EFFECT OF SHIP SIZE, FORWARD SPEED AND WAVE DIRECTION ON RELATIVE WAVE HEIGHT OF CONTAINER SHIPS IN ROUGH SEAS

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ABSTRACT

This paper deals with the numerical calculations of relative wave height of ships in the rough seas. Linear potential theory has been applied for describing fluid motion and 3-D sink-source technique has been used to determine hydrodynamic forces for surface ship advancing in waves at constant forward speed. The numerical results are compared not only with some experimental results but also with some other contemporary methods in frequency domain analysis used by others researchers. The numerical results of 3-D Green Function which has been solved by the method of singularities distributed over the hull surface is then used to analysis the results in time domain. For the simulation of the random sea, a fully probabilistic technique with unequal frequency spacing has been applied. Empirical non-linear roll damping has been incorporated to predict motion response in rough sea and time domain simulation of relative wave height of typical ship like container ships of different size and speed in short crested irregular waves have been carried out with different sea states. The numerical results of the maximum and significant values of irregular relative wave heights for different sea states have been discussed by comparing with some requirements by a Classification Society of shipping in order to assess if its rule consider enough allowance of deck load issue in case of severe sea states and it is evident from the numerical simulation that irrespective of the size of the ships, there is more prone to bow slamming or propeller emergence for the case of most severe sea state considered in this paper.

Keywords: *Container Ship, Relative Wave Height, Rough Sea, Source-sink Method*

1.0 INTRODUCTION

The prediction of seakeeping parameters like ship response, wave load, deck wetness, slamming (sudden impact on the bottom of the ship) *etc*. in a realistic seaway is some of the most important aspects of ship design. Wave induced motions are capable of making the ship's intended roles impossible, whilst extreme wave loadings on deck may have catastrophic consequences during her voyage to ocean route and this issue of wave load on deck is getting more and more importance by the designers of ocean going vessel specially after the tragic accident of the Derbyshire in the year 1980. For determination of deck load and designing of out fittings such as hatch cover / fore deck fittings, relative wave height has been considered as an essential parameter and this has been further emphasized by the IACS [1] and Classification societies of shipping for improving the safety of ship considering the wave load issue for the design of the outfittings on deck and hull structure itself. Previously simple 2-D Strip Method, 2.5–D Slender ship theory and 3-D method without forward speed had been used more frequently for the seakeeping problems of ship. But due to neglect of 3-D and forward speed effects on hydrodynamic forces of the ship, these methods do not necessarily give good estimation of seakeeping performance. On the other hand, 3-D Source–sink method is expected to provide better estimation of all relevant responses, so 3-D Source-sink method is becoming very useful and popular day by day. Also the modern developments in computer performance and numerical technique have made it possible to solve 3-D problem with forward speed more easily than in the past.

The 3-D Green function method is the most popular among 3-D seakeeping methods striving to overcome insufficiencies of strip methods. For the problems without forward speed, the Green function is easy to compute. In this case of forward speed, many numerical and theoretical difficulties appear. Despite the numerical difficulties involved in its computations, the advantage of this Green function are an automatic fulfillment of the linearised free-surface and radiation conditions, the absence of mesh on the free surface avoiding reflection on the boundary and the filtering of smaller wave lengths. Development of a practical scheme requires an efficient from of the functions. Two main types based on alternative representations are available, Noblesse and Yang[2]. First one is defined by Simple Fourier Integrals that involve relatively complicated special functions applied which has been applied in this paper and second one is the expression by single Fourier Integrals along the Steepest descent integration path in the complex Fourier Plane(namely Bessho's method) applied, for example, by Maury *et al* [3]. Another increasingly popular approach is Rankine panel methods which could in principle capture all steady-flow effects. Although, Rankine panel method uses simple Rankine singularities but it deserves special attention in satisfying the radiation condition when the speed frequency parameter is less than 0.25 and the number of unknown is much higher in the Rankine panel method than in the Green function method [4], as the free surface should also be discretised. Also the size of the free surface domain should be carefully chosen, specially when the solutions in the low-frequency range are of interest. That is why, among the state-of-the-art seakeeping tools linked to the finite element structural analysis packages, in practice, the computer codes developed based on the Green function method are dominant in the shipbuilding industries [4].

In this paper, Kelvin singularity with translating and pulsating Green function in the form presented by Inglis and Price [5] has been used. The problem is solved by the method of singularities distributed over the hull surface. Hess and Smith method [6] is used to obtain the density of these singularities. The numerical solution for the case of surface ship is approximately obtained by considering the hull as a position of plane polygonal elements, bearing a constant singularity distribution. Velocity potential at any particular point in the free surface is determined by using 3-D Green function with forward speed which satisfies the boundary conditions for a pulsating source in the fluid and a computer code has been developed. The accuracy of the present computer code has been tested in an extensive manner. Firstly, the calculation of Green function has been tested for a point source moving along a radial distance with forward speed and then the present numerical code has been applied for a more realistic ship form of Series60 ship of C_B=0.7. A comparative study has been shown with the numerical results of present 3-D source-sink method with some available experiment data as well as some contemporary analytical techniques used by many researchers in this field. After satisfying the capability of the present coding, a detailed calculation has been performed for some Container vessels. Hydrodynamic co-efficient such as added mass, damping and exciting forces of different direction have been calculated at first and then these numerical results have been used for simulation of short crested irregular waves. To get longer simulation time, unequal frequency spacing method has been used for the simulation of random sea. The result of the maximum and significant values of irregular relative wave heights for various sea conditions has been calculated. The effect of speed and wave direction on irregular relative wave height has been considered and finally some conclusions have been drawn based on the numerical calculations which may provide some valuable information for the design of ocean going vessel.

2.0 MOTION RESPONSES OF SHIP

A right-hand Cartesian coordinate system (x, y, z) has been considered with Z directed vertically upwards and origin at the water line of the center plane of the ship. Let the ship is moving in the X direction with forward speed U and oscillating with encountering frequency ω_ε in wave with frequency of ω. Let us assume that fluid is inviscid and incompressible and the free surface extends to infinity. If both incoming wave elevation and body oscillation are small, then a harmonically oscillating flow field containing such fluid is described by the velocity potential and total velocity potential can be written as

$$\phi = \phi_w + \phi_7 + \sum_{j=1}^{6} - i\omega_e \overline{X}_j \phi_j \tag{1}$$

Where, the cases j = 1, 2, 3, 4, 5 and correspond to surge, sway, heave, roll, pitch, and yaw, respectively.

The singularity distribution over the hull boundary surface can be expressed by Green function of the translating and pulsating source and can be written as [7]:

$$G(x_p, y_p, z_p; x_Q, y_Q z_Q) = \left(\frac{1}{R} - \frac{1}{R_1}\right) + \frac{2g}{\pi}\left\{\int_0^\gamma \int_0^\alpha + \int_\gamma^{\pi/2} \int_{L_1} + \int_{\pi/2}^{\pi} \int_{L_2}\right\} f(\theta, k)\, d\theta\, dk \tag{2}$$

where,

$$f(\theta,k) = \frac{k e^{k\lfloor (z_p+z_Q) + i(x_p-x_Q)\cos\theta \rfloor} \cos[k(y_p-y_Q)\sin\theta]}{gk - (\omega + kU\cos\theta)^2} \tag{3}$$

$$\beta = U\omega/g, \quad \gamma = 0, \text{ if } \beta, < 0.25 \text{ and}$$
$$\gamma = \arccos(1/4\beta), \text{ if } \beta \geq 0.25 \tag{4}$$

$$R^2 = (x_p - x_Q)^2 + (y_p - y_Q)^2 + (z_p - z_Q)^2 \quad \text{and}$$
$$R_1^2 = (x_p - x_Q)^2 + (y_p - y_Q)^2 + (z_p + z_Q)^2 \tag{5}$$

The fundamental singularity G defined by Equation (2) is a function of parameter $\beta = U\omega_e/g$ and $k = \omega_e^2/g$. The behaviour of this function is similar to the kelvin singularity (1960) but produces four free waves associated with the singularities k_1, k_2, k_3 and k_4 which can be expressed as Inglis and Price [5].

$$\sqrt{gk_1}, \sqrt{gk_3} = \frac{1 - \sqrt{1 - 4\beta\cos\theta}}{2\beta\cos\theta}\,\omega_e \qquad \text{and}$$

$$\sqrt{gk_2}, -\sqrt{gk_4} = \frac{1 - \sqrt{1 + 4\beta\cos\theta}}{2\beta\cos\theta}\,\omega_e \tag{6}$$

If $\sigma_j(Q)$ is considered as the strength of source distributed over the hull boundary surface at point Q then the potential at any point P inside the fluid can be expressed by the singularity distribution over the hull boundary surface (x_Q, y_Q, z_Q) and Green function as:

$$\phi_j(P) = -\frac{1}{4\pi}\left[\iint_{S_H} G(P,Q)\sigma_j(Q)ds + \frac{U^2}{g}\oint_{C_H} G(P,Q)\sigma_j(Q)n_1 dl\right] \tag{7}$$

Where, contour integral is over the intersection of the hull surface S_H and the free surface and derivations are given in Inoue and Makino [8].

After getting the velocity potentials with the help of numerical calculation, the radiation forces (i = 1, 2, 3) and moments (i = 4, 5, 6) caused by the dynamic fluid pressure acting on the body due to the j-th mode can be obtained by :

$$Fij = \rho \iint_s \left(\omega_e^2 \overline{X} j\phi j + i\omega_e U \overline{X} j \frac{\partial\phi_j}{\partial x}\right) n_i\, ds \tag{8}$$

From radiation forces and moments added mass and damping coefficients are obtained by:

$$a_{ij} = -\rho\, Re \iint_s \left(\phi_j + i\frac{U}{\omega_e}\frac{\partial\phi_j}{\partial x}\right) n_i\, ds \tag{9}$$

$$b_{ij} = -\rho\omega\, e\, Im \iint_s \left(\phi_j + \frac{U}{\omega_e}\frac{\partial\phi_j}{\partial x}\right) n_i\, ds \tag{10}$$

Wave exciting forces and moments can be obtained by.

$$Fi = i\rho\omega_e e^{-i\omega_e t} \iint_s \left\{(\phi_w + \phi_7) + i\frac{U}{\omega_e}\frac{\partial(\phi_w + \phi_7)}{\partial x}\right\} n_i\, ds \tag{11}$$

3.0 MOTION EQUATION IN TIME DOMAIN

The motion of a floating body in time domain under an arbitrary external force can be expressed by

$$\sum_{j=1}^{6}(M_{ij} + m_{ij})\ddot{X}_j + \int_{-\infty}^{t} R_{ij}(t-\tau)\ddot{X}_j\, d\tau + B_n|x|x + C_{ij}X_j = F_i(t) \qquad (12)$$

for $i = 1, 2, \ldots, 6$ and where

Frequency independent added mass matrix and retardation function have the following form:

$$m_{ij} = a_{ij}(\omega) + \frac{1}{\omega}\int_{0}^{\infty} R_{ij}(t)\sin(\omega t)\, dt \qquad (13)$$

$$R_{ij} = \frac{2}{\pi}\int_{0}^{\infty} b_{ij}(\omega)\cos(\omega t)\, d\omega \qquad (14)$$

