Marine Structures 9 (1996) 609–629

0951-8339/96/$15.00

0951-8339(94)00030-1

Analysis of Forces due to Irregular Waves Exerted on a Ship Near a Harbor Entrance

Wing-kai Weng, Yi-yu Kuo

National Chiao Tung University, Hsin Chu, Taiwan

& Chung-Ren Chou

National Taiwan Ocean University, Keelung, Taiwan

(Received 7 December 1994)

ABSTRACT

Waves near the harbor which are affected by both seabed topography and also breakwaters could cause additional problems for ship sailing in this area. A numerical method was developed in this paper for predicting wave forces exerted on a ship near the harbor entrance when the ship is affected by uni-directional irregular waves. Three different positions of ship staying and wave conditions were considered and discussed. In addition, the validity of this method was experimentally verified by a model test.

Key words: ship, near harbor entrance, external forces, irregular wave, boundary element method.

NOTATION

m_f	Wave component number
f_i^*	Representative frequency of each spectral interval
$\Phi(t)$	Error function
Γ_n	Boundary of domain ($n = 1, \cdots, 5$)
I, II	Region
σ	Wave angular frequency
k	Wave number

g	Acceleration of gravity
h	Water depth of outer sea
$\Phi(x, y, z; t)$	Velocity potential
ϕ_0	Potential function of incident wave
ϕ_s	Potential function of scattering wave
ϕ_I	Potential function in domain I
ϕ_{II}	Potential function in domain II
$\bar{\phi}_i$	Normal derivative of potential function on boundary
ζ_i	Surface elevation
ζ_0	Amplitude of incident wave
ω	Incident wave angle
$(\bar{x}_0, \bar{y}_0, \bar{z}_0)$	Position of ship's center of gravity
P	Dynamic fluid pressure
F_i	the component of external force in the x', y', z' direction $(i = x', y', z')$
M_i	the component of external moment in the x', y', z' direction $(i = x', y', z')$

1 INTRODUCTION

The most important role of a harbor lies in providing for the safe and efficient activities of ships. For this purpose, harbor engineers spend most of their efforts in maintaining the water basin calm. Furthermore, many papers concerning harbor stabilities had been discussed, not only in regular but also irregular wave theory, by many authors in experimental and numerical analysis's manners. Some authors, e.g., Bruun[1] and Sawaragi,[2] have proposed that the harbour tranquillity should essentially be estimated in terms of ship motion. This idea would be a more explicit index for users. Besides, Sawaragi[3] discussed the critical condition of ship motion in a harbor, indicating that five phases of behavior of ship motion in a harbor, i.e., entering, berthing, mooring, loading/unloading and leaving, should be considered when harbour tranquillity is discussed.

Waves near the harbor are influenced by the seabed topography. Additionally, the interaction between incident and reflected waves which arise due to presence of breakwaters can produce short crest waves in this area. Forces acting on ships in this area are naturally different from those in the deep sea. Besides, harbor is the base for ships, providing its optimum service for those ships wishing to enter or leave the harbor rapidly and safely. A proper understanding of the phenomenon which influences the behavior of ships near the harbor is therefore necessary for improving the design of a harbor. However, relatively few articles are available which are concerned with the impact of wave forces upon ships near the harbor. External forces induced by irregular waves acting on a ship near the harbor are discussed in this paper from the entering or leaving perspective.

Several kinds of methods, e.g., significant wave representation method, probability calculation method, spectral calculation method, are currently available which deal with both the transformation and action of random sea waves. Spectral calculation is the most applicable towards describing the ship motions and forces among these methods. The primary emphasis of the spectral method holds the view that the wave field is composed of an infinite number of wave components with different frequencies and directions. Random sea waves can therefore be analyzed by the calculation of each spectral component wave which is considered as a regular wave with the same frequency. A fishing ship with zero forward speed which is situated near a harbour entrance is analyzed in this paper. Irregular wave forces exerting themselves on the ship are calculated by (a) first predicting those external forces induced by irregular waves and (b) verifying the validity of those results by a model test. One-dimensional wave power spectrum is applied in situations where the analysis of external forces induced by irregular waves is predicted. The spectral analysis was dealt with in the same manner as Nagai's.[4] The spectrum is divided into several spectral components, which possess equal wave energy in each frequency interval. The force response spectra can be obtained after the calculation of the response of each component wave in turn, in accordance with the representative frequency.

2 NUMERICAL ANALYSIS

2.1 Component waves of spectrum

The wave spectrum of natural sea waves includes the distribution of energy not only in the frequency domain but also in the direction domain. For the convenience of understanding the phenomena of wave forces acting on a ship, the responses of a ship near the harbor entrance are discussed here only when uni-directional irregular waves have exerted themselves on the ship.

A typical spectrum, the Bretschneider spectrum, is applied in this paper as the incident wave spectrum towards estimating the external force and moment responses of a ship near a harbor entrance. This spectrum can be expressed as:

$$S(f) = \frac{3{\cdot}45}{8}\frac{\bar{H}^2}{\bar{T}^4 f^5}\exp\left\{-\frac{0{\cdot}675}{\bar{T}f^4}\right\}, \tag{1}$$

where $\bar{T}$ and $\bar{H}$ are the average period and the average height of waves, respectively; f is wave frequency; and $\bar{T} = 0{\cdot}9\,T_{1/3}$, $\bar{H} = 1/1{\cdot}6\,H_{1/3}$.

For the convenience of both comparison and discussion, the power spectrum can be normalized by significant wave height $H_{1/3}$ and wave period $T_{1/3}$. The nondimensional power spectrum is:

$$S^*(f^*) = S(f^*)/H_{1/3}^2 = S(f)/(H_{1/3}^2 T_{1/3}) \tag{2}$$

where $f^* = T_{1/3}\,f$.

The theoretical spectrum is finally obtained as:[4]

$$S^*(f^*) = af^{*-5}\exp\{-(bf^{*-4})\} \tag{3}$$

where

$$a = b/4, \quad b = 1{\cdot}0288. \tag{4}$$

The wave spectra can be divided into several spectral components since the random waves can be regarded as a composition which is based on the linear superposition of many component waves with different frequencies. Since the division of frequency range is dealt with in the same way as Nagai's method, each individual wave frequency interval possess the same amount of wave energy. The representative frequency in each interval can be determined on the basis of the considerations of the mean of the second spectral moment of each interval. The formula for the representative frequency of each interval is:

$$f_i^* = \frac{1}{0{\cdot}9}\sqrt{2{\cdot}9124\, m_f\left\{\Phi\left[\sqrt{2ln\left(\frac{m_f}{i-1}\right)}\,\right] - \Phi\left[\sqrt{2ln\left(\frac{m_f}{i}\right)}\,\right]\right\}} \tag{5}$$

$$(i = 1, 2, \cdots m_f)$$

where m_f is component number. $\Phi(t)$ is the error function which is expressed as:

$$\Phi(t) = \int_0^t \frac{\exp(-z^2/2)}{\sqrt{2\pi}}\,dz. \tag{6}$$

Once the representative frequency of each component wave has been determined, wave forces and moments acting on a ship can be calculated for each component wave in the same manner as a regular wave.

