Keelung Port, Taiwan, ROC—R.L. Wiegel

PART V

SHIP MOTIONS

Composite Breakwater near Taipei—H. Lee Butler

A Numerical Simulation of the Moored Container Ship Movements Induced by Wind

T Z Cheng * & N K Liang **

ABSTRACT

In the past, only the ship motion due to wave is studied. This study is focused on the ship motion induced by a steady oscillating wind. The oscillating wind is assumed to be sinusoidal of a constant frequency. The wind direction θ, number of mooring lines and the wind frequency are the parameters in simulating an Evergreen's Ever Garden class container ship. The results show that the worst angle between the quay and the prevailing wind direction is 45°. Surge and roll are the most significant motions induced by the oscillating wind. By changing the number of mooring lines, the natural frequency can be kept away from the dominant wind frequency, except roll.

INTRODUCTION

The wave affects the ship motion significantly. Hence, in the past only ship motion due co wave is studied (Lewis, 1929; Korvin-Kroukovsky, 1961; Salvesen, et al, 1970). However, there are harbours which are well sheltered by the breakwater from suffering the invasion of waves but attacked by strong moonson wind. It is self-understood that the wind is oscillating. The oscillating wind may induce ship motion. The purpose of this paper is to understand the characteristics of the wind-induced ship motion by numerical simulation qualitatively. The results can be used for the guide line of harbour design.

THEORY

There are two coordinate systems: One is the equilibrium axes (Fig. 1), which is fixed. C.G. is the center of gravity. 0 is the mean position of ship motion. The other one is the body axes which is moved with the ship (Fig. 2). The definition of 6 ship motions is also shown in Fig. 2. The 3 translation motions are surge $x(t)$, sway $y(t)$ and heave $z(t)$. The 3 angular motions are roll $\phi(t)$, pitch $\theta(t)$ and

---

* Graduate student, Institute of Oceanography, National Taiwan University, Taiwan, R.O.C.

** Director, Institute of Harbour & Marine Technology, Wuchi, Taiwan R.O.C.

yaw $\psi(t)$. In order to construct the equations of motion, the following assumptions are made:

1. The ship is a rigid body.
2. The ship is symmetric and slender.
3. The ship motion amplitude is small, equations can be linearized.
4. Except roll, the effect of viscosity is neglected.
5. The wind direction is fixed.
6. There is no incident wave.
7. No coupling between the longitudinal motion— surge, heave and pitch, and the transverse motion—sway, roll and yaw.

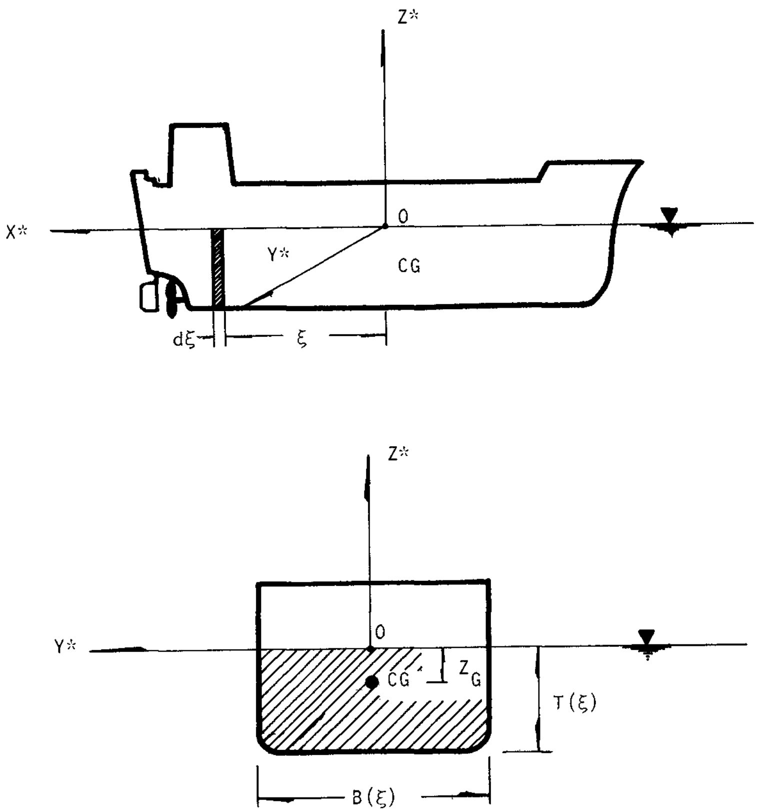

Fig 1. The definition of equilibrium axes

For longitudinal motion

$$
\begin{aligned}
M'\ddot{x} + M'Z_g\ddot{\theta} &= X_I + X_D + X_H + X_M + X_W \\
M'\ddot{z} &= Z_I + Z_D + Z_H + Z_M + Z_W \qquad (1) \\
I_2\ddot{\theta} + M'Z_g\ddot{x} &= M_I + M_D + M_H + M_M + M_W
\end{aligned}
$$