The wave exciting force in short crested waves in time domain is written as follows:

$$F_i(t) = \sum_m\sum_n T^i_{mn} a_{mn}(\omega_m, \beta_n)\cos(\omega_m t - k_m x\cos\beta n - k_m y\sin\beta_n + \varepsilon_{mn}) \qquad (15)$$

Where, T^i_{mn} is complex transfer function of wave exciting force with frequency ω_m and direction of propagation β_n, ε_{mn} is random phase, a_{mn} is the amplitude of component wave with frequency ω_m and direction of propagation β_n and is calculated by using the wave spectrum $S(\omega_m, \beta_n)$ as follows:

$$a_{mn}(\omega_m, \beta_n) = \sqrt{2S(\omega_m, \beta_n)\,\Delta\omega\,\Delta\beta} \qquad (16)$$

The incident wave elevation at a point (x, y) can be written by:

$$\zeta_w(t) = \sum_m\sum_n a_{mn}(\omega_m, \beta_n)\cos(\omega_m t - k_m x\cos\beta_n - k_m y\sin\beta_n + \varepsilon_{mn}) \qquad (17)$$

The relative wave height at arbitrary point of ship is calculated as follows:

$$z_r(x_r, y_r) = \zeta_w(x_r, y_r) - \zeta(x_r, y_r) \qquad (18)$$

where, the vertical displacement at arbitrary point of the ship can be obtained by:

$$\zeta(x_r, y_r) = X_3 - (x_r, y_G)X_5 + y_r X_4 \qquad (19)$$

4.0 VALIDATION STUDY

It is very important to verify and validate the numerical code before using it for practical purpose. That is why emphasis is put on the verification against results not only from other codes, but also validation against model tests is made. A very precise verification which would require an exact match of the results, could have been made with a program using the same theory and the same algorithms. But such results are not always available and even if the type of theory was the same, the method for determining hydrodynamic coefficient such as added mass and damping could be different. In this paper, the accuracy of the present numerical coding has been tested at first by using point source moving along some radial distance and then numerical

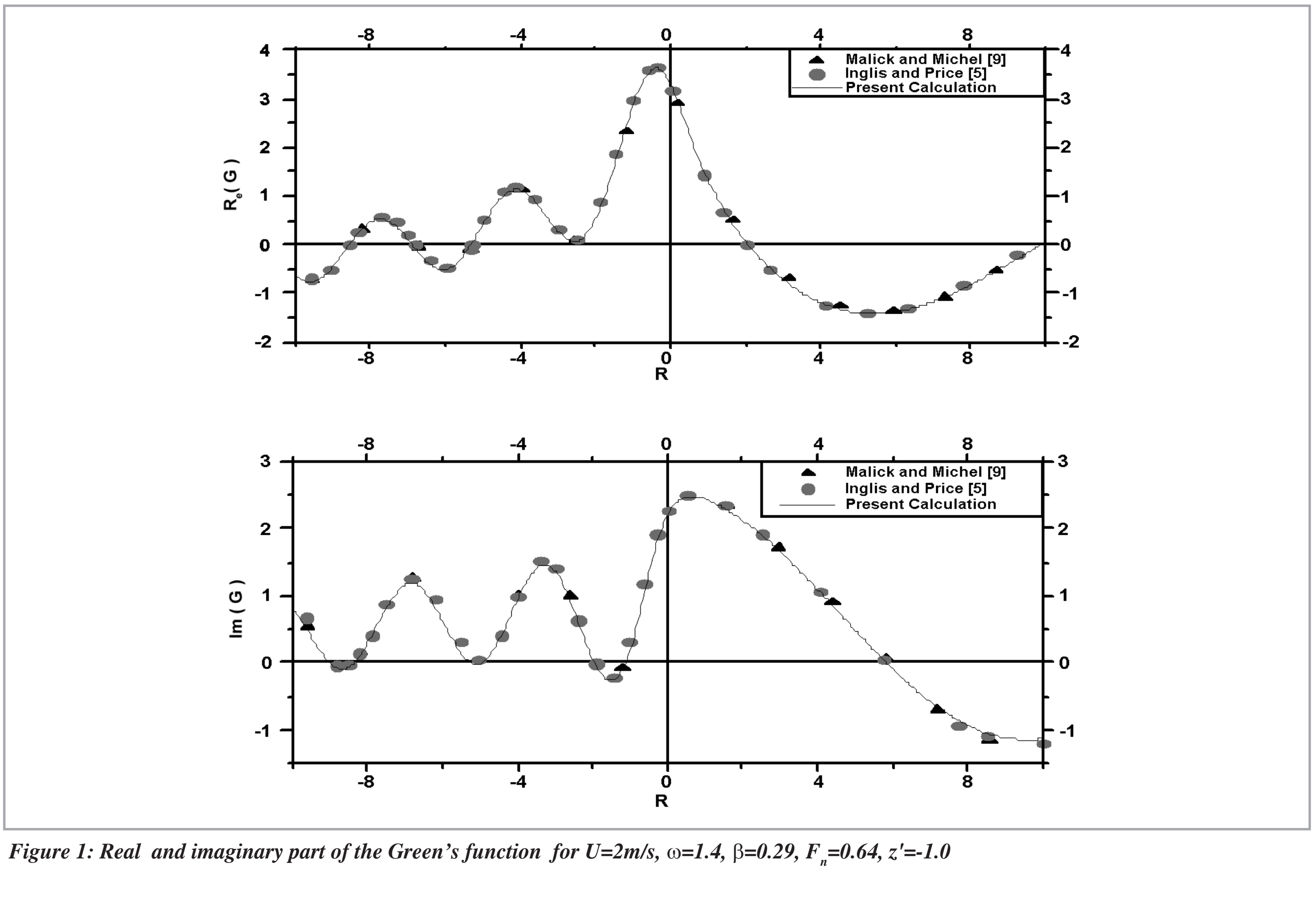

Figure 1: Real and imaginary part of the Green's function for U=2m/s, ω=1.4, β=0.29, F_n=0.64, z'=-1.0

result of the Green function and its derivatives have been examined comparing some published results such as Ba and Guilbaud [9]. Figure 1 shows the real and imaginary part of the Green function with forward speed U=2 m/s and ω=1.4 rad/s for the point source located at (0,0,-1) and here very good convergence has been found among the numerical methods. Next, Series60 ship (L/B=7.0, B/d=2.5, C_B=0.70) has been used for numerical calculations which would enable to judge the effectiveness of the present numerical calculation for the case of more realistic ship form rather than any mathematical ship form. Numerical results from other codes as well as experimental data have been taken from Baiely *et al*.[10] for the comparison.

For the heave responses, as shown in Figure 2, the present numerical computation along with other theoretical methods are in close agreement with each other and agreement with the experimental data is also close. The three different theoretical