2.2 Ship's responses in regular wave

A region is schematically shown in Fig. 1 as being enclosed by the harbor, the breakwaters and the open sea. Cartesian coordinates, (x, y, z), were chosen, with $z = 0$ the undisturbed free water surface, pointing positively upwards. An imaginary boundary, Γ_1, was drawn away from the harbor where wave scattering due to breakwaters and harbor would be negligibly small. The region under consideration was then further divided into two sub-regions, i.e., an outer sea region, *I*, and a harbor region *II*. The fluid was assumed to be inviscid and incompressible; in addition, wave motions were also assumed to be irrotational, with its capillary effects being neglected.

A small amplitude wave is considered with a angular frequency of $\sigma(= 2\pi/T, T$ is the wave period) and an amplitude ζ_0 in the region far away from the harbor. Fluid motions in these sub-regions would both have velocity potentials $\Phi(x, y, z;\ t)$, and are expressed as:

$$\Phi(x, y, z;\ t) = \frac{g\zeta_0}{\sigma}\phi(x, y, z)\,\mathrm{e}^{-i\sigma t} \tag{7}$$

where g is acceleration due to gravity, and $\phi(x, y, z)$ must satisfy the Laplace equation:

$$\nabla^2\phi(x, y, z) = 0. \tag{8}$$

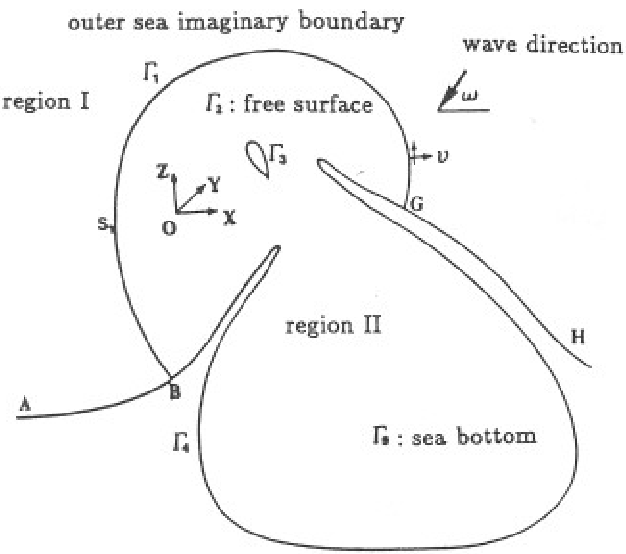


Fig. 1. Definition sketch.

2.2.1 Velocity potential of the outer sea region

The outer sea region I, assumed to have a constant water depth, h, is enclosed by a boundary S_1 (line boundary on the free surface of Γ_1), coast lines $\overline{AB}$, $\overline{GH}$ and a boundary at infinity. The velocity potential of this region can then be separated into two functions. The first one ϕ_0 is the potential function of incident wave. The second ϕ_s is the potential function of scattering wave which is itself a result of scattering of incident wave due to obstacles or bottom configurations in the harbor region. The potential functions of this region can therefore be conveniently expressed as:

$$\phi_I(x, y, z) = \{\phi_0(x, y) + \phi_s(x, y)\} \frac{\cosh k(z + h)}{\cosh kh} \tag{9}$$

where k is the solution of $\sigma^2 h/g = kh \tanh kh$.

When incoming waves bisect the x-axis with an angle ω, its potential function can be expressed as:

$$\phi_0(x, y) = -i \cdot \exp[-ik(x\cos\omega + y\sin\omega)]. \tag{10}$$

Substituting eqn (9) with eqn (8) yields an equation for ϕ_s which satisfies the Helmholtz equations with the form:

$$\frac{\partial^2\phi_s}{\partial x^2} + \frac{\partial^2\phi_s}{\partial y^2} + k^2\phi_s = 0. \tag{11}$$

For the outer sea region, the effects of scattering wave induced by harbor, sea bottom and ship can be neglected if the boundary S_1 is far away from the harbor entrance, and potential function $\phi_s(x, y)$ can be taken as zero. The scattering potential on the imaginary boundary at infinity, which satisfies the Sommerfeld radiation condition, can also be considered as infinitely small. The potential function for any point, $\phi_s(x, y)$ within domain I can thus be found through the application of Green's integral technique, and is provided as:

$$c\phi_s(x, y) = \int_{S_1} \left[\phi_s(\xi, \eta) \frac{\partial}{\partial v}\left[-\frac{i}{4} H_0^{(1)}(kr)\right] - \left[-\frac{i}{4} H_0^{(1)}(kr)\right] \frac{\partial}{\partial v}\phi_s(\xi, \eta)\right] \mathrm{d}s \tag{12}$$

where $\phi_s(\xi, \eta)$ is the potential function specified by the geometrical boundary of domain I, with $\partial\phi_s(\xi, \eta)/\partial v$ being the first normal derivative (directed positively outward). $H_0^{(1)}(kr)$ is the zeroth order Hankel function of the first kind. v is the unit normal vector, and r is the distance between the point under consideration and the boundary,

$$r = \sqrt{(x-\xi)^2 + (y-\eta)^2}.$$

The boundary S_1, where $c = 1/2$, is divided into N segments during the following numerical analysis; in addition, eqn (12) is rewritten in the matrix form:[5]

$$\{F^*\} = [K^*]\{\bar{F}^*\} \tag{13}$$

where $\{F^*\}$ is the potential function and $\{\bar{F}^*\}$ is its normal derivative. $[K^*]$ is a coefficient matrix, being related to the shape of the geometrical boundary.

2.2.2 *Velocity potential of harbor region*

The harbor region *II*, with an arbitrary water depth, is a closed three-dimensional domain. This region is bounded by the imaginary boundary, Γ_1, the free surface, Γ_2, the immersed ship surface, Γ_3, the harbor and breakwaters, Γ_4, and an uneven sea bottom, Γ_5. According to Green's second identity law, the velocity potential of any point inside this region can be determined by velocity potential on the boundary and its first normal derivative, i.e.:

$$c\phi(x,y,z) = \iint\left[\frac{\partial}{\partial v}\phi(\xi,\eta,\zeta)\left(\frac{1}{4\pi}\frac{1}{r}\right) - \phi(\xi,\eta,\zeta)\frac{\partial}{\partial v}\left(\frac{1}{4\pi}\frac{1}{r}\right)\right]\mathrm{d}A \tag{14}$$

where $r = \sqrt{(x-\xi)^2 + (y-\eta)^2 + (z-\zeta)^2}$.

