\left(\eta_k\right) \right\} \tag{26}$$

3.2.2 Tow line tension

The tow line connects masses P_α and P_{n+1} where $\alpha = n$ for towing in a following sea and $\alpha = 1$ for towing in a head sea. The tow-line tension on each body is equivalent to a force-couple system at the centre of mass of each body. Since we are neglecting local rotations relative to the wave surface, the couples are resisted by opposing couples from the wave surface. We therefore consider only the effect of the tow-line tension at the centres of mass of the bodies. The line stiffness is denoted by k_T and the unstretched length is L_0. In order to allow for tension but not compression we write the tow-line tension in the form $k_T W_2$ where $W_2 = \frac{1}{2}\left\{(W_1 - L_0) + |W_1 - L_0|\right\}$ and W_1 is the instantaneous length of the tow-line, computed from the positions of the two bodies. The magnitude of the damping force is the product of a damping coefficient c_T and the component of the relative velocity between the bodies along the tow line. If $\overrightarrow{e}$ is the unit vector along the tow-line from P_α to P_{n+1} and the velocity of P_{n+1} relative to P_α is denoted by $\overrightarrow{v}^R$, the damping force on P_α is $c_T W_3$ where $W_3 = \left(\overrightarrow{v}^R \cdot \overrightarrow{e}\right)\mathrm{sign}(W_2)$. We will assume that when the bodies are moving towards each other the line damping is negligible. This means that we write the damping force in the tow line as $c_T W_4$ where $W_4 = \frac{1}{2}\left(W_3 + |W_3|\right)$. The force on P_k due to the tow line is then

$$\overrightarrow{F_k}^{\text{Towline}} = \chi_k \overrightarrow{e} \qquad (k = 1, \ldots, n+1) \tag{27}$$

where $\chi_\alpha = k_T Y_2 + c_T Y_4$, $\chi_{n+1} = -\chi_\alpha$ and $\chi_k = 0$ for $k \neq \alpha, n+1$. The generalised force on body k due to the tow line is $G_{kr}^{\text{Towline}} = \overrightarrow{v}_{kr} \cdot \overrightarrow{F_k}^{\text{Towline}}$ which is evaluated as

$$G_{kr}^{\text{Towline}} = E_k \delta_{kr} \tag{28}$$

where

$$E_k = (e_x + \eta_k' e_z)\, \chi_k \qquad (k = 1, \ldots, n+1) \tag{29}$$

and e_x, e_z are the x, z components of unit vector $\overrightarrow{e}$. The generalised force on the system due to the towline is $F_r^{\text{Towline}} = \sum_{k=1}^{n+1} G_{kr}^{\text{Towline}}$, i.e.

$$F_r^{\text{Towline}} = E_r \quad (r = 1, \ldots, m) \tag{30}$$

4 Equations of Motion

The equations of motion are (Kane and Levinson, 1985)

$$F_r^* + F_r^E + F_r^T + F_r^{DT} + F_r^{\text{Towline}} = 0 \quad (r = 1, \ldots, m) \tag{31}$$

Using equations (10), (20), (21) and (30), we find from (31)

$$\dot{u}_r = -\left(\frac{B_r + D_r + E_r + F_r^T + F_r^{DT}}{A_r + C_r} \right) \qquad (r = 1, \ldots, m) \tag{32}$$

Define the $2m$-dimensional vector $\{y\}$ by $y_r = q_r$, $y_{m+r} = u_r$, $(r = 1, \ldots, m)$. The dynamic system is then represented by the equation

$$\left\{ \dot{y} \right\} = \begin{pmatrix} \left\{ \dot{q} \right\} \\ \left\{ \dot{u} \right\} \end{pmatrix} \tag{33}$$

which is solved by the MATLAB® (MathWorks Inc.,Natick,MA,USA) Runge-Kutta routine "ode45" with specified initial conditions.

5 Typical Results

We use the numerical model to predict the tow loads for the towing of a 150-person liferaft in an irregular wave specified by the Pierson-Moskowitz wave spectrum (http://www.eustis.army.mil/WEATHER/Weather_Products/seastate.htm) as follows: Sea state 5 with significant wave height $H_s = 4\ m$, mean centroidal wave period $T_1 = 7$ sec, wind speed 13 $m/$sec in x direction.