For transverse motion

$$
\begin{aligned}
M'\ddot{y} - M'Zg\ddot{\phi} &= Y_I + Y_D + Y_H + Y_M + Y_W \\
I_1\ddot{\phi} - I_{13}\ddot{\psi} - M'Z_g\ddot{y} &= K_I + K_D + K_H + K_M + K_W \qquad (2) \\
I_3\ddot{\psi} - I_{13}\ddot{\phi} &= N_I + N_D + N_H + N_M + N_W
\end{aligned}
$$

where,
- M' mass of ship
- M moment for pitch
- K moment for roll
- N moment for yaw
- X force for surge
- Y force for sway
- Z force for heave
- I_1, I_2, I_3 moment of inertial with respect to X^*, Y^* and Z^* axes
- I_{13} Product of inertial with respect to $X^* - Z^*$ axes.

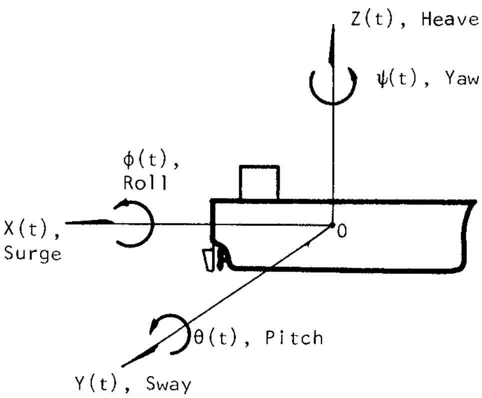

Fig. 2 The definition of six ship motions

the subindex

I	inertial
D	damping
H	hydrostatic restoring
M	mooring line restoring
W	wind excitation

8. Strip theory approximation
The hydrodynamic forces and moments can be integrated along the ξ - axis, i.e. the longitudinal axis of the ship.

For longitudinal motion

$$
\begin{aligned}
X_1 &= -\int m_x(\xi)\,d\xi\cdot\ddot{x} + \int Zs(\xi)m_x(\xi)\,d\xi\cdot\ddot{\theta} \\
X_D &= -\int n_x(\xi)\,d\xi\cdot\dot{x} + \int Zs(\xi)n_x(\xi)\,d\xi\cdot\dot{\theta} \\
X_H &= 0 \\
Z_1 &= -\int m_z(\xi)\,d\xi\cdot\ddot{z} + \int \xi m_z(\xi)\,d\xi\cdot\ddot{\theta} \\
Z_D &= -\int n_z(\xi)\,d\xi\cdot\dot{z} + \int \xi n_z(\xi)\,d\xi\cdot\dot{\theta} \qquad (3) \\
Z_H &= -\rho_w g\int B(\xi)\,d\xi\cdot z + \rho_w g\int \xi B(\xi)\,d\xi\cdot\theta \\
M_I &= \int Zs(\xi)m_x(\xi)\,d\xi\cdot\ddot{x} + \int \xi m_z(\xi)\,d\xi\cdot\ddot{z} - \int[\xi^2 m_z(\xi) \\
&\quad + Z_s^2(\xi)m_x(\xi)]\,d\xi\cdot\ddot{\theta} \\
M_D &= \int Zs(\xi)n_x(\xi)\,d\xi\cdot\dot{x} + \int \xi n_z(\xi)\,d\xi\cdot\dot{z} - \int[\xi^2 n_z(\xi) \\
&\quad + Z_s^2(\xi)n_x(\xi)]\,d\xi\cdot\dot{\theta} \\
M_H &= \rho_w g\int \xi B(\xi)\,d\xi\cdot z - \rho_w g\int \xi^2 B(\xi)\,d\xi\cdot\theta
\end{aligned}
$$

where

$m_x(\xi)$	sectional added mass per unit length for surge.
$m_z(\xi)$	sectional added mass per unit length for pitch.
$n_x(\xi)$	sectional damping coefficient per unit length for surge.
$n_z(\xi)$	sectional damping coefficient per unit length for pitch.
$B(\xi)$	sectional width.
$Zs(\xi)$	distance between water surface to the center of the sectional added mass.