After dividing the surface of the boundaries, Γ_1–Γ_5, into N_1 to N_5 discrete areas with constant elements, the integral can then be transformed into a matrix form ready for calculation:[6]

$$\{\phi_i\} = [K_{ij}]\{\bar{\phi}_j\}\,(i,j = 1,2\cdots 5) \tag{15}$$

where $\{\phi_i\}$ is the potential function of the boundary and $\{\bar{\phi}_j\}$ is its normal derivative. $[K_{ij}]$ is a coefficient matrix, which is related to the shape of the geometrical boundary.

2.2.3 *The boundary conditions*

The boundary conditions are summarized in the following:

1) the free surface condition is:

$$\bar{\phi} = \frac{\sigma^2}{g}\phi, \quad z = 0; \tag{16}$$

2) the condition at the sea floor is:

$$\bar{\phi} = 0; \tag{17}$$

3) the requirement of continuity of mass and energy flux on the boundary Γ_1 is expressed as:

$$\bar{\phi}_I(\xi, \eta, z) = \bar{\phi}_{II}(\xi, \eta, z) \tag{18}$$

$$\phi_I(\xi, \eta, z) = \phi_{II}(\xi, \eta, z). \tag{19}$$

Together with eqn (9) and multiplying with $\cosh k(h+z)$, eqn (18) yields an equation of the form:

$$\int_{-h}^{0} \bar{\phi}(\xi, \eta, z) \cosh k(z+h)\, \mathrm{d}z = \int_{-h}^{0} [\bar{\phi}_0(\xi, \eta) + \bar{\phi}_s(\xi, \eta)] \frac{\cosh^2 k(z+h)}{\cosh kh}\, \mathrm{d}z.$$

Dividing the surface of the imaginary boundary, Γ_1, into n segments vertically, and m segments horizontally, yields $m \times n$ elements on the surface Γ_1. Normal potential of the scattering wave at any position on the boundary can then be calculated through:

$$\bar{\phi}_s(\xi_i, \eta_i) = \frac{k}{N_0 \sinh kh} \sum_{j=1}^{n} \bar{\phi}(\xi_i, \eta_i, \zeta_i) \cosh k(z_j + h) \Delta z_j - \bar{\phi}_0(\xi_i, \eta_i) \qquad (i = 1, 2, \cdots, m) \tag{20}$$

where $N_0 = 0{\cdot}5(1 + 2kh/\sinh 2kh)$.

Substituting eqn (9) into eqn (19), yields:

$$\phi(\xi_i, \eta_i, \zeta_i) = [\phi_0(\xi_i, \eta_i) + \phi_s(\xi_i, \eta_i)] \frac{\cosh k(z_i + h)}{\cosh kh} \qquad (i = 1, 2, \cdots, m \times n). \tag{21}$$

The following matrix expression can be obtained by combining eqns (13), (20) with eqn (21), i.e.:

$$\{\phi_1\} = [R]\{F^0 - K^* \bar{F}^0\} + c^*[R][K^*][Q]\{\bar{\phi}_1\} \tag{22}$$

where $c^* = k/N_0 \sinh kh$, subscript '1' denotes the boundary Γ_1, and $[R]$, $[Q]$ are coefficient matrices provided by:

$$[R] = \begin{bmatrix} \{A_{1j}\} & & & & & \\ & \{A_{2j}\} & & & 0 & \\ & & \ddots & & & \\ & & & \{A_{ij}\} & & \\ & 0 & & & \ddots & \\ & & & & & \{A_{mj}\} \end{bmatrix} \tag{23}$$

$$A_{i,j} = \frac{\cosh k(z_{i,j} + h)}{\cosh kh}, \quad (i = 1, 2, \cdots, m;\ j = 1, 2, \cdots, n)$$

$$[Q] = \begin{bmatrix} \{B_{1j}\} & & & & & 0 \\ & \{B_{2j}\} & & & & \\ & & \ddots & & & \\ & & & \{B_{ij}\} & & \\ & 0 & & & \ddots & \\ & & & & & \{B_{mj}\} \end{bmatrix} \tag{24}$$

$$B_{i,j} = \cosh k\,(z_{i,j} + h)\,\delta z_j\,, \quad (i, = 1, 2, \cdots, m;\ j = 1, 2, \cdots, n).$$

$\{A\}$ and $\{B\}$ are column matrix and row matrix, respectively;

4) the conditions on the breakwaters of the harbor:

the breakwaters and quay are assumed to be impermeable. Therefore, boundary condition on breakwaters and quay is:

$$\bar{\phi}(\xi, \eta, \zeta) = 0; \tag{25}$$

5) boundary conditions on immersed ship surface:

the ship can be set in fixed state whenever the wave forces and moments exerting themselves on the ship are calculated. The boundary condition on an immersed ship surface is therefore:

$$\bar{\phi} = 0. \tag{26}$$

2.2.4 Wave forces and moments exerting themselves on a ship

When a ship is located at or near a harbor entrance, forces and moments exert themselves on that ship due to the pressure of a fluid. As Fig. 2 shows, coordinates $O' - x'y'z'$ were fixed at the center of gravity of the

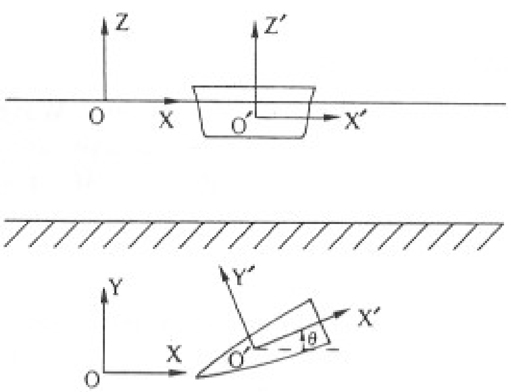


Fig. 2. Definition of coordinates system.