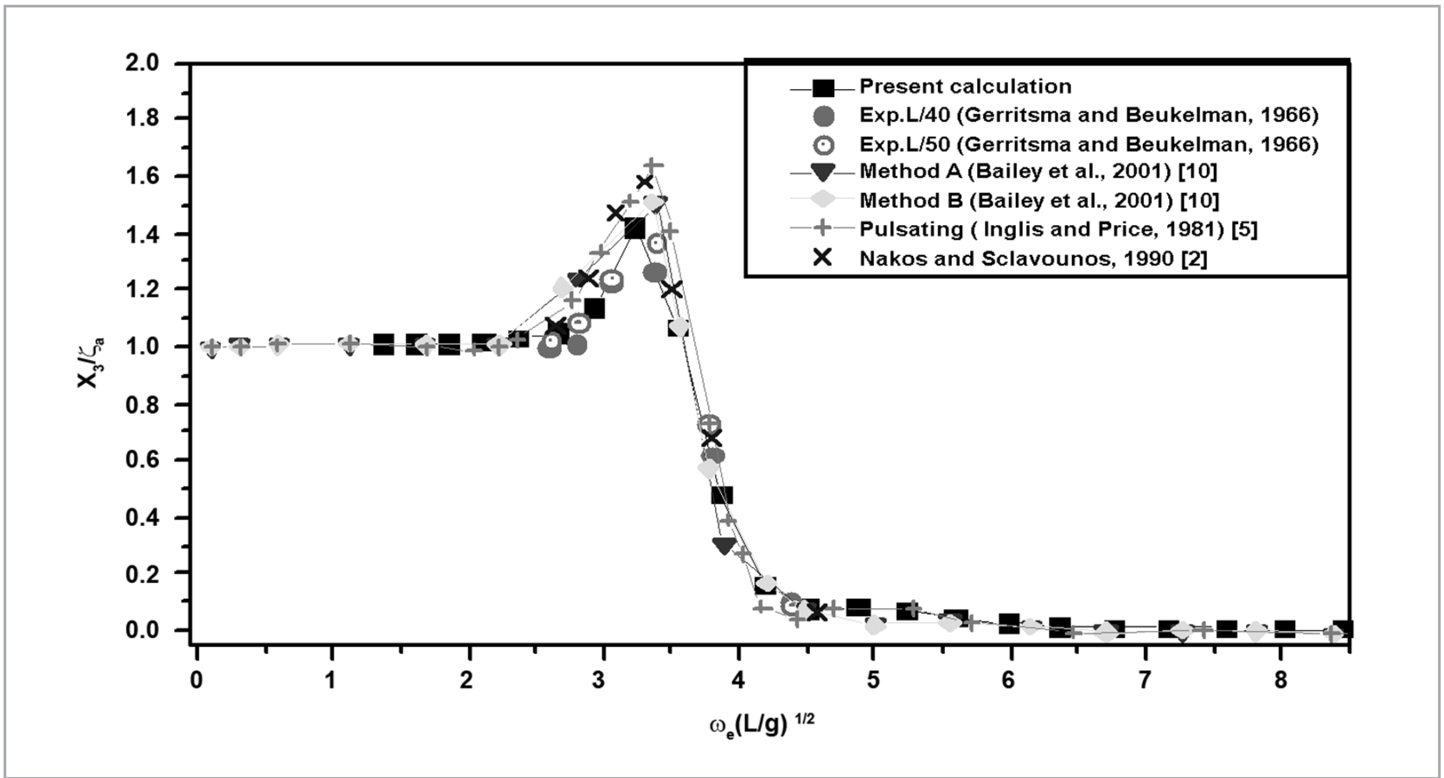

Figure 2: Heave motion for Series60 ship of C_B=0.7 at F_n=0.2 in head sea

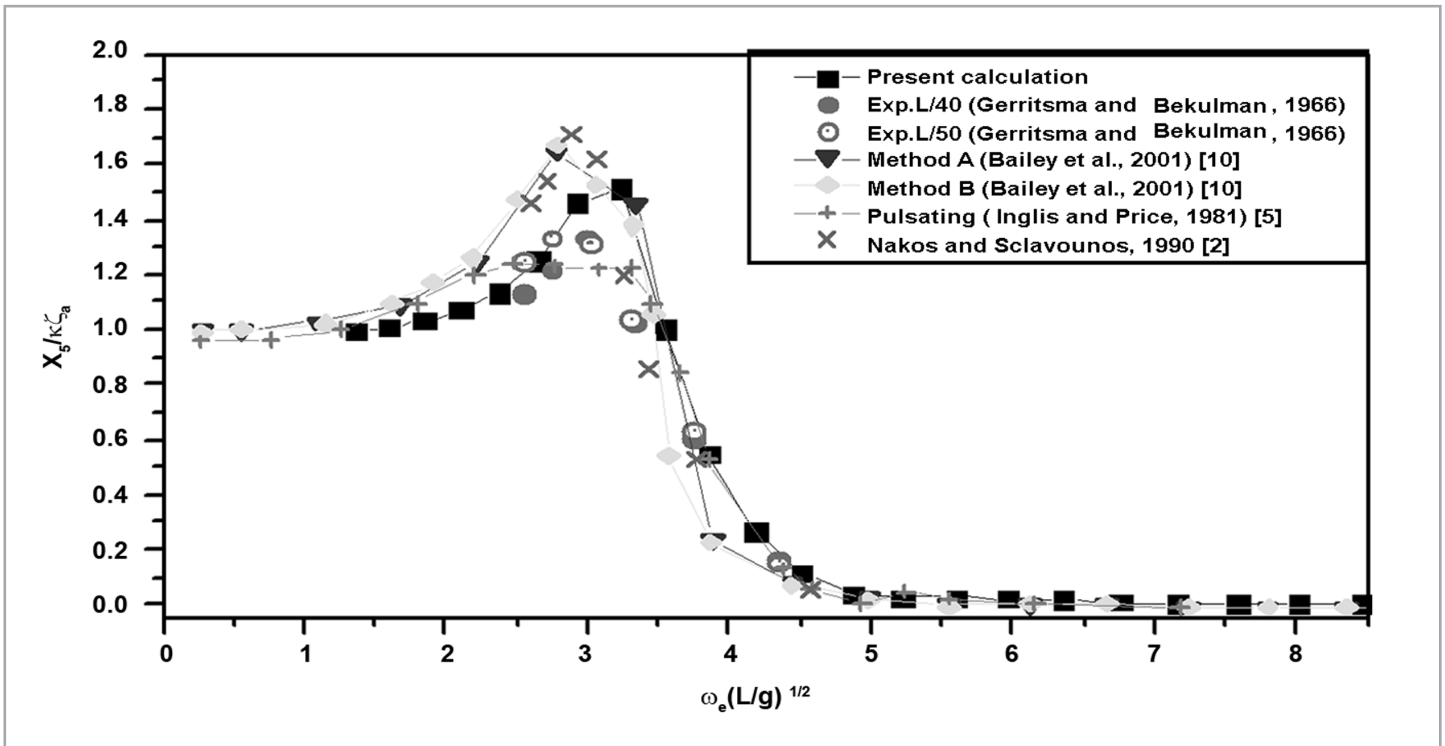

Figure 3: Pitch motion for Series60 ship of C_B=0.7 at F_n=0.2 in head sea

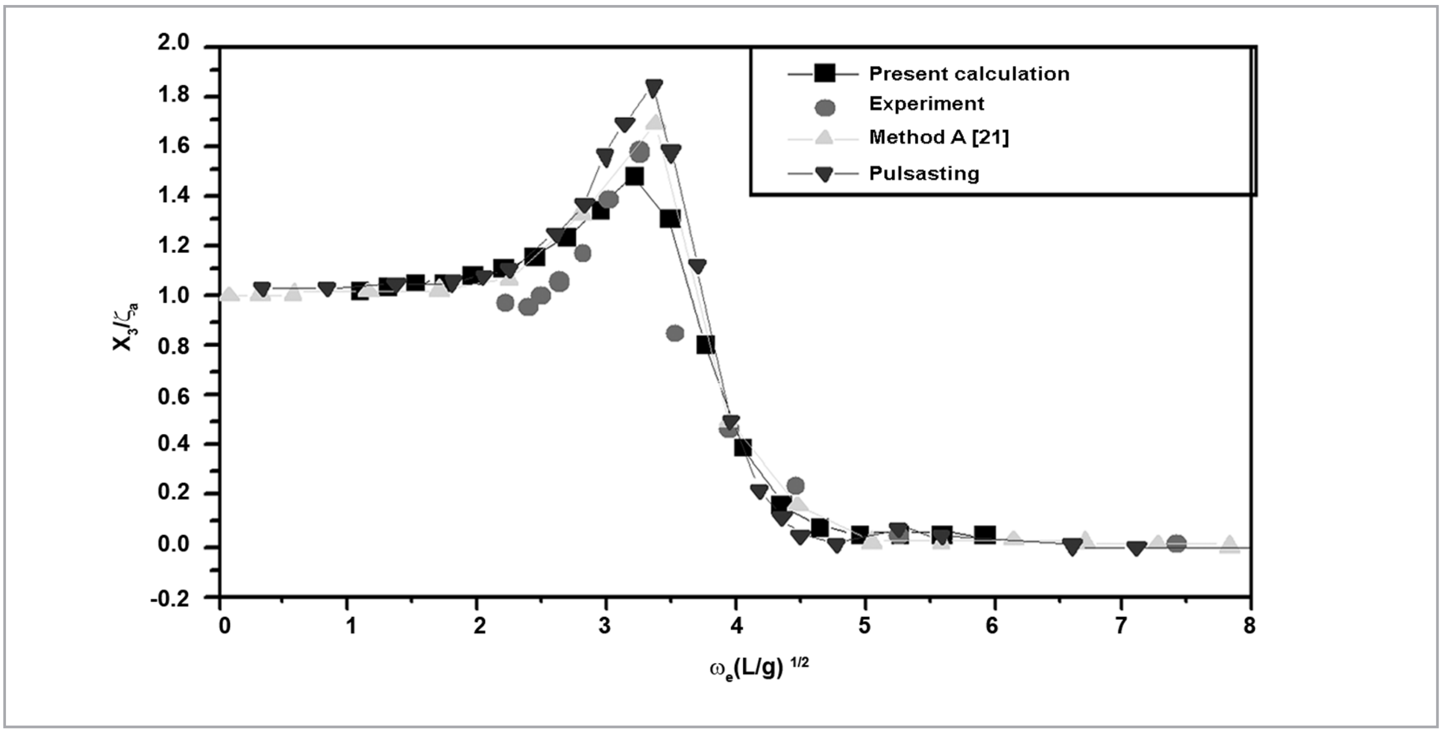

Figure 4: Heave responses for the series 60 ship of C_B=0.7 at F_n=0.2 in oblique waves with heading angle, x = 135°

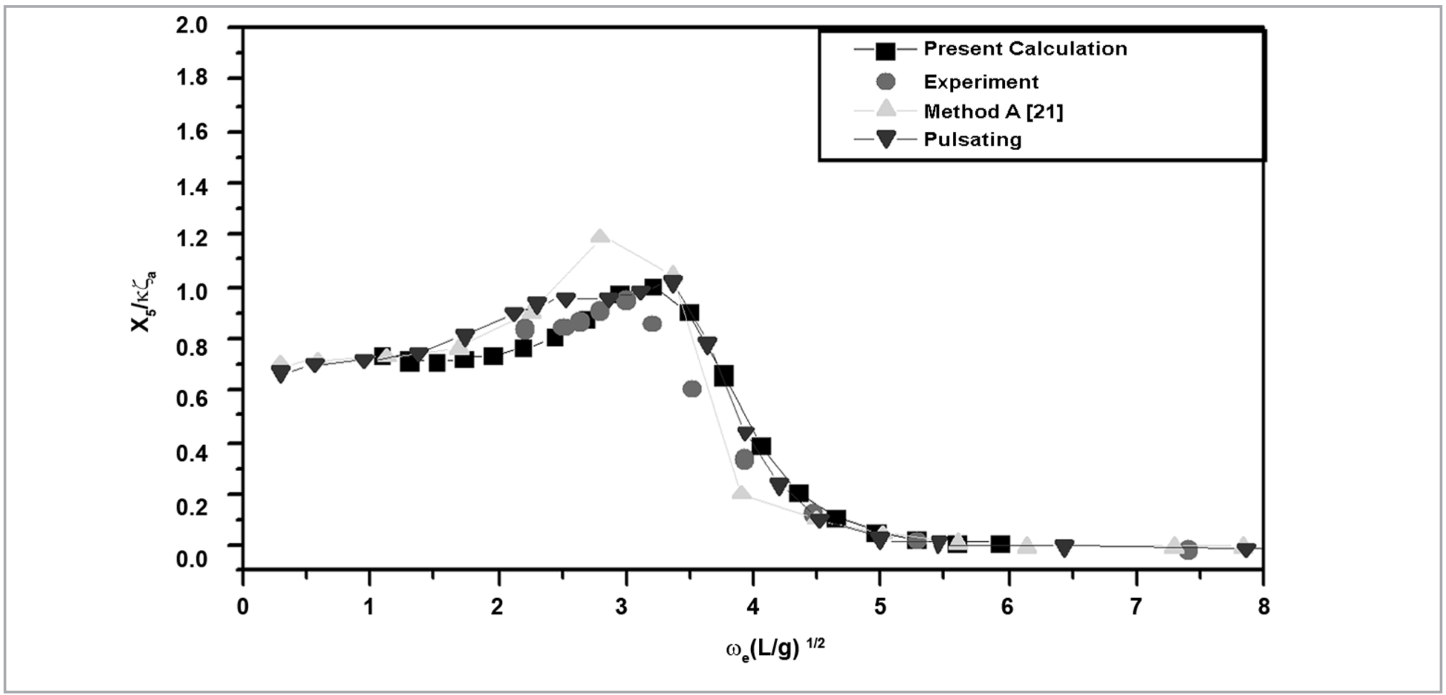

Figure 5: Pitch responses for the series 60 ship of C_B=0.7 at F_n=0.2 in oblique waves with heading angle, x = 135°

methods accurately predicts the resonant response although over-estimated by them all, but the present method gives the more closer one. For pitch response, as shown in Figure 3, the present computation as well as methods A and B, together with the Rankine panel methods of Makos and Sclavounos [11] exhibit the correct trends with frequency with accurately predict the resonance frequency when compared to experimental data. As it with the heave response the pitch resonance responses over predicted, in this case by a greater amount. The pulsating source method provides predictions in closer agreement to the experimental data in the region of resonance, if anything under-estimating the magnitude of the resonant response. The experimental data indicate a sharper resonant response than is predicted by the pulsating source method. This is reflected in the predictions of methods and those of Makos and Sclavounos[11]. It has been appeared that pitch resonance move to an marginally higher frequency with the increase of the wave height, something the linear methods are unable to demonstrate.