For transverse motion

$$
\begin{aligned}
Y_I &= -\int m_y(\xi)\,d\xi\cdot\ddot{y} - \int \xi m_y(\xi)\,d\xi\cdot\ddot{\psi} - \int m_{y\phi}(\xi)\,d\xi\cdot\ddot{\phi} \\
Y_D &= -\int n_y(\xi)\,d\xi\cdot\dot{y} - \int \xi n_y(\xi)\,d\xi\cdot\dot{\psi} - \int n_{y\phi}(\xi)\,d\xi\cdot\dot{\phi}
\end{aligned}
$$

$$
\begin{aligned}
Y_H &= 0 \\
K_I &\doteq -\int m_{y\phi}(\xi)d\xi\cdot\ddot{y} - \int m_{\phi}(\xi)d\xi\cdot\ddot{\phi} - \int \xi m_{y\phi}(\xi)d\xi\cdot\ddot{\psi} \\
K_D &= -\int n_{y\phi}(\xi)d\xi\cdot\dot{y} - \int n_{\phi}(\xi)d\xi\cdot\dot{\phi} - \int \xi n_{y\phi}(\xi)d\xi\cdot\dot{\psi} \\
&\quad -\int N_{\phi}'(\xi)d\xi\cdot\dot{\phi} \\
K_H &= -\rho_w g\nabla\cdot\overline{GM}\cdot\phi \\
N_I &= -\int \xi m_y(\xi)d\xi\cdot\ddot{y} - \int \xi^2 m_y(\xi)d\xi\cdot\ddot{\psi} - \int \xi m_{y\phi}(\xi)d\xi\cdot\ddot{\phi} \\
N_D &= -\int \xi n_y(\xi)d\xi\cdot\dot{y} - \int \xi^2 n_y(\xi)d\xi\cdot\dot{\psi} - \int \xi n_{y\phi}(\xi)d\xi\cdot\dot{\phi} \\
N_H &= 0
\end{aligned}
\tag{4}
$$

where

∇	displaced volume of the ship
$\overline{GM}$	metacentric height
$m_y(\xi)$, $n_y(\xi)$	sectional added mass and damping coefficient per unit length for sway.
$m_{\phi}(\xi)$, $n_{\phi}(\xi)$	sectional added mass and damping coefficient per unit length for roll.
$m_{y\phi}(\xi)$, $n_{y\phi}(\xi)$	sectional added mass and damping coefficient per unit length for coupling between roll and sway.
$n_{\phi}'(\xi)$	sectional damping coefficient due to viscosity for roll.

9. All unit added mass and damping coefficient are only a function of frequency.
   Eq.(3) and (4) can be rewritten: (The coefficient Aij, Bij and Cij are calculated according to NSRDC ship-motion and sea-load computer program).

$$
\begin{aligned}
X_I &= -A_{11}\ddot{x} - A_{15}\ddot{\theta} & Y_I &= -A_{22}\ddot{y} - A_{24}\ddot{\phi} - A_{26}\ddot{\psi} \\
X_D &= -B_{11}\dot{x} - B_{15}\dot{\theta} & Y_D &= -B_{22}\dot{y} - B_{24}\dot{\phi} - B_{26}\dot{\psi} \\
X_H &= 0 & Y_H &= 0
\end{aligned}
\tag{5}
$$

where

Aij: added mass coefficient
Bij: damping coefficient
Cij: hydrostatic restoring coefficient

10. The tension of the mooring line follows Hooke's Law, the mooring line is assumed as a straight line.
    The static mooring forces & moments and the resistance of fender

at the equilibrium position are balanced with the average wind force. Therefore only the dynamic mooring forces or moments are considered. The dynamic mooring forces and moments are the following:

$$
\begin{aligned}
X_M &= - k_{11}x - k_{13}z - k_{15}\theta \\
Y_M &= - k_{22}y - k_{24}\phi - k_{26}\psi \\
Z_M &= - k_{33}z - k_{31}x - k_{35}\theta \\
K_M &= - k_{44}\phi - k_{42}y - k_{46}\psi \\
M_M &= - k_{55}\theta - k_{51}x - k_{53}z \\
N_M &= - k_{66}\psi - k_{62}y - k_{64}\phi
\end{aligned}
\tag{6}
$$

And the dynamic mooring line force coefficients are:

$$
\begin{aligned}
k_{11} &= \Sigma(K\cos^2\alpha) \\
k_{13} &= k_{31} = \Sigma(K\cos\alpha\cos\gamma) \\
k_{15} &= k_{51} = \Sigma(KZ_L\cos^2\alpha - KX_L\cos^2\gamma) \\
k_{33} &= \Sigma(K\cos^2\gamma) \\
k_{35} &= k_{53} = \Sigma(KZ_L\cos\alpha\cos\gamma - KX_L\cos^2\gamma) \\
k_{55} &= \Sigma[K(X_L\cos\gamma - Z_L\cos\alpha)^2] \\
k_{22} &= \Sigma(K\cos^2\beta) \\
k_{24} &= k_{42} = \Sigma(-KZ_L\cos^2\beta) \\
k_{26} &= k_{62} = \Sigma(KX_L\cos^2\beta) \\
k_{44} &= \Sigma(KZ_L^2\cos\beta) \\
k_{46} &= k_{64} = \Sigma(-KX_L Z_L\cos^2\beta) \\
k_{66} &= \Sigma(KX_L^2\cos^2\beta)
\end{aligned}
$$