ship, with the x'-axis in the aft direction. Wave forces and moments exerting on the ship can therefore be obtained by integrating the immersed surface of the ship, which is expressed as:

$$
\begin{aligned}
F_{x'} &= \rho g \zeta_0 \int\int_{\Gamma_3} i\phi \frac{\partial x'}{\partial v} \mathrm{d}\Gamma\, \mathrm{e}^{i\sigma t} \\
F_{y'} &= \rho g \zeta_0 \int\int_{\Gamma_3} i\phi \frac{\partial y'}{\partial v} \mathrm{d}\Gamma\, \mathrm{e}^{i\sigma t} \\
F_{z'} &= \rho g \zeta_0 \int\int_{\Gamma_3} i\phi \frac{\partial z'}{\partial v} \mathrm{d}\Gamma\, \mathrm{e}^{i\sigma t}
\end{aligned} \tag{27}
$$

$$
\begin{aligned}
M_{x'} &= \rho g \zeta_0 \int\int_{\Gamma_3} i\phi \left[y' \frac{\partial z'}{\partial v} - z' \frac{\partial y'}{\partial v} \right] \mathrm{d}\Gamma\, \mathrm{e}^{i\sigma t} \\
M_{y'} &= \rho g \zeta_0 \int\int_{\Gamma_3} i\phi \left[z' \frac{\partial x'}{\partial v} - x' \frac{\partial z'}{\partial v} \right] \mathrm{d}\Gamma\, \mathrm{e}^{i\sigma t} \\
M_{z'} &= \rho g \zeta_0 \int\int_{\Gamma_3} i\phi \left[x' \frac{\partial y'}{\partial v} - y' \frac{\partial x'}{\partial v} \right] \mathrm{d}\Gamma\, \mathrm{e}^{i\sigma t}
\end{aligned} \tag{28}
$$

where

$$
\begin{aligned}
x' &= (x - \bar{x}_o)\cos\theta + (y - \bar{y}_o)\sin\theta \\
y' &= -(x - \bar{x}_o)\sin\theta + (y - \bar{y}_o)\cos\theta \\
z' &= z - \bar{z}_o
\end{aligned} \tag{29}
$$

$$
\begin{aligned}
\frac{\partial x'}{\partial v} &= \frac{\partial x}{\partial v}\cos\theta + \frac{\partial y}{\partial v}\sin\theta \\
\frac{\partial y'}{\partial v} &= -\frac{\partial x}{\partial v}\sin\theta + \frac{\partial y}{\partial v}\cos\theta \\
\frac{\partial z'}{\partial v} &= \frac{\partial z}{\partial v}
\end{aligned} \tag{30}
$$

where $(\bar{x}_o, \bar{y}_o, \bar{z}_o)$ is center of gravity for a ship. Wave forces exerting themselves on a ship, relating to $x'-, y'-, z'$-axis, are expressed as $F_{x'}$, $F_{y'}$, $F_{z'}$, respectively, and moments are $M_{x'}$, $M_{y'}$, $M_{z'}$, respectively.

2.2.5 The system of equations

Equation (15) expresses the relations of the potential functions to their normal derivatives on the boundaries. ϕ_i and $\bar{\phi}_j$, as yet unknown, express velocity potential and their normal derivatives on all of the boundaries of the domain, respectively. Velocity potential and their normal derivatives include the effects of incident and scattering wave. Subscripts 'i' and 'j' denote the boundary. $[K_{ij}]$, expressing the influence between boundary and others, is a coefficient matrix and is decided by the shape of the geometrical boundary. Each value of the matrix can be obtained via Green's integral technique. Subscript 'ij' expresses the influence from j-th boundary on the i-th boundary. By using eqns (16), (17), (22), (25), (26), eqn (15) can be rewritten in the following form:

$$\begin{bmatrix} [k_{11} - c^* RK^* Q] & \frac{\sigma^2}{g} k_{12} & 0 & 0 & 0 \\ k_{21} & \frac{\sigma^2}{g} k_{22} - I & 0 & 0 & 0 \\ k_{31} & \frac{\sigma^2}{g} k_{32} & -I & 0 & 0 \\ k_{41} & \frac{\sigma^2}{g} k_{42} & 0 & -I & 0 \\ k_{51} & \frac{\sigma^2}{g} k_{52} & 0 & 0 & -I \end{bmatrix} \begin{bmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \\ \phi_5 \end{bmatrix} = \begin{bmatrix} R[F^0 - K^* \bar{F}^0] \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{31}$$

where I is a unit matrix. Equation (31) can solve the potential function on the boundaries 2–5, and the normal derivative of the velocity potential on boundary Γ_1. The forces and moments exerting themselves on the ship body can be obtained by using eqns (27) and (28).

2.3 Ship's responses in irregular waves

The irregular waves can be decomposed on the basis of the spectral analysis method into several wave components with different frequencies; in addition, the force response which is induced by each wave component can be obtained by numerical analysis as described in the previous section. Therefore, both the response spectrum of force and also the moment of the ship induced by irregular waves can be obtained. The transfer function between wave (input) and acting force or moment (output) can be defined in following formula:

$$S_{ff}(f) = |H_{\zeta f}(f)|^2 \, S_{\zeta\zeta}(f) \tag{32}$$

where $S_{ff}(f)$ expresses either force or moment response spectrum; $S_{\zeta\zeta}(f)$ is wave power spectrum of water surface elevation; and $H_{\zeta f}(f)$ is the transfer function corresponding to each representative frequency and is expressed in eqns (27) and (28).

3 RESULTS AND DISCUSSION

A fishing boat was taken here as an example for the numerical analysis. Its responses were investigated when sailing near a harbor entrance. A fishing boat 31·5 m long and weighing 30 tons, which type is common in Taiwan, was used as the ship model, as shown in Fig. 3. In simplifying this problem, the harbor was calculated as a square, having a length of 10 h for each side, and an entrance width 5 h. The breakwaters and quay were assumed to be impermeable. The origin of the coordinate system is shown in Fig. 4 to have been located at the center of the harbor entrance for convenience of analysis. On the other hand, the Bretschneider spectrum was used as an incident wave spectrum for the convenience of making a comparison with experimental results. External force and moment acting on the ship were calculated by using significant period $T_{1/3} = 1{\cdot}0, 1{\cdot}5$ and 2·0 s (under the consideration of scale 1:25) and wave direction $\omega = 90°$.

Numerical results were verified here by performing a model test in a wave tank of 25 m wide, 1·0 m high and 30 m long. The water depth was maintained at a constant 30 cm. A fishing boat, as in the previous description, was reduced to a scale of 1:25 and used as the model ship. A six-components loadcell was set up at the center of gravity of the model ship for measuring external forces and moments.

3.1 Comparison of numerical with experimental results

When the numerical analysis is being processed, the number of component waves m_f is to be 32. The representative frequency of each component wave is then calculated by eqn 5 according to the significant period which is available from the wave condition. Once the representative frequency

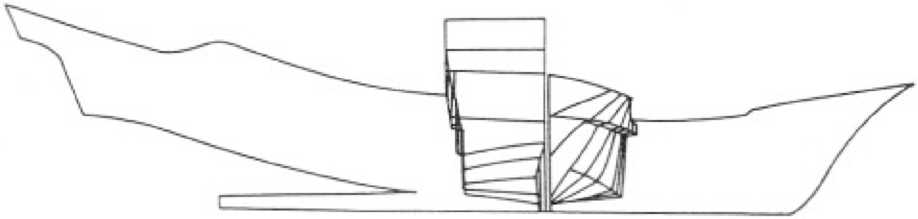


Fig. 3. Model ship.