The raft was modeled using $n = 7$ lumped masses. The following parameters were used for the simulation. The hydrodynamic coefficients are estimates only and experimental work is required to determine appropriate values.

- *Fast Rescue Craft :* mass=2621 kg, added mass coefficient in surge =0.1, drag coefficient = 0.007, wetted surface area=13.25 m^2, propulsive thrust = 5000 N and 8000 N

- *150-person liferaft :* Mass=13000 kg,length=15 m, elastic modulus =3 GPa, material cross-sectional area = 5 m^2, added mass coefficient in surge =0.2, drag coefficient = 0.07, total wetted surface area=70 m^2

- *Tow Line :* diameter =20 mm, length=30 m, modulus of Elasticity =2 GPa, damping constant=647 $N.\sec.m^{-1}$. The damping constant c is estimated as $c = 2\zeta\sqrt{EA \times \frac{1}{3}\text{ mass per unit length}}$ where E is the elastic modulus, A is the cross-sectional area and ζ is the damping ratio chosen as 1 for critical damping.

- *Initial conditions* : Stern of liferaft at origin for following sea, bow of liferaft at origin for head sea, zero initial velocity.

The x coordinates and tow line tensions predicted by the numerical model are shown in Fig. 2 to Fig. 5 for towing in a following sea and head sea with FRC thrusts of 5 kN and 8 kN. Fig.2 (following sea) and Fig. 4 (head sea) indicate that a FRC thrust of 5 kN is inadequate for towing the raft in this sea state, since the trajectories of the FRC and raft bow intersect. Fig. 3 indicates that a FRC thrust of 8 kN is barely adequate for towing the raft in the following sea condition but Fig. 5 shows that in the head sea condition, the trajectories intersect so that the FRC thrust of 8 kN is inadequate for this case also. We note that after collision, the results are not valid. The graphs indicate the occurrence of snap loads (i.e. the sudden re-tensioning of the line from a slack condition), as expected.

6 Conclusions

The coupled equations of motion for the towing of a flexible liferaft by a fast rescue craft in irregular waves have been formulated in two dimensions and solved numerically. The numerical model can be used by designers, manufactures and regulators to evaluate the motions of the liferaft and FRC as well as the tow tension in severe sea conditions. The model may also be used in the selection of tow line length and elasticity for the reduction of snap loading. We emphasise the importance of getting good estimates of the input parameters before using the mathematical model. We expect that the results of the model will be useful in designing the liferafts and tow lines against structural failure as well as determining the tow force required for various sea states. This will assist regulatory agencies in setting appropriate safety standards.

Acknowledgements

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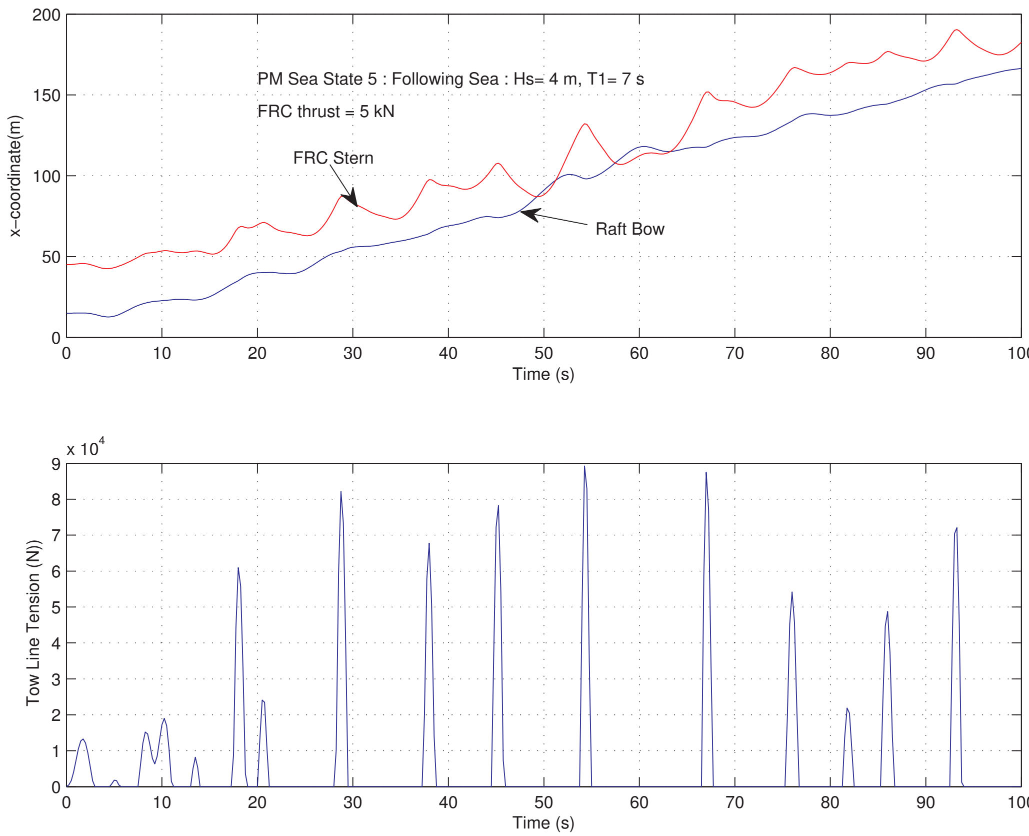