where

- E modulus of elasticity
- A sectional area of the rope
- $K = EA/L$ spring constant , L length of the rope
- (X_L, Y_L, Z_L) coordinates of the end of rope on the ship's deck.
- (α, β, γ) angles between the rope from the land-end and the X*, Y*, Z* axes (shown in Fig-3)
- Σ summantion over the total ropes.

11. The air is an incompressible viscous fluid. It is assumed:

wind force is $F(t) = \frac{1}{2}\rho C_D A U^2(t)$

where

$U(t)$	the wind velocity
ρ	air density
C_D	drag coefficient
A	Projecting area of the object to the plane which is perpendicular to the wind direction.

$$U(t) = \bar{U} + u(t) = \bar{U} + u_o \cos \omega t, \quad u_o << \bar{U}$$

then $U^2(t) \doteq \bar{U}^2 + 2\bar{U} u_o \cos\omega t$

$$F(t) = \frac{1}{2}\rho C_D A U^2(t) \doteq \frac{1}{2}\rho C_D A\bar{U}^2 + \frac{1}{2}\rho C_D A(2\bar{U}u_o)\cos\omega t$$
$$= \bar{F} + f_o \cos\omega t$$

where $\bar{F} = \frac{1}{2}\rho C_D A\bar{U}^2$

$f_o = \rho C_D A\bar{U}u_o$

As shown in Fig(4), $F_x(t)$ and $F_y(t)$ are the wind force component in X* and Y* axes, respectively.
Because C_D and A are function of θ_o, then

$$F_x(t;\ \theta_o) = \bar{F}_x(\theta_o) + f_x(\theta_o)\cos\omega t$$

$$F_y(t;\ \theta_o) = \bar{F}_y(\theta_o) + f_y(\theta_o)\cos\omega t$$

where

$$\bar{F}_x(\theta_o) = \frac{1}{2}\rho C_{DX}(\theta_o)\ A(\theta_o)\ \bar{U}^2$$

$$\bar{F}_y(\theta_o) = \frac{1}{2}\rho C_{DY}(\theta_o)\ A(\theta_o)\ \bar{U}^2$$

$$f_x(\theta_o) = \rho C_{DX}(\theta_o)\ A(\theta_o)\ \bar{U}u_o$$

$$f_x(\theta_o) = \rho C_{DY}(\theta_o)\ A(\theta_o)\ \bar{U}u_o$$

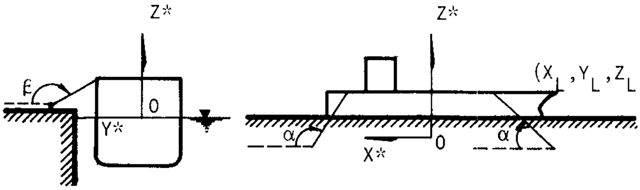

Fig.3 The definition of mooring line parameters

According to the above-mentioned assumptions, 6 second order simultaneous partial differential equations with 6 unknowns are as follows:

$$
\begin{aligned}
&(M'+A_{11})\ddot{x} + B_{11}\dot{x} + k_{11}x + (A_{15}+M'Z_g)\ddot{\theta} + B_{15}\dot{\theta} + k_{15}\theta \\
&+ k_{13}z = Xw \\
&(M'+A_{22})\ddot{y} + B_{22}\dot{y} + k_{22}y + (A_{24}-M'Zg)\ddot{\phi} + B_{24}\dot{\phi} + K_{24}\phi \\
&+ A_{26}\ddot{\psi} + B_{26}\dot{\psi} + k_{26}\psi = Yw \\
&(M'+A_{33})\ddot{z} + B_{33}\dot{z} + (C_{33}+k_{33})z + k_{31}x + A_{35}\ddot{\theta} + B_{35}\dot{\theta} \\
&+ (C_{35}+k_{35})\theta = Zw \\
&(I_1+A_{44})\ddot{\phi} + B_{44}\dot{\phi} + (C_{44}+k_{44})\phi + (A_{42}-M'Z_g)\ddot{y} + B_{42}\dot{y} \\
&+ k_{42}y + (A_{46}-I_{13})\ddot{\psi} + B_{46}\dot{\psi} + k_{46}\psi = Kw \\
&(I_2+A_{55})\ddot{\theta} + B_{55}\dot{\theta} + (C_{55}+k_{55})\theta + (A_{51}+M'Z_g)\ddot{x} + B_{51}\dot{x} \\
&+ k_{51}x + A_{53}\ddot{z} + B_{53}\dot{z} + (C_{53}+k_{53})z = Mw \\
&(I_3+A_{66})\ddot{\psi} + B_{66}\dot{\psi} + k_{66}\psi + A_{62}\ddot{y} + B_{62}\dot{y} + k_{62}y + (A_{64}-I_{13})\ddot{\phi} \\
&+ B_{64}\dot{\phi} + k_{64}\phi = Nw
\end{aligned}
\tag{7}
$$