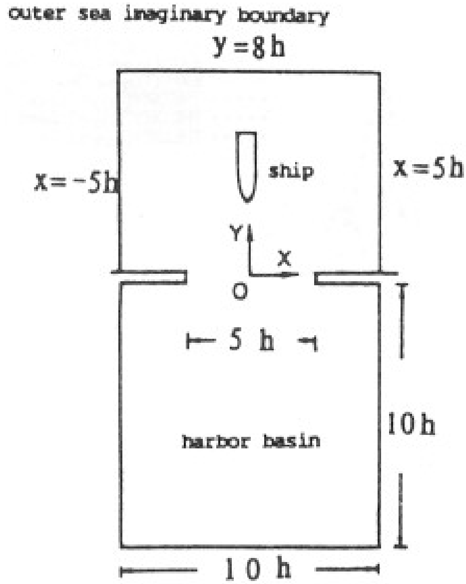


Fig. 4. Setups of the imaginary boundary.

has been determined, the response of the ship at each frequency (or the transfer function) can be obtained via the method described in Section 2.2. The force and moment spectrum are then obtained by eqn 32. The numerical results are presented in Figs 6–8 with a solid line.

When the experiment was being processed, record data were received by an A/D convert recorder, and the power spectra were calculated by the Fast Fourier Transform method. Each test condition was carried out three times and a mean average of the experimental results was taken. The wave spectrum is presented in Fig. 5. When the fishing boat in its longitudinal direction along the y-axis was affected by the previous wave conditions, wave forces and rotative moments acting on the lateral section of ship were so small that $F_{y'}$, $M_{x'}$, $M_{z'}$ could be ignored. The experimental results are presented in Figs 6–8 with a dashed line.

Most experimental results are in sufficient correlation with numerical analysis results, as observed from their comparison with each other. The prominent characteristics of force and moment spectra induced by irregular waves are therefore confirmed here as being capable of being validly predicted. However, the prediction results are observed to be larger than the experimental results when the significant period $T_{1/3}$ is 2·0 s. Those errors are apparently caused by the bias which occurs between experimental and theoretical wave spectra. As Fig. 5 shows, for $T_{1/3} = 2{\cdot}0$ s conditions, the wave spectrum in the experiment loses some

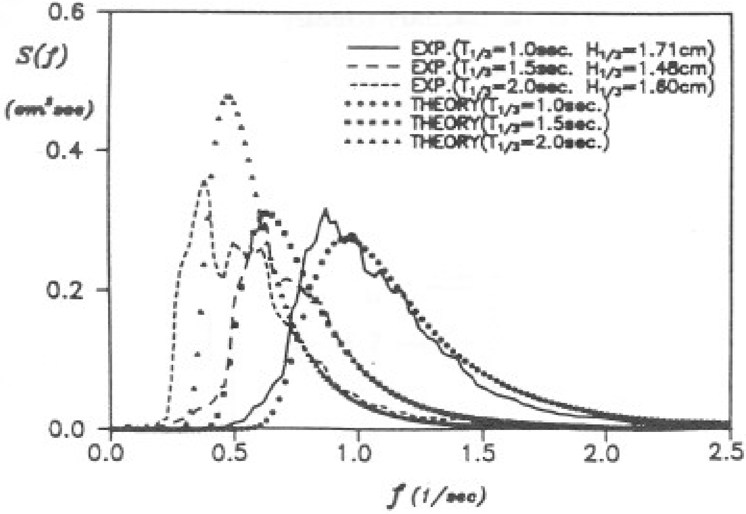


Fig. 5. Wave spectra.

energy in the range near its peak frequency, and it will cause the differences involving response spectra between numerical analysis and experiment.

Force spectra of $F_{x'}$, $F_{z'}$ and moment spectra of $M_{y'}$ are shown in Fig. 6(a)–(c), when the center of gravity of the ship is located at $(\bar{x}_o, \bar{y}_o) = (0, 2h)$ and is affected by a wave with significant period $T_{1/3} = 1{\cdot}0$ s (corresponding peak frequency is 0·952 Hz). Force spectra of $F_{x'}$ and moment spectra of $M_{y'}$ are found here to have a similar distribution relating to frequency. These spectra all have a maximum value at a frequency of $f = 0{\cdot}72\,Hz$, in addition, and most of the energy is concentrated on the neighborhood of this frequency. The results of $T_{1/3} = 1{\cdot}5$ s, with a corresponding peak frequency of 0·635 Hz, are provided in Fig. 7(a)–(c). Similar to the results of $T_{1/3} = 1{\cdot}0$ s, force spectra of $F_{x'}$ and moment spectra of $M_{y'}$ always have a similar distribution in the frequency domain; however, they have another peak value at frequency $f = 0{\cdot}58\,Hz$. The results of $T_{1/3} = 2{\cdot}0$ s, with a corresponding peak frequency of 0·476 Hz, are provided in Fig. 8(a)–(c). These results exhibit the same tendency as in the previous description. Moment $M_{y'}$ is generally influenced by force $F_{x'}$ and $F_{z'}$. Additionally, force $F_{x'}$ is shown in Figs 6–8 to be the major influential factor for moment $M_{y'}$. Furthermore, most response energy is notably concentrated on some specific frequency and the peak frequency of response phenomenon implies that a large wave energy is unnecessary for stimulating such a large response.