Heave and pitch responses for the series 60 travelling in oblique regular waves with heading angle, X = 135°are shown in the Figures 4 and 5. Present numerical computation has been compared with the pulsating source method together with those form of method A and with experimental measurements. Once again the present calculation gives overall good prediction of heave response well across the whole frequency range, providing a good estimate of the resonance frequency, although, the magnitude is slightly under-predicted. The heave amplitude at resonance is greater in oblique waves than in head waves. This is the case both in the theoretical predictions and the experimental measurements, although the experimental measurements show a greater increase. The pitch resonant frequency is also well predicted and also good prediction than the head wave case. Both the pulsating source and the present computation give a much less sharp resonance response with the prediction of magnitude is better than method A. Both experiments and theoretical predictions show a decrease in the pitch response compared to head sea.

5.0 NUMERICAL RESULT AND DISCUSSION

As for numerical examples, container ships of different sizes have been chosen. The principal particulars of these ships are summarised in Tables 1. The numerical simulations have been performed for three different sea states which are moderate gale, strong gale and hurricane and the significant wave height and mean wave period of these three sea states are listed in Table 2. For container ship-I, the calculation has been performed for Froude number 0.18 with the main direction of angle of attack 180 deg (head sea) and for container ship-II and III, the calculations have been done for Froude number 0.20 with the same sea conditions. The principal particulars and other data, used in table1, are determined base on actual ships in the paper of Inoue *et al*. [12]. Figure 6 shows the typical mesh arrangement of container ship for the numerical calculation in frequency domain analysis where the wetted surface of the vessel is discretised by quadrilateral panels.

Table 1: Principal particulars of container ships

Items	Container-I	Container-II	Container-III
LBP	160.0 m	218.0 m	270.0 m
B	25.70 m	32.10 m	32.20 m
D	8.24m	13.67m	24.71m
d	9.01 m	10.0 m	10.85 m
Δ	56097 m^3	41147 m^3	56097 m^3
U	13.9kts	18.0kts	20.0kts
C_b	0.6328	0.588	0.598
C_w	0.757	0.757	0.757
C_m	0.950	0.950	0.950
KG	10.04m	13.42m	10.12 m
L.C.G.	-1.43 m	-3.85 m	-3.49 m
GM	1.03 m	0.64m	1.15 m
K_{xx}	37.5 % B	37.5 % B	37.5 % B
K_{yy}	24.8 % LBP	24.8 % LBP	24.8 % LBP
K_{zz}	24.8 % LBP	24.8 % LBP	24.8 % LBP

Table 2: Sea state for numerical simulation

Sea state	Mean period	Significant wave height
Moderate gale	T=6 Sec	H = 5 m
Strong gale	T=10 Sec	H=10m
Hurricane	T=10 Sec	H=15m

Using the numerical results given by frequency domain analysis, the motion Equation(12) has been solved using Newmark [13] generalised acceleration method. Non – linear roll damping has been incorporated which is based on the experimental works of Watanabe [14]. As for wave spectrum, ISSC spectrum has been used in this paper.

Figure 7 shows an example of wave profile for strong gale condition in short crested irregular waves using unequal frequency spacing technique. Figures 8 to 10 show the motion responses of heave, roll and pitch with respect to center of gravity of ship in this condition solving Equation (12) for container ship-II at crusing speed of 18 knots. Roll motion is induced even in head seas because of directional component of short crested irregular waves. Using Equation (18), the relative wave height at different positions of ship, such as Midship position, F. P. Position and A.P. position, have been shown in Figures 11 to 13.

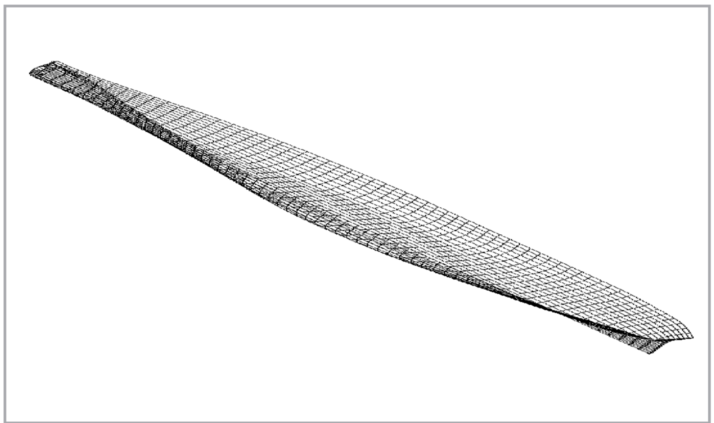

Figure 6: Grid modeling of body surface of container vessel

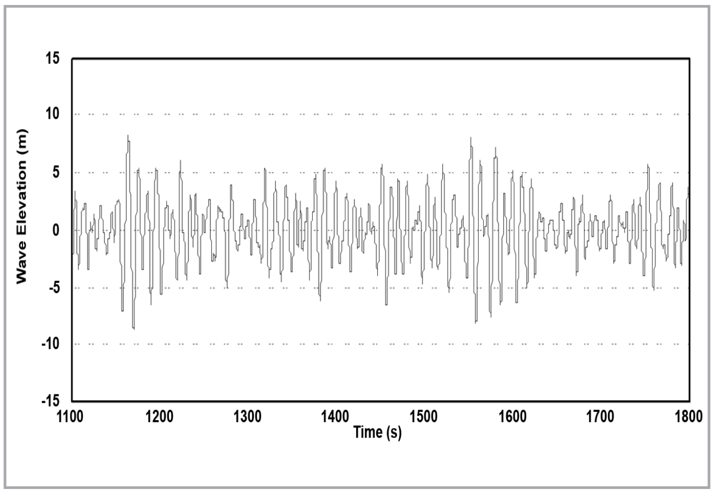

Figure 7: Wave profile of short crested irregular wave in strong gale (H=10m, T=10sec)

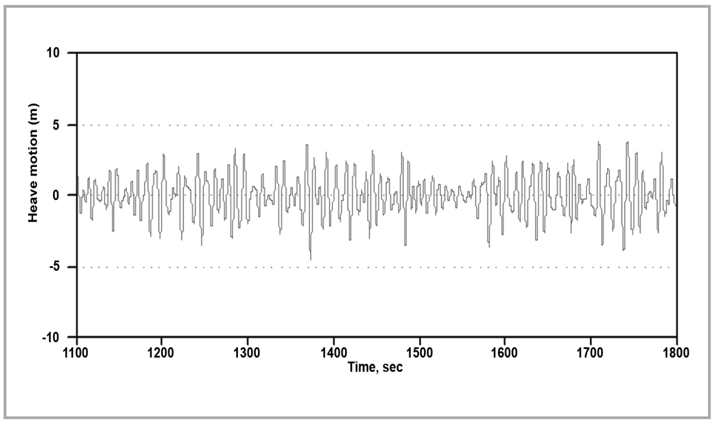

Figure 8: Heave motion of container ship-II in strong gale

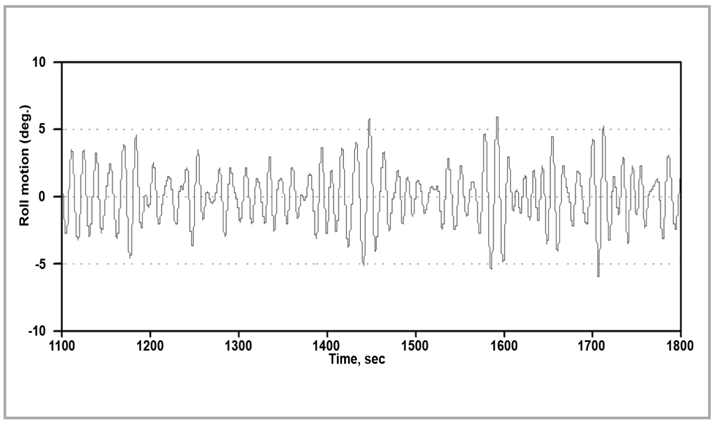

Figure 9: Roll motion of container ship-II in strong gale

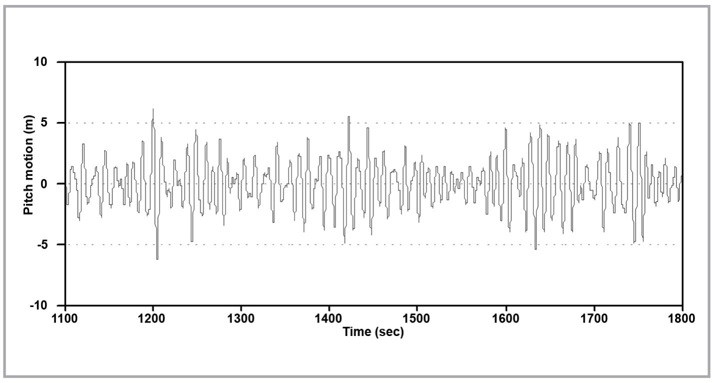

Figure 10: Pitch motion of Container ship-II in strong gale

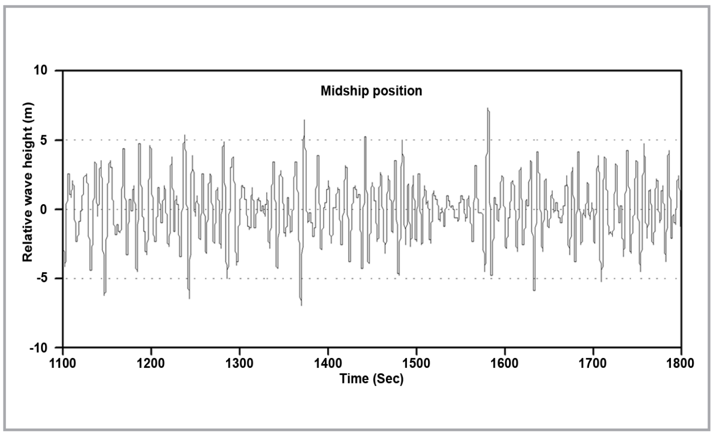

Figure 11: Relative wave height of container ship-II in strong gale at midship position

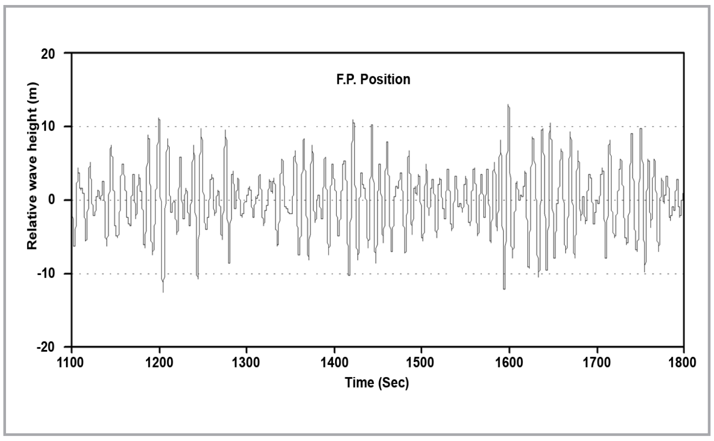

Figure 12: Relative wave height of container ship-II in strong gale at midship position