Figure 2: Sea State 5 : Following Sea, FRC thrust= 5 kN

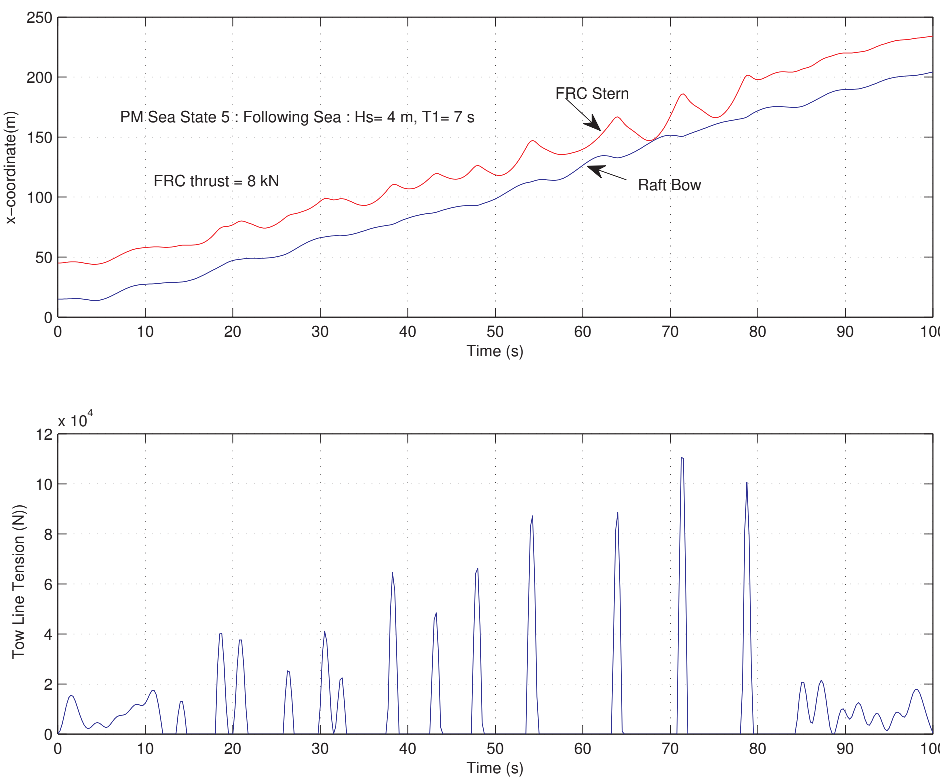

Figure 3: Sea State 5: Following Sea, FRC thrust=8 kN