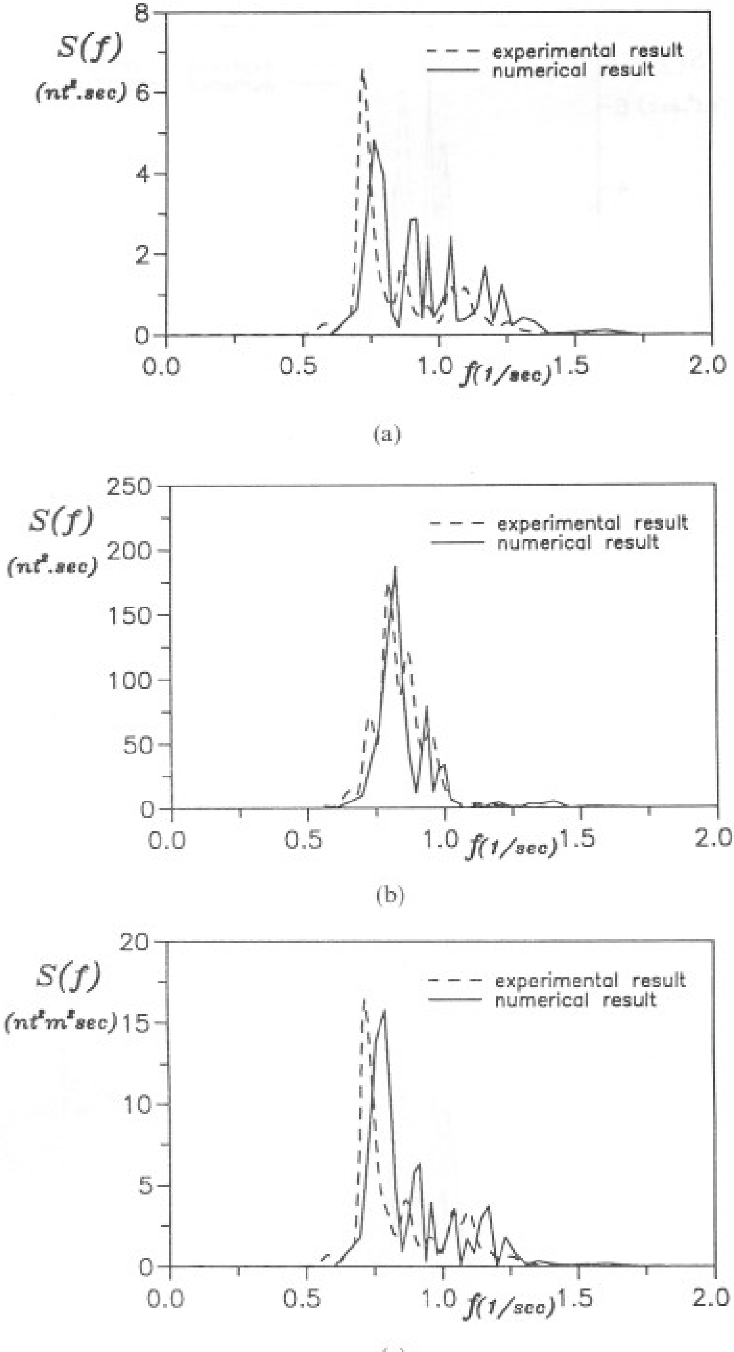
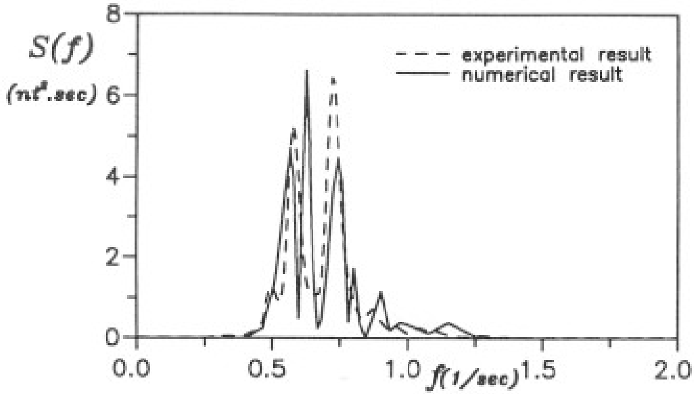
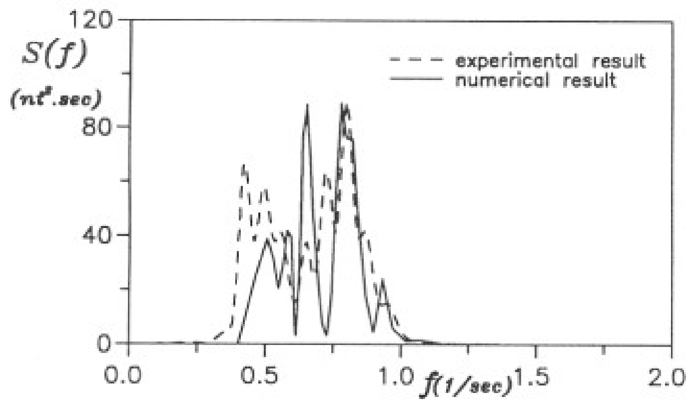


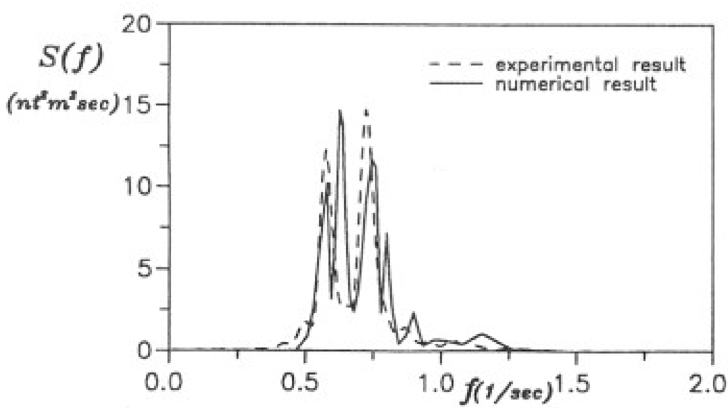
Fig. 6 $T_{1/3} = 1{\cdot}0$ s, $(\bar{x}_o, \bar{y}_o) = (0, 2h)$, response spectra of ship. (a) Force spectrum of $F_{x'}$; (b) force spectrum of $F_{z'}$; (c) force spectrum of $M_{y'}$.



(a)

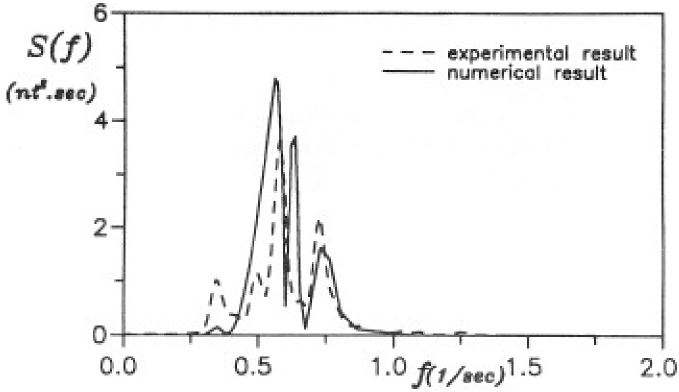


(b)