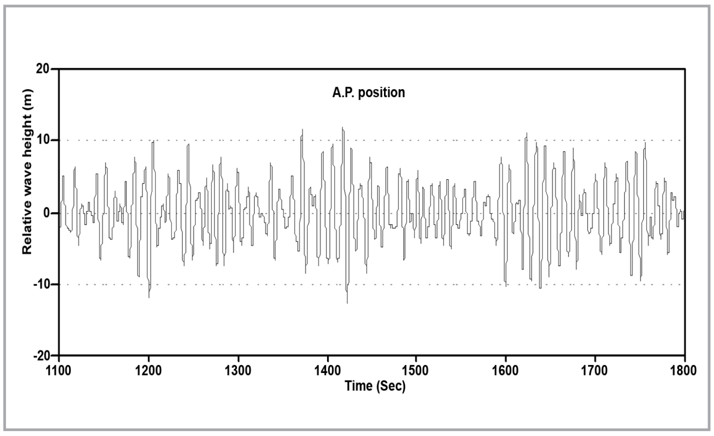

Figure 13: Relative wave height of Container ship-II in strong gale at midship position

From this computation of relative wave height at side wall of main hull from the load water line in short crested irregular waves, the maximum and the 1/3 highest mean values of time domain simulations have been calculated along the ship length. The deck load for weather deck given as a function of vertical distance from the designed maximum load line to the weather deck at side is not to be less than the value required by *NK* rules and guidance [15] and this is referred as the minimum deck load for weather deck. From this requirement, we can determine the corresponding height at where the weather deck load becomes zero and this corresponding height of deck load has been assumed as above the height of the maximum relative wave height. The rule also requires closing appliances for the openings of outfitting on deck and also it may be omitted where some height of openings exceeds the decks. The height at where closing appliances may be omitted has been considered as the value above the 1/3 highest mean values of relative wave height. These two kinds of heights are referred to the relative wave heights in various sea states.

Figures 14-16 show the results of the maximum and the 1/3 highest mean of relative wave heights along the ship length of container ship-II for 3 different sea states mentioned above. For moderate gale, relative wave heights are below the corresponding height of deck and the height of closing appliances omission. But in hurricane, the relative wave heights are over the reference heights and bottom slamming may be occurred. In strong gale the maximum values does not exceed the corresponding height of deck at fore and aft but bow slamming is appeared sometimes.

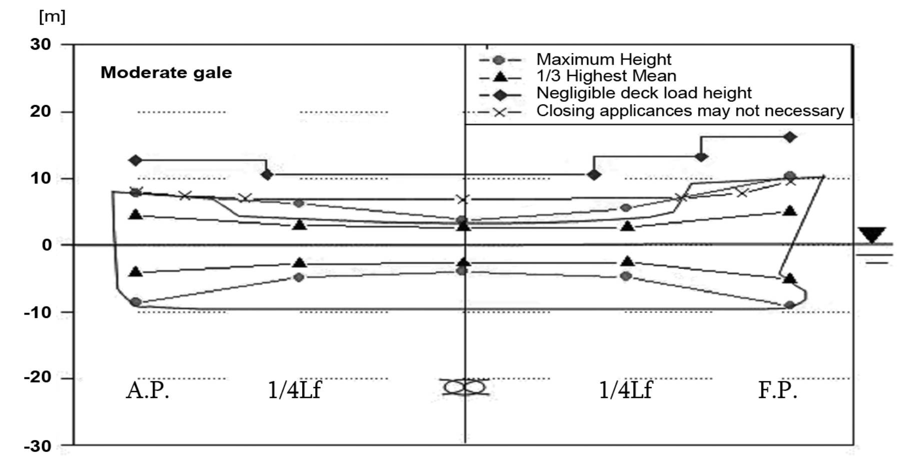

Figure 14: Relative wave height of container ship-II in moderate gale

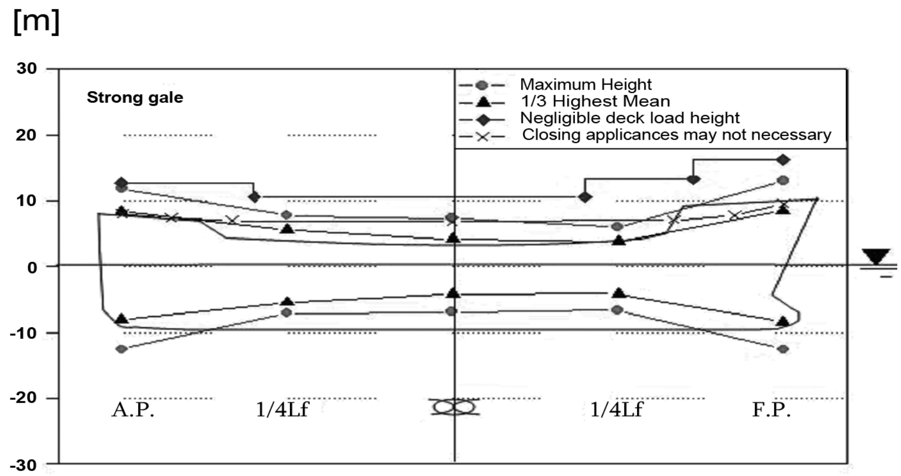

Figure 15: Relative wave height of container ship-II in strong gale

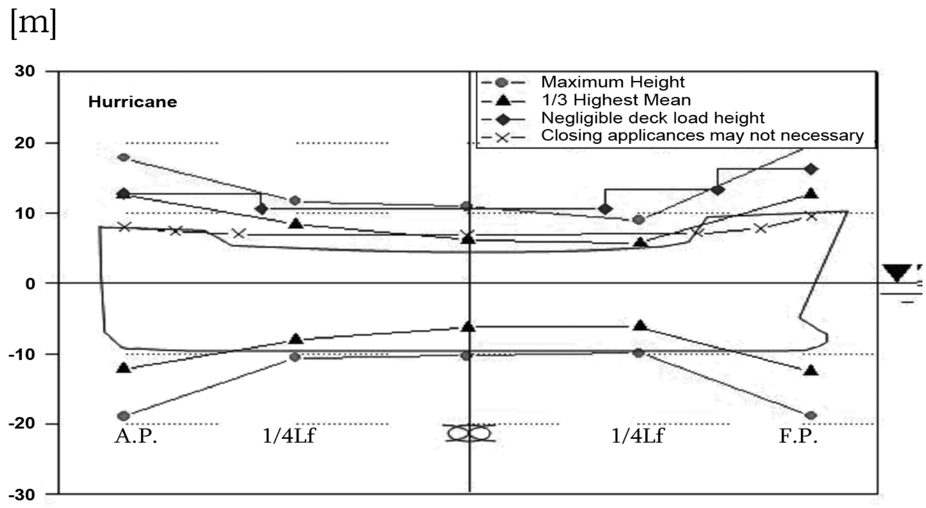

Figure 16: Relative wave height of container ship-II in hurricane

Figures 17-19 show the results of smallest container ship (Container ship-I) for 3 different states. Bottom slamming and propeller racing are more evident for the case of hurricane. Figures 20-22 show the results of Panamax container ship (Container ship-III) for 3 different states; the maximum and the 1/3 height mean values both exceed the corresponding reference height in fore and aft positions and also bottom slamming seems to be very severe for hurricane condition.