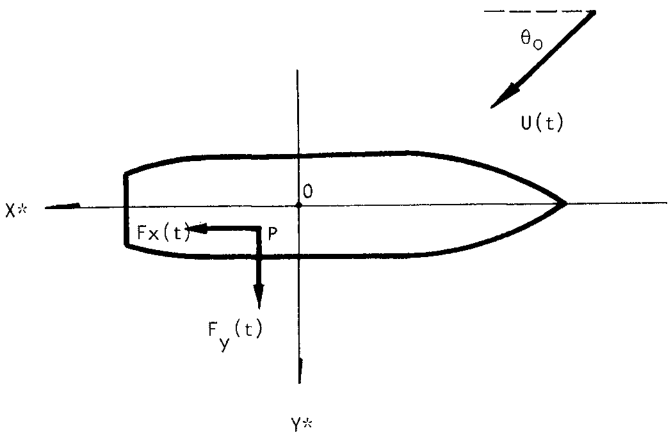

Fig. 4 The definition of wind direction θ_0

The wind force is sinusoidal, it can be represented as follows:

$$Xw = \overline{W}_1\ e^{-i\omega t}, \quad Yw = \overline{W}_2\ e^{-i\omega t} \quad Zw = \overline{W}_3\ e^{-i\omega t}$$
$$Kw = \overline{W}_4\ e^{-i\omega t}, \quad Mw = \overline{W}_5\ e^{-i\omega t} \quad Nw = \overline{W}_6\ e^{-i\omega t} \qquad (8)$$

$\overline{W}_1$, $\overline{W}_2$, ...$\overline{W}_6$ are the amplitudes of wind forces and moments. At steady state, the solution will be also sinusoidal, then

$$x = x_o\ e^{-i\omega t}, \quad y = y_o\ e^{-i\omega t}, \quad z = z_o\ e^{-i\omega t}$$
$$\phi = \phi_o\ e^{-i\omega t}, \quad \theta = \theta_o\ e^{-i\omega t}, \quad \psi = \psi_o\ e^{-i\omega t} \qquad (9)$$

substituding eq(8), (9) into eq(7), a new 6 simultaneous linear equcations are obtained.
To make the equations dimensionless M', L and $\sqrt{L/g}$ are used as mass, length and time scale. The index "'" to indicated the dimensionless symbols is omitted.
It can be written in the matrix form:

$$\{([C]+[k]) - \omega^2([M]+[A]) - i\omega[B]\} * [X] = [W] \qquad (10)$$

in which

$$[X] = \begin{pmatrix} X_o \\ Y_o \\ Z_o \\ \phi_o \\ \theta_o \\ \psi_o \end{pmatrix}, \quad [W] = \begin{pmatrix} W_1 \\ W_2 \\ W_3 \\ W_4 \\ W_5 \\ W_6 \end{pmatrix}, \quad [M] = \begin{pmatrix} 1 & 0 & 0 & 0 & Z_G & 0 \\ 0 & 1 & 0 & -Z_G & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & -Z_G & 0 & I_1 & 0 & -I_{13} \\ Z_G & 0 & 0 & 0 & I_2 & 0 \\ 0 & 0 & 0 & -I_{13} & 0 & I_3 \end{pmatrix}$$

$$[A] = \begin{pmatrix} A_{11} & 0 & 0 & 0 & A_{15} & 0 \\ 0 & A_{22} & 0 & A_{24} & 0 & A_{26} \\ 0 & 0 & A_{33} & 0 & A_{35} & 0 \\ 0 & A_{42} & 0 & A_{44} & 0 & A_{46} \\ A_{51} & 0 & A_{53} & 0 & A_{55} & 0 \\ 0 & A_{62} & 0 & A_{64} & 0 & A_{66} \end{pmatrix}, [B] = \begin{pmatrix} B_{11} & 0 & 0 & 0 & B_{15} & 0 \\ 0 & B_{22} & 0 & B_{24} & 0 & B_{26} \\ 0 & 0 & B_{33} & 0 & B_{35} & 0 \\ 0 & B_{42} & 0 & B_{44} & 0 & B_{46} \\ B_{51} & 0 & B_{53} & 0 & B_{55} & 0 \\ 0 & B_{62} & 0 & B_{64} & 0 & B_{66} \end{pmatrix}$$