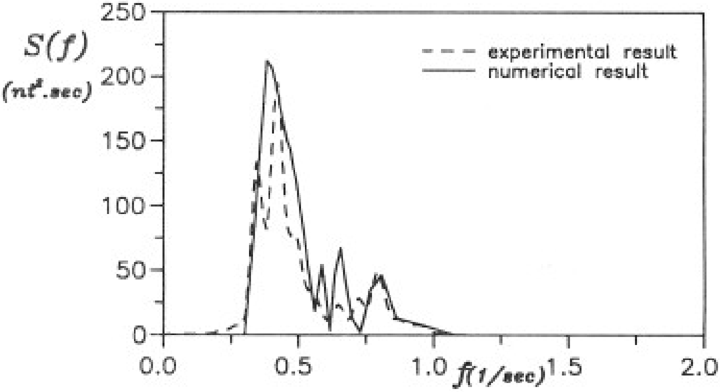


(c)

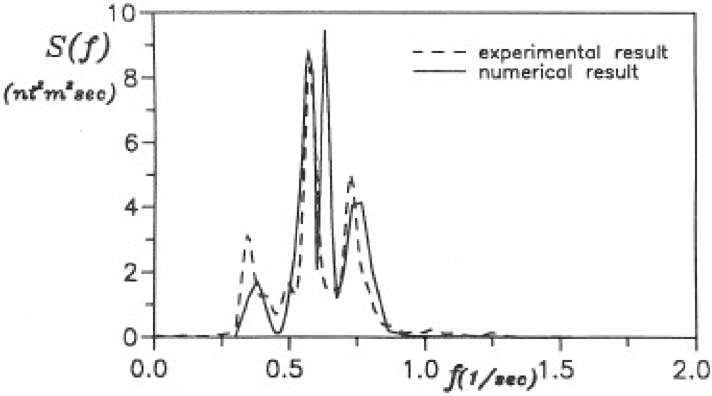
Fig. 7. $T_{1/3} = 1{\cdot}5$ s, $(\bar{x}_o, \bar{y}_o) = (0, 2h)$, response spectra of ship. (a) Force spectrum of $F_{x'}$; (b) force spectrum of $F_{z'}$; (c) force spectrum of $M_{y'}$.



(a)



(b)



(c)

Fig. 8. $T_{1/3} = 2{\cdot}0$ s, $(\bar{x}_o, \bar{y}_o) = (0, 2h)$, response spectra of ship. (a) Force spectrum of $F_{x'}$; (b) force spectrum of $F_{z'}$; (c) force spectrum of $M_{y'}$.

3.2 The influence of ship position near harbor entrance

The position of ship staying is an important factor for the external forces and moments acting on a ship. Therefore, three positions, $(\bar{x}_o, \bar{y}_o) = (0, 0), (0, 2h)$ and $(0, 4h)$ are considered, for discussion of their differences. The response spectra were first calculated with the same significant wave height. The area of response spectra was then integrated. Furthermore, the influence of the ship position on the total response energy was investigated. For the convenience of understanding the influence of ship position, the total response energy of the case with $T_{1/3} = 1{\cdot}0$ s and $(\bar{x}_o, \bar{y}_o) = (0, 0)$ was taken here as the unit and the results of other cases were normalized.

The maximum response would occur when the ship is located at $(0, 2h)$ for a significant period $T_{1/3} = 1{\cdot}5, 2{\cdot}0$ s, as observed in Fig. 9(a) from the comparison results of total energy of $F_{x'}$. However, the minimum response also occurs at the same position when $T_{1/3} = 1{\cdot}0$ s. The total energy of $F_{z'}$ has large differences depending on the ship position as shown in Fig. 9(b). A wave with a longer significant period generally causes a larger response for a ship at all three positions. The total energy of moment of a ship is shown in Fig. 9(c) at three positions near the harbor entrance. The response induced by a wave with $T_{1/3} = 1{\cdot}5, 2{\cdot}0$ s is generally larger than that induced by a wave with $T_{1/3} = 1{\cdot}0$ s.

3.3 The influence of the number of wave components

When the analysis is being processed, the number of component waves would have an effect on the results of numerical analysis. Seven kinds of component wave numbers ($m_f = 4$, 8, 16, 24, 32, 40, 64) were used here for discussion. The total energy of the response spectrum relating to the component wave number m_f is shown in Fig. 10(a)–(c) when (a) the ship is located at $(0, 2h)$, and (b) irregular waves with significant period $T_{1/3} = 2{\cdot}0, 1{\cdot}5, 1{\cdot}0$ s are acting. The total energy of component number $m_f = 64$ was taken here as the unit and the results of other component numbers were normalized. The response energy of prediction was observed to be capable of being influenced by the component number. For the wave with longer period $T_{1/3} = 2{\cdot}0, 1{\cdot}5$ s, the component wave number m_f must be larger than 24 to get adequate prediction results. If m_f is smaller than 16, analysis will cause a large error. However, for the condition of a wave with a shorter period $T_{1/3} = 1{\cdot}0$ s, numerical analysis needs a larger component wave number for analysis so as to avoid the error.