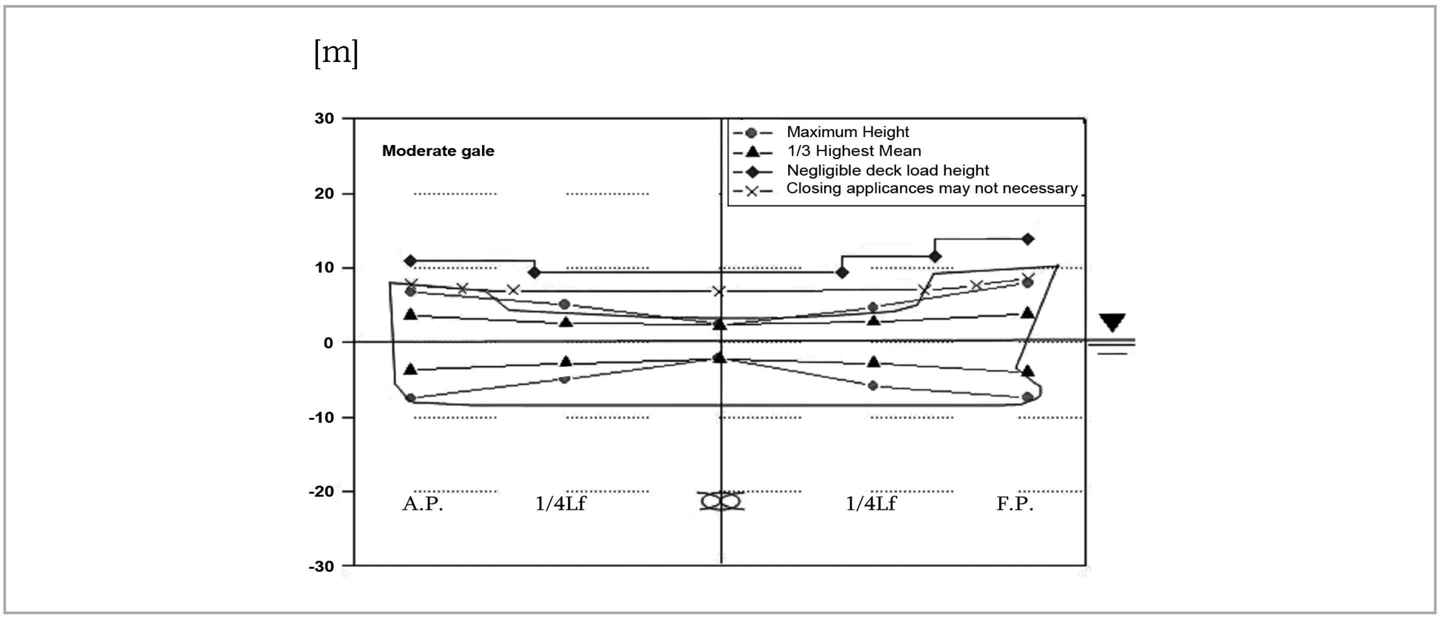

Figure 17: Relative wave height of Container Ship-I in moderate gale

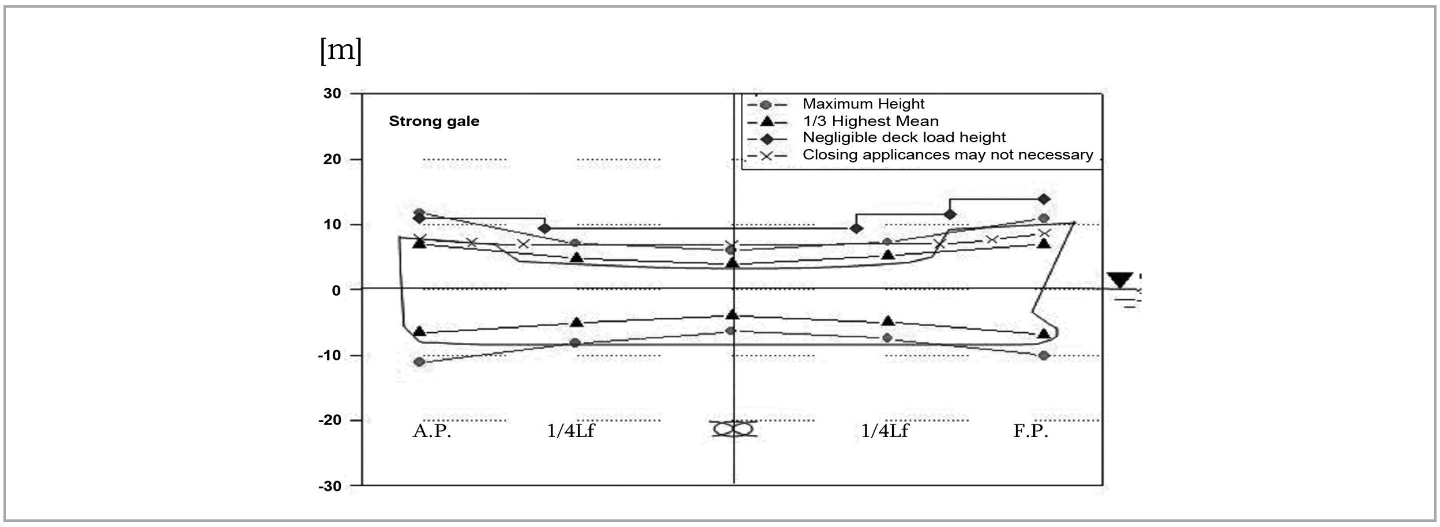

Figure 18: Relative wave height of container ship-I in strong gale

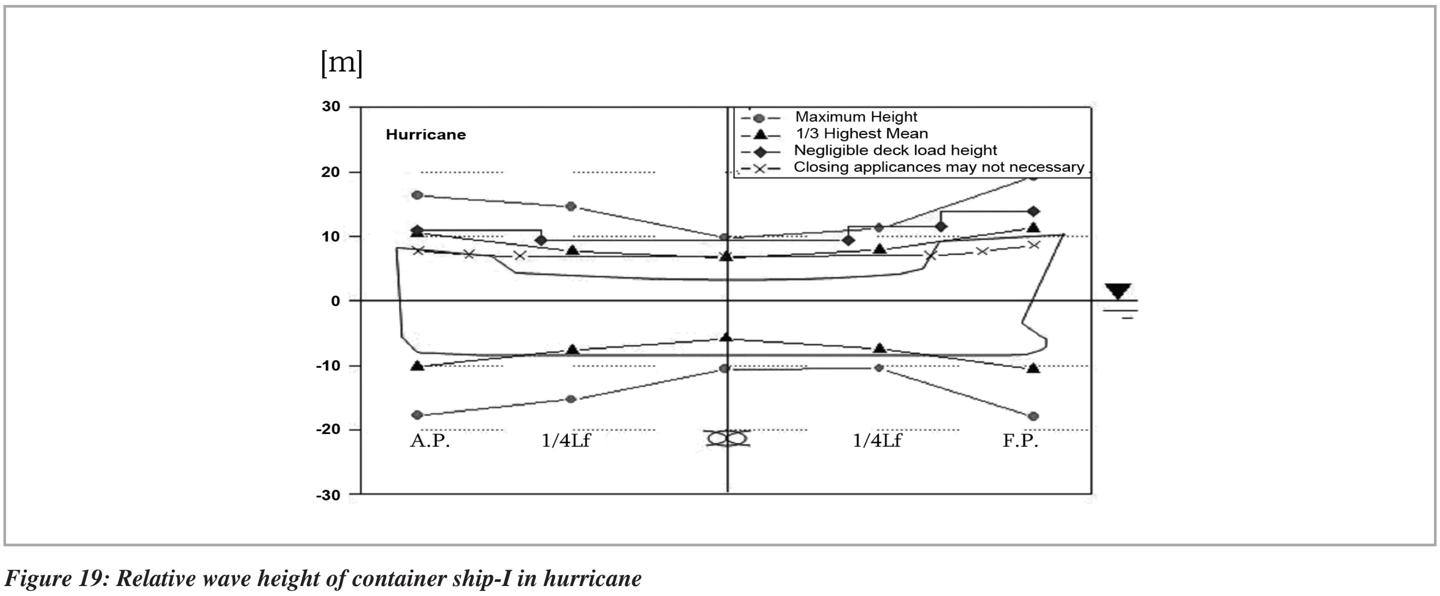

Figure 19: Relative wave height of container ship-I in hurricane

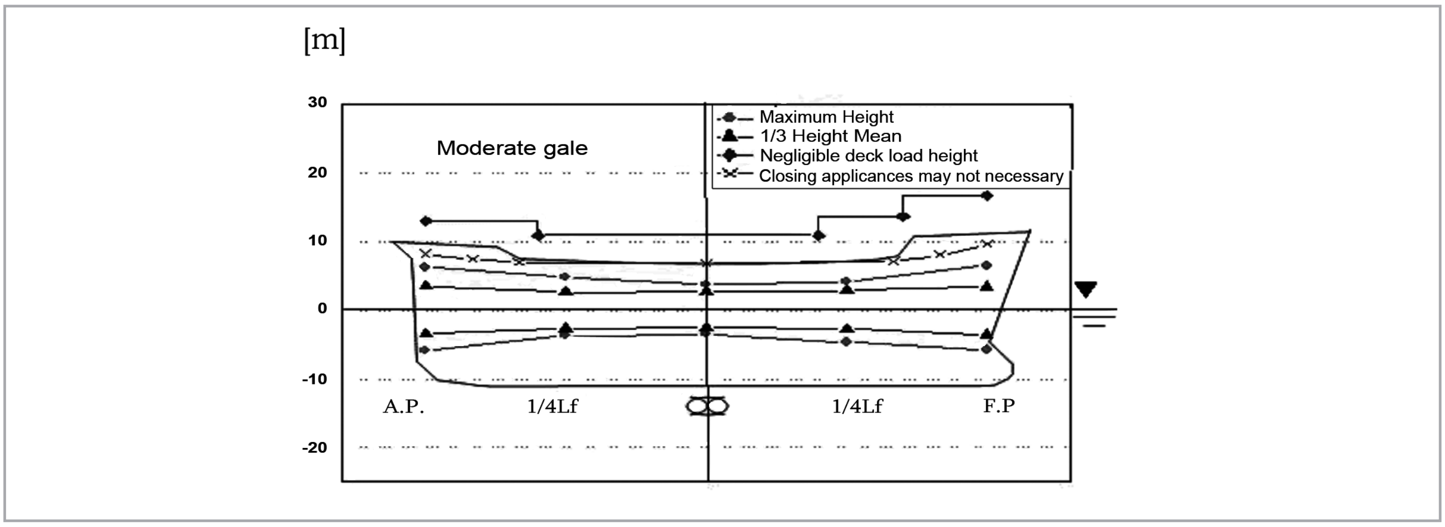

Figure 20: Relative wave height of panamax container ship in moderate gale with F_n =0.2

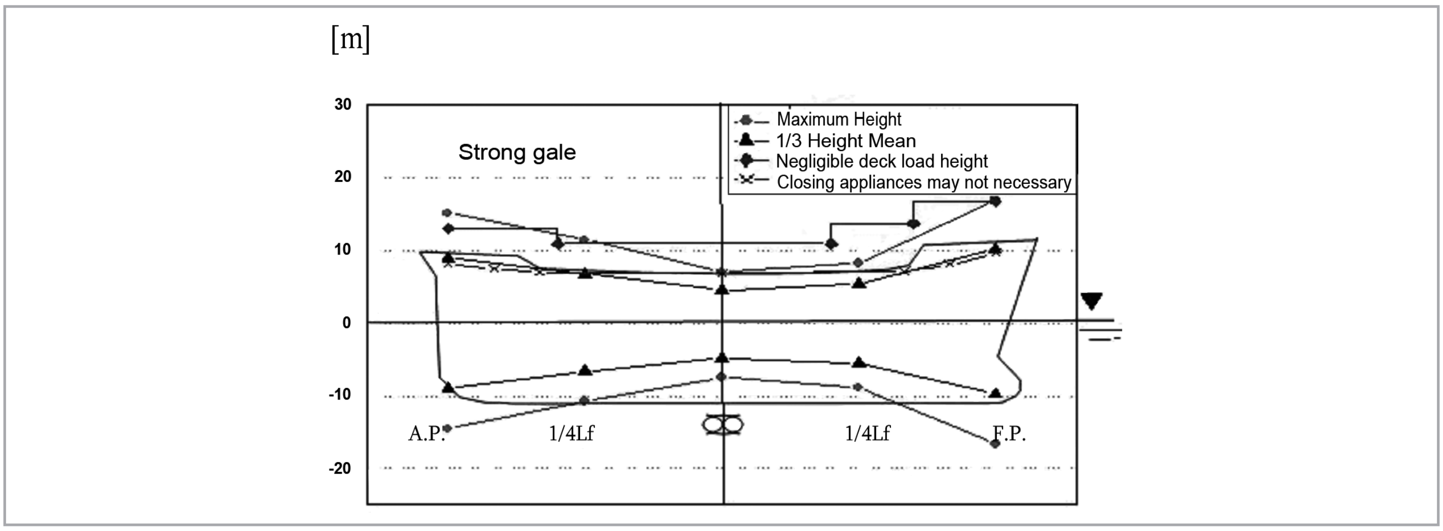

Figure 21: Relative wave height of panamax container ship in strong gale with F_n =0.2