$$[C] = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & C_{33} & 0 & C_{35} & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & C_{53} & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}, [k] = \begin{pmatrix} k_{11} & 0 & k_{13} & 0 & k_{15} & 0 \\ 0 & k_{22} & 0 & k_{24} & 0 & k_{26} \\ k_{31} & 0 & k_{33} & 0 & k_{35} & 0 \\ 0 & k_{42} & 0 & k_{44} & 0 & k_{46} \\ k_{51} & 0 & k_{53} & 0 & k_{55} & 0 \\ 0 & k_{62} & 0 & k_{64} & 0 & k_{66} \end{pmatrix}$$

EXAMPLE

Evergreen's Ever Garden class container ship is used as an example to simulate the ship motion induced by the oscillating wind. The dimensions of the ship and the arrangement of the mooring lines are shown in Fig. 5. The other conditions are as follows:

D.W.T. 42,000 ton
$\bar{U}$ = 60 ft/sec, u_o = 30 ft/sec
wind direction θ_0= 0°, 45° 90°
number of mooring lines, 0, 2, 4, 6, 8, 10

Because the equations are linear, the amplitudes (x, y, z, θ, ψ, φ) are proportional to amplitude($\bar{W}$), which is proportional to $\bar{U}u_o$. If $\bar{U}u_o$ is changed, the relationship of the various ship motions remains the same. The results to the wind direction 45° are shown in Fig. (6) (7), (8), (9), (10), (11).

The results are samarized as follows:

1. Increasing the number of the mooring line increases the natural frequency, except roll.
2. The natural periods for different number of mooring lines are as follows:

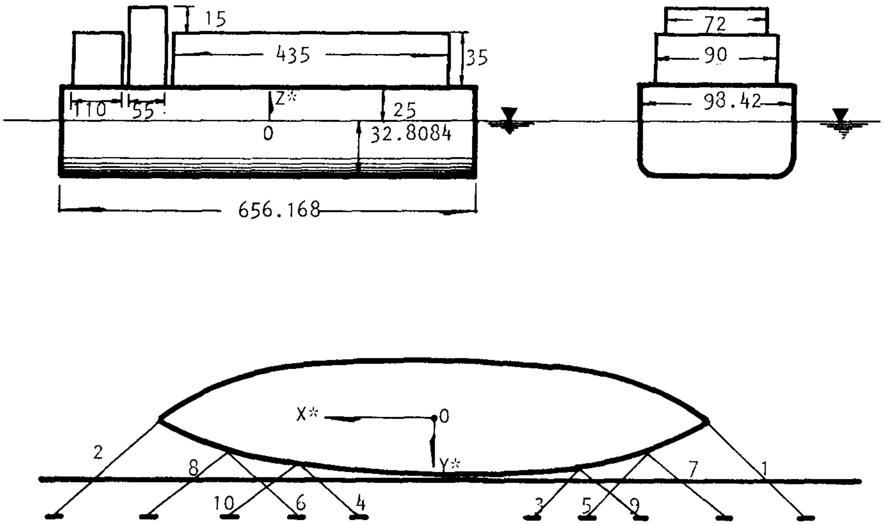

Fig. 5 Dimension of the container ship

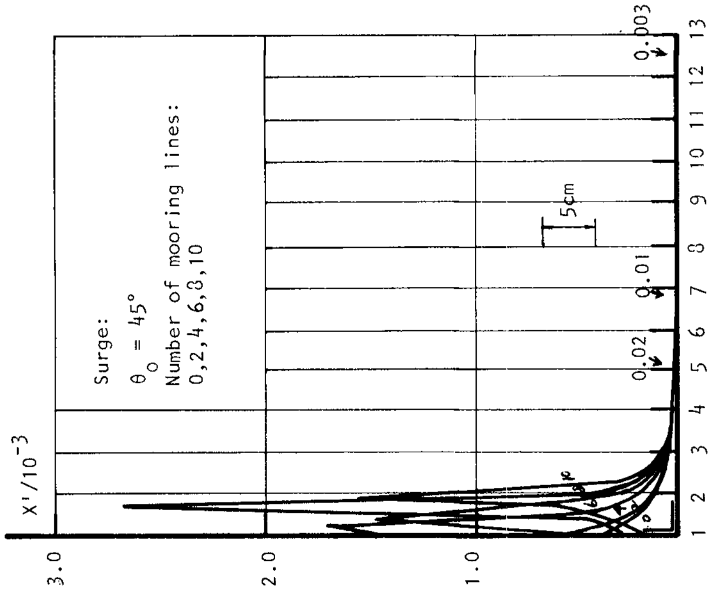

Fig. 6 Amplitude of surge

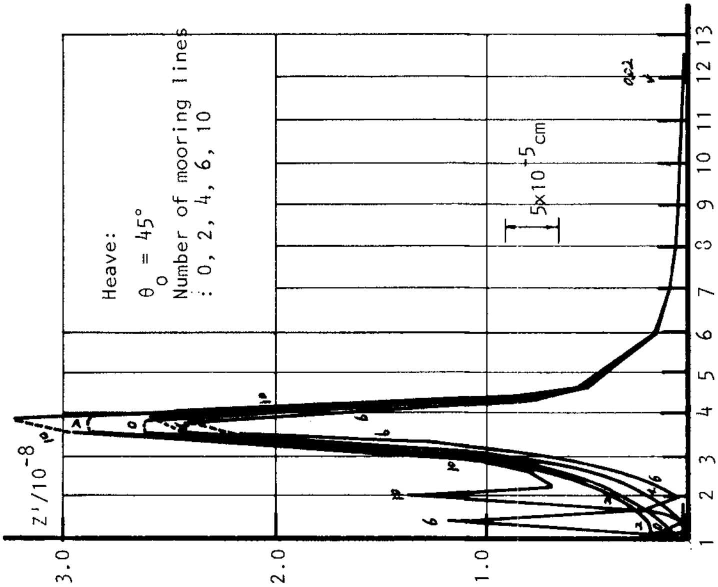

Fig. 7 Amplitude of heave

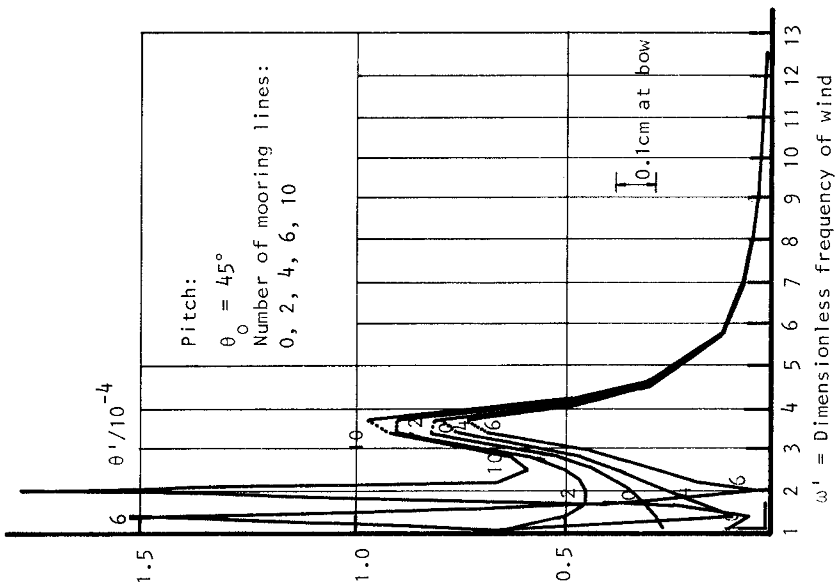

Fig. 8 Amplitude of pitch

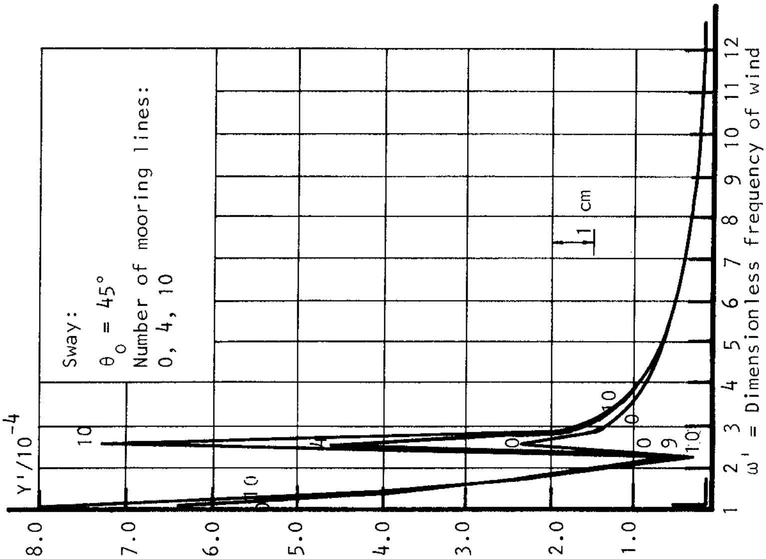

Fig. 9 Amplitude fo sway

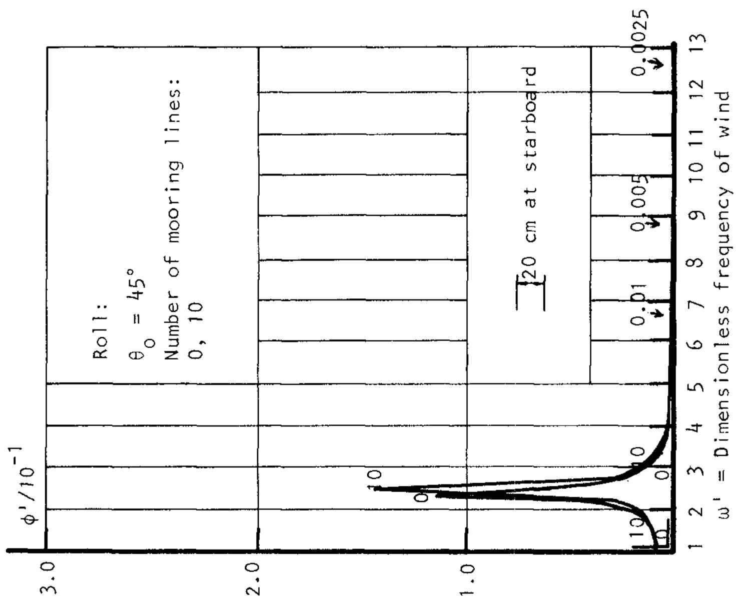

Fig. 10 Amplitude of roll

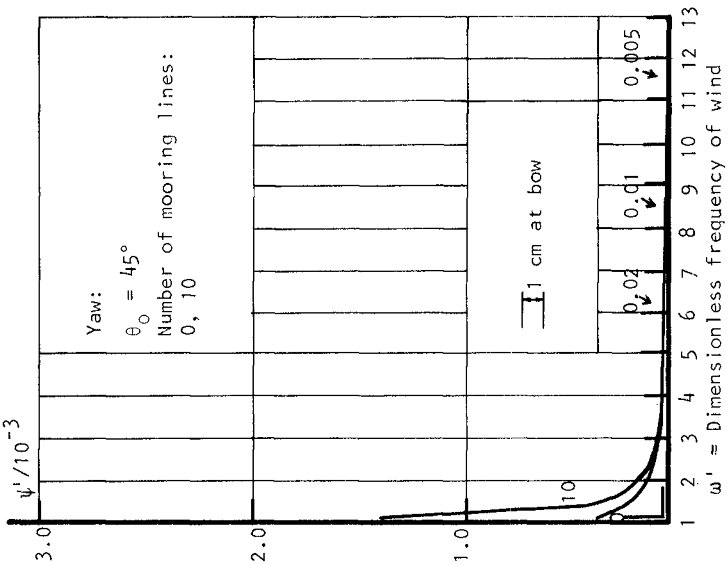

Fig. 11 Amplitude of yaw

surge	14-28 sec
heave	14-28 sec, 8sec.
pitch	14-28 sec, 8sec.
sway	14-28 sec, 11sec.
roll	11 sec
yaw	> 28 sec

3. Surge, pitch, heave, yaw and roll are maximum for $\theta_o = 45°$. However, sway is maximum for $\theta_o = 90°$.

4. The amplitude in the range of natural frequency for different number of mooring lines and $\theta_o = 45°$ are as follows:

surge 30-50 cm
sway 5-15 cm
heave very small
yaw 5-15 cm
roll(interpretted as the heave at starboard)
170-220 cm
pitch(interpretted as the heave at bow)
0.7-1.7 cm

5. In the vicinity of natural frequency, the magnitude order of the 6 motions is as follows:

surge > sway >> heave
roll >> yaw > pitch

The only exception is sway (90°) > surge (90°)

CONCLUSIONS

1. The induced ship motions by the oscillating wind are the greatest, as the angle between the quay and the prevailing wind direction is 45°. Of course, the 0°-direction quay is the best design.

2. Surge and roll are the most significant motions induced by the oscillating wind.

3. By changing the number of mooring lines, the natural frequency can be kept away from the dominant wind frequency, except roll.

REFERENCES

1. Korvin-Kroukovsky, B.V. (1961) "Theory of Seakeeping"

2. Lewis, F. M. (1929) "The inertia of water surrounding a vibrating ship" Trans. SNAME, 27, 1-20.

3. Salvesen, N.,E.O. Tuck & O. Faltinsen (1970) "Ship motions and sea load" Trans. SNAME, 78, 250-287

4. "NSRDC ship motion and sea load computer program" NSRDC report No. 3376, 1975.