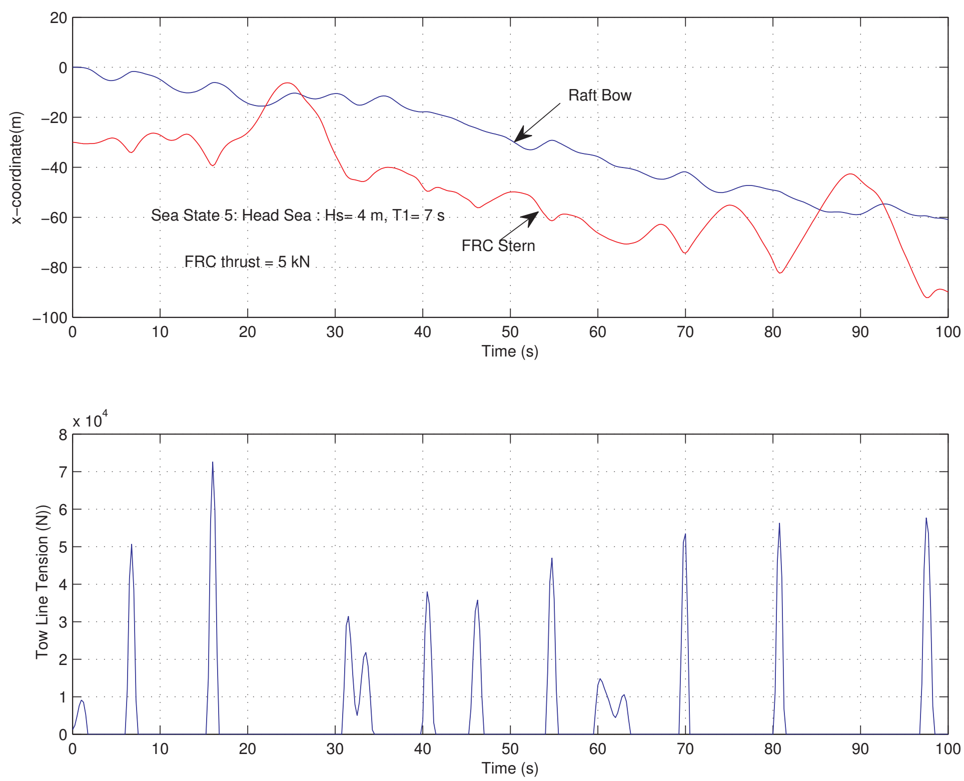

Figure 4: Sea State 5 : Head Sea, FRC thrust = 5 kN

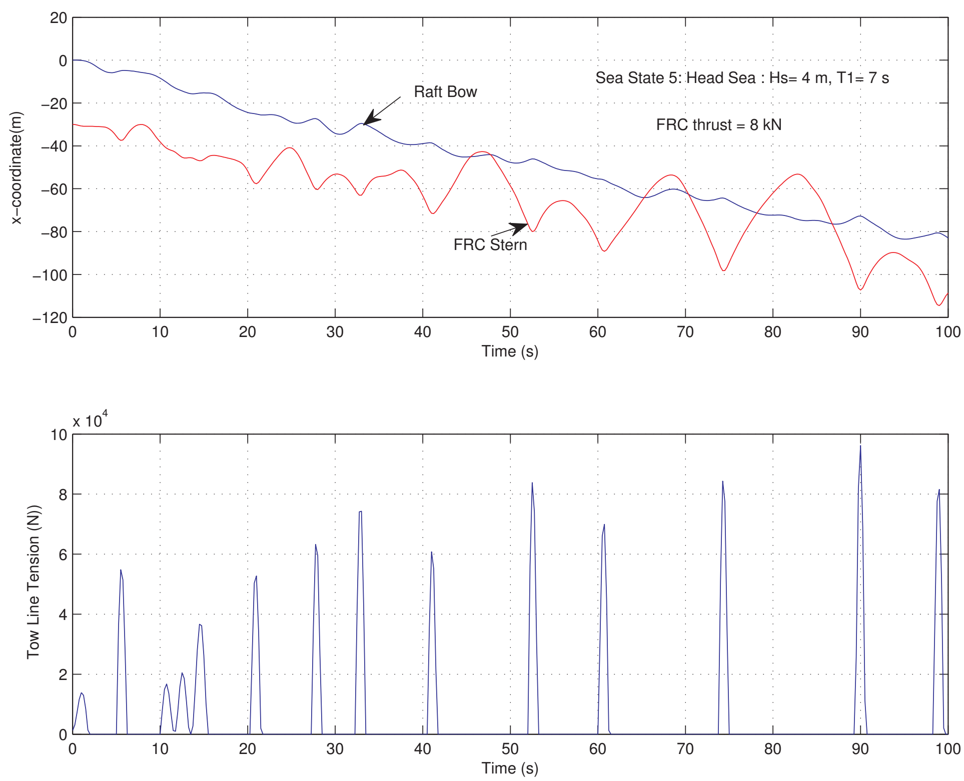

Figure 5: Sea State 5 : Head Sea, FRC thrust =8 kN