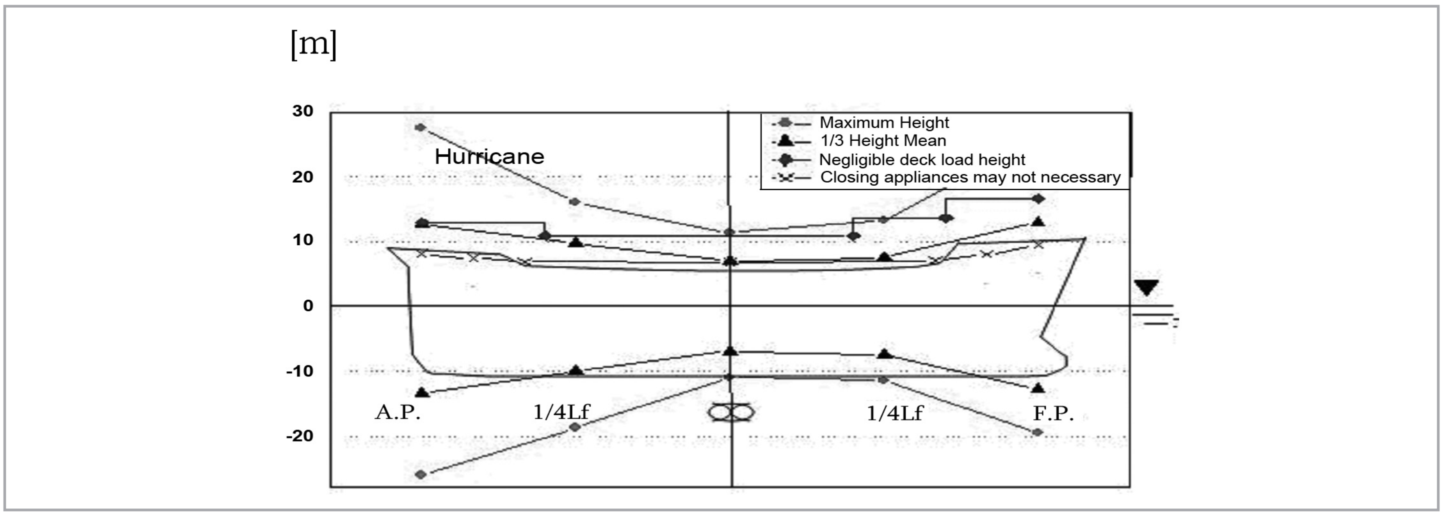

Figure 22: Relative wave height of panamax container ship in hurricane with F_n =0.2

To show the numerical result of relative wave height for the case of reducing speed and different wave heading angle, Figures 23-30 have been introduced. Figures 23-25 show the maximum and 1/3 height mean value for the case of reduced speed of 15 knots (F_n=0.15) and Figures 26-28 shows the same for the case of 12 knot (F_n=0.12) speed. From these Figures, the numerical simulation show some reduced value of both maximum and 1/3 height mean value for that reduced speed. When the wave heading angle changing from 180 *deg*. to 165 *deg*., again some reduced relative height has been noticed in this case as shown in the Figures 29-30.

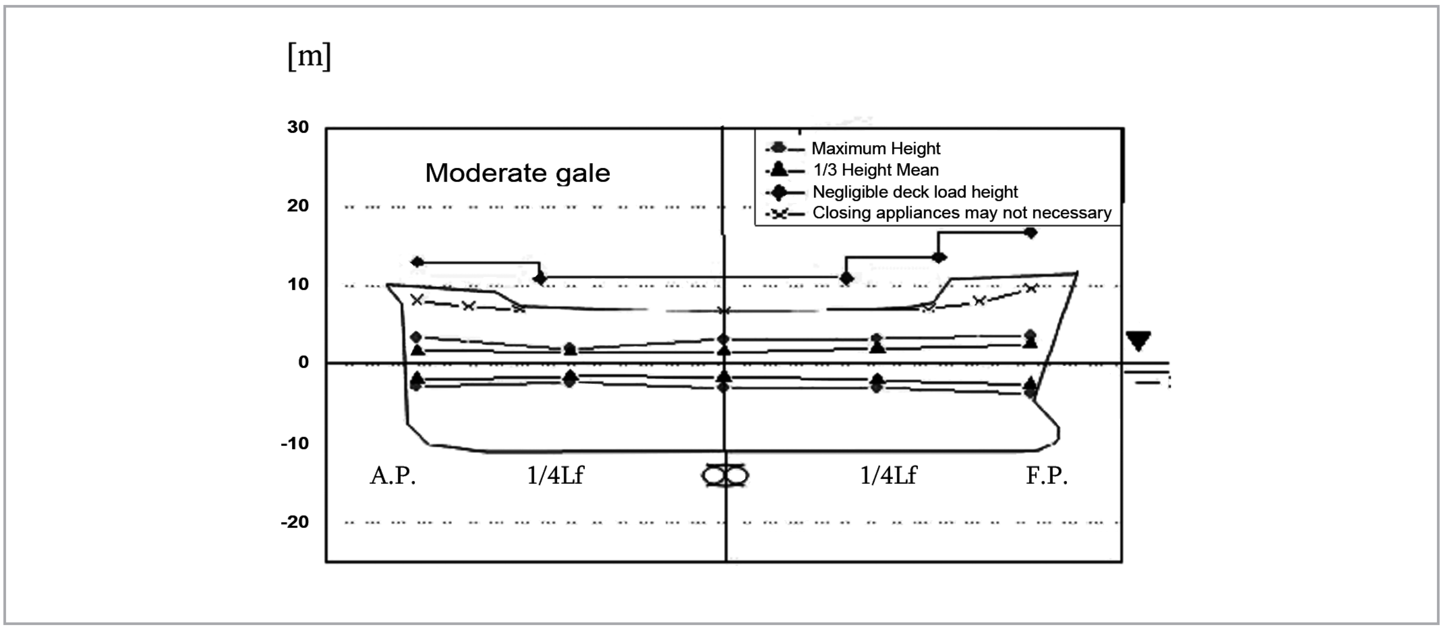

Figure 23: Relative wave height of container ship in moderate gale with F_n=0.15

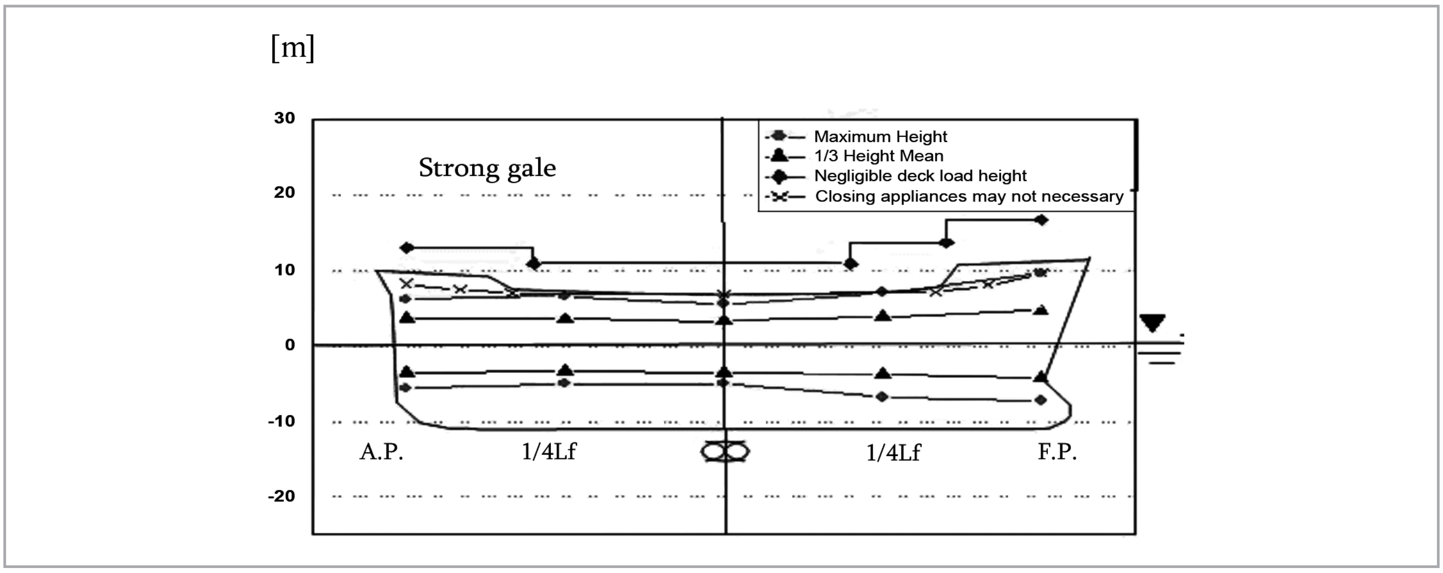

Figure 24: Relative wave height of panamax container ship in strong gale with F_n=0.15

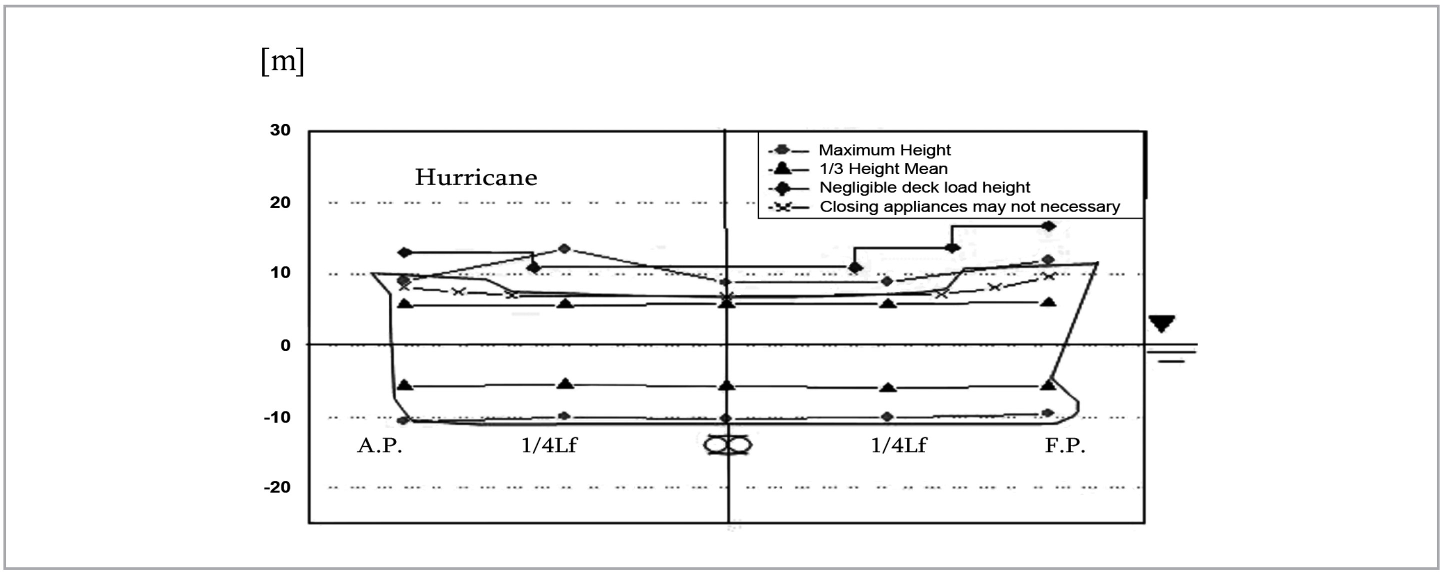

Figure 25: Relative wave height of panamax container ship in hurricane with F_n=0.15

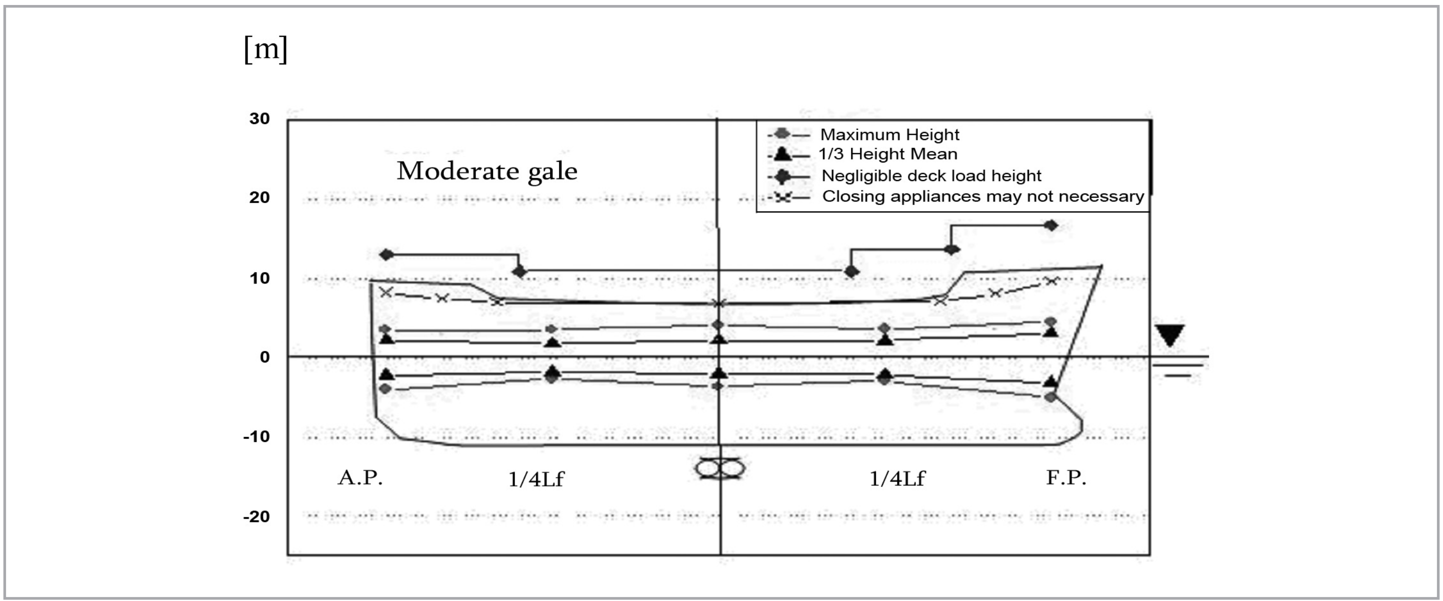

Figure 26: Relative wave height of panamax container ship in moderate gale with F_n=0.12

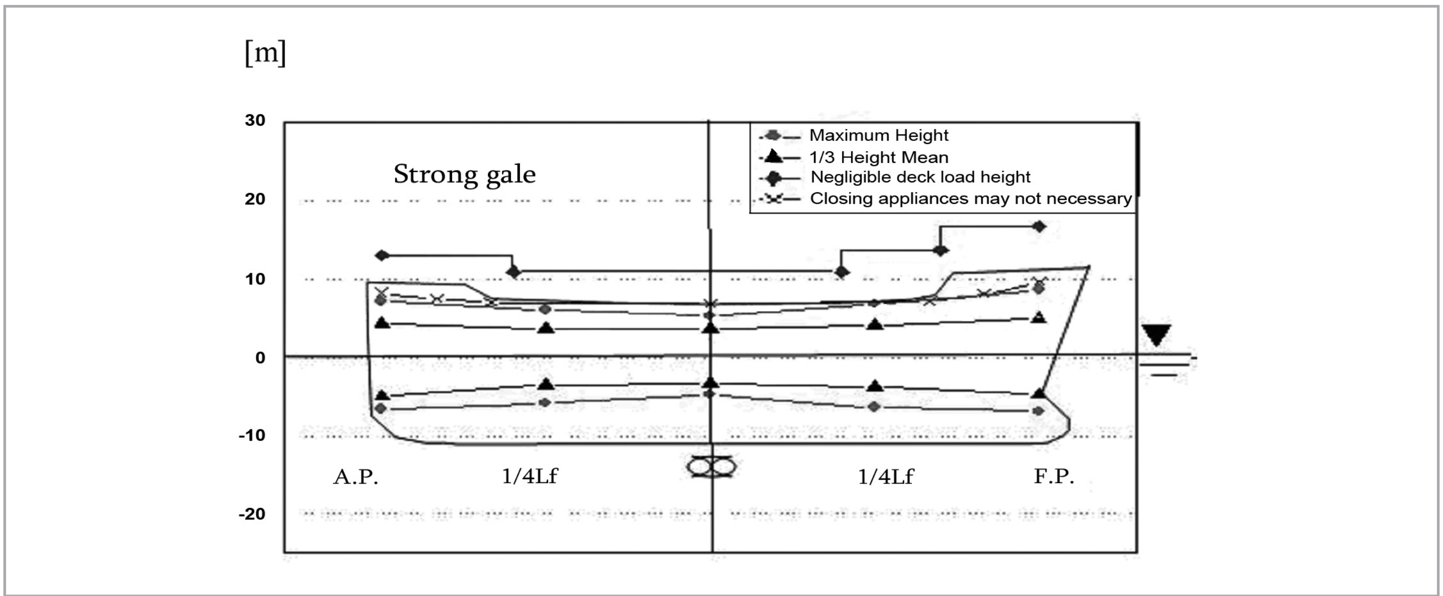

Figure 27: Relative wave height of panamax container ship in strong gale with F_n=0.12

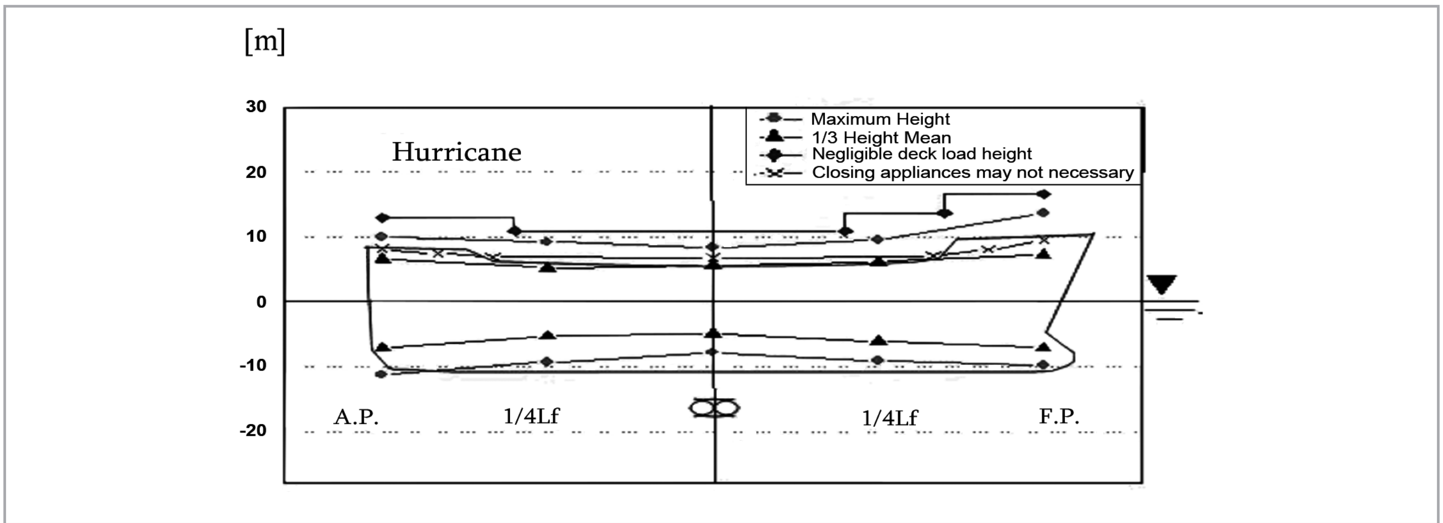

Figure 28: Relative wave height of panamax container ship in hurricane with F_n=0.12

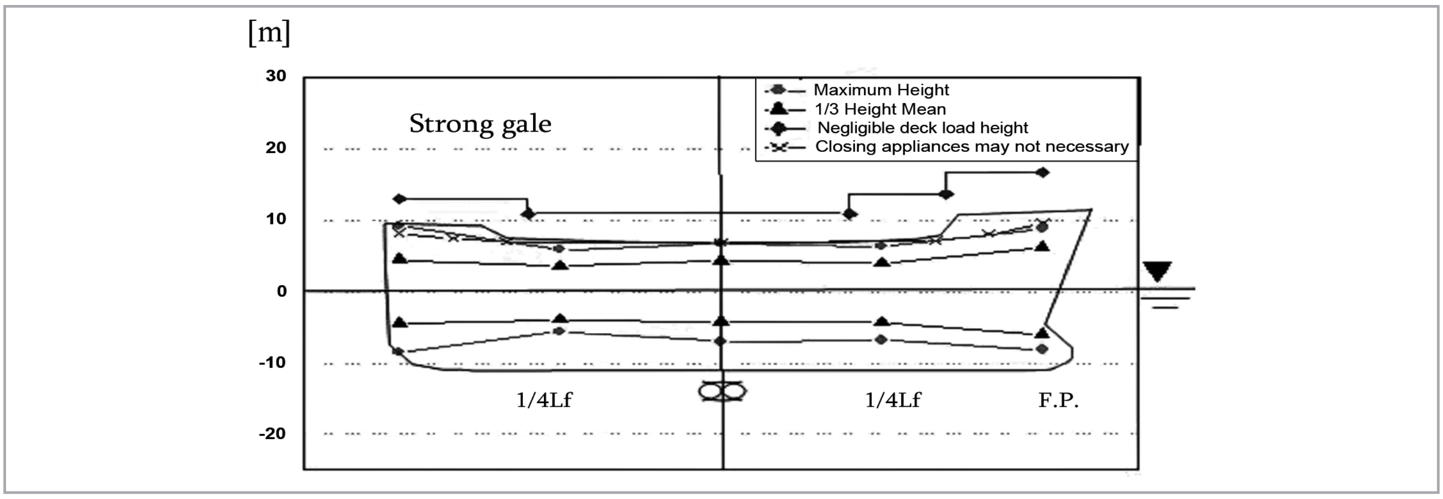

Figure 29: Relative wave height of panamax container ship at heading angle of 165⁰