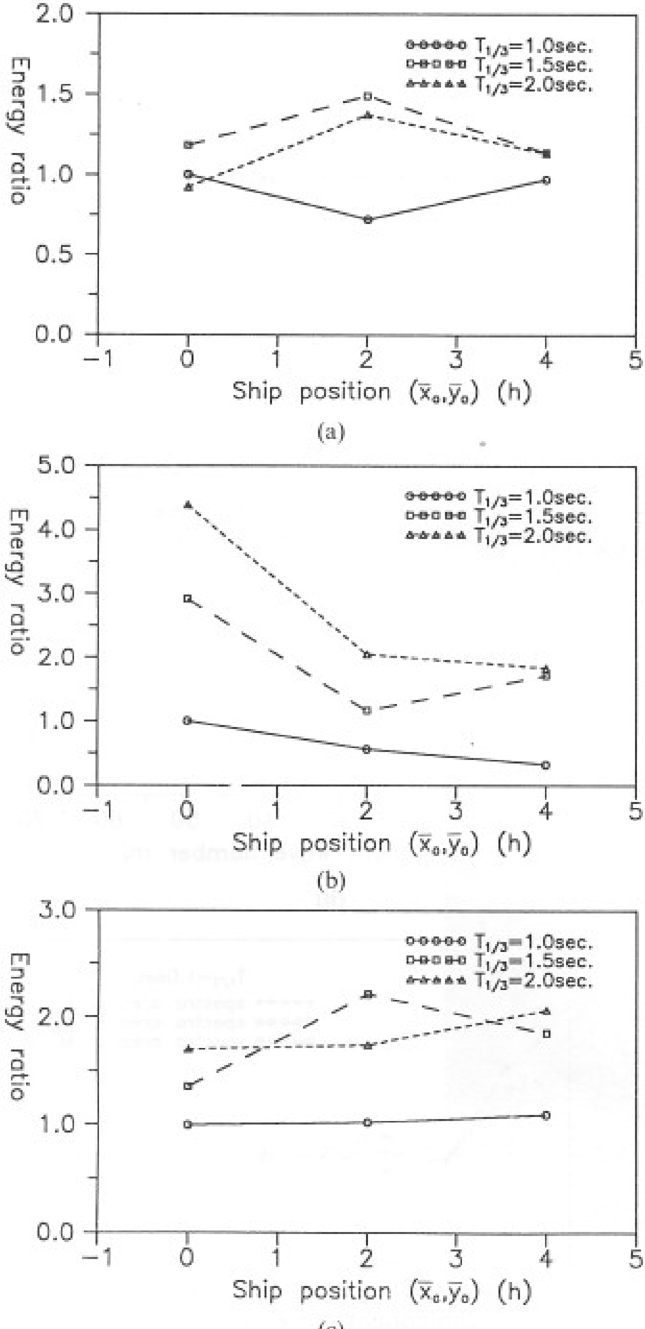
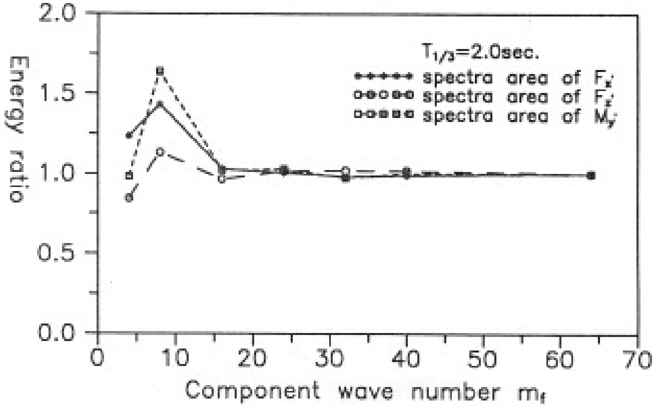
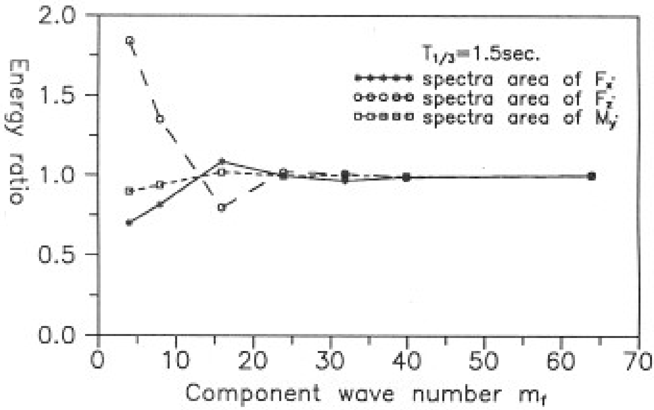


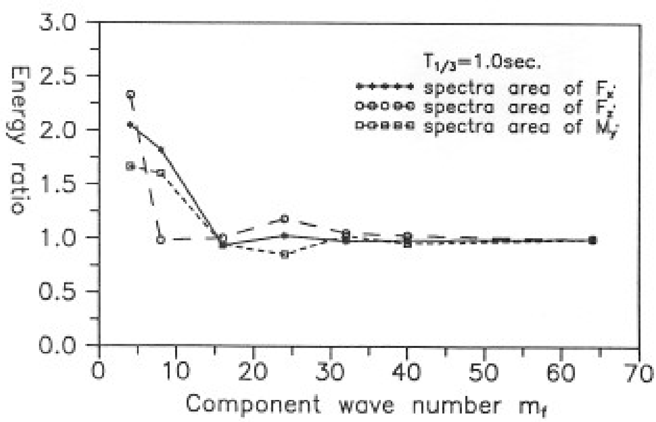
Fig. 9. Comparison of response spectrum areas in positions $(0, 0)$, $(0, 2h)$, $(0, 4h)$. (a) Force spectrum area of $F_{x'}$ in various positions; (b) force spectrum area of $F_{z'}$ in various positions; (c) moment spectrum area of $M_{y'}$ in various positions.



(a)



(b)



(c)

Fig. 10. The influence of m_f for numerical analysis. (a) The influence of m_f for $T_{1/3} = 2{\cdot}0$ s; (b) the influence of m_f for $T_{1/3} = 1{\cdot}5$ s; (c) the influence of m_f for $T_{1/3} = 1{\cdot}0$ s.

4 CONCLUSION

The safety and activities of a ship can be regarded as an explicit index for harbor tranquillity. The understanding for both wave forces acting on ship and ship motions near a harbor entrance are therefore able to provide an efficient manner for improving the design of a harbor. Waves near the harbor are affected by the seabed topography. Moreover, the interaction of incident, reflected and scattered waves, due to the presence of breakwaters and marine structures, always causes the characteristics of a wave to become more complex in this area. A proper understanding of the phenomenon which influences the behavior of ships near the harbor is therefore necessary for improving the design of a harbor. A fishing boat which is typically found in Taiwan was taken as an example for predicting the external forces of a ship, when it is near a square harbor entrance and is affected by a uni-directional irregular wave. External forces and moments which exert themselves on a ship can be completely estimated by combining the linear superposition method for spectral analysis with the boundary element method for numerical analysis. The validity of the method is adequately verified by experimental results. However, ship speed is ignored in this paper so as to simplify this problem. Developing an advanced analytical method would be necessary for forcasting the response of a ship which moves in the random sea.

REFERENCES

1. Bruun, P., Breakwater or mooring system? Dock and Harbour Authority, 1981, pp. 126–129.
2. Sawaragi, T. & Kubo, K., Some considerations on port planning for security of ships in a harbour basin. *Proc. 8th Int. Harbour Congress*, 1983, pp. 2.21–2.28.
3. Sawaragi, T.& Aoki, Shin-ichi, Prediction and attenuation of wave-induced ship motion in a harbour. *Coastal Engng*, **34** (1991) 243–265 (in Japanese).
4. Nagai, Kohei, Computation of refraction and diffraction of irregular sea. *Report Port and Harbour Res. Inst.*, **11** (1972), 47–119 (in Japanese).
5. Chou, C. R., Application of boundary element method on water problem. National Taiwan Ocean Univ. 1983 (in Chinese).
6. Chou, C. R. & Lin, J. G., Numerical analysis of harbour oscillation with absorber. In *11th Conf. Ocean Engng*, Taiwan, 1989, pp. 111–129 (in Chinese).
7. Goda, Yoshimi, *Random Seas and Design of Maritime Structures*. University of Tokyo Press, Tokyo, 1985, pp. 41–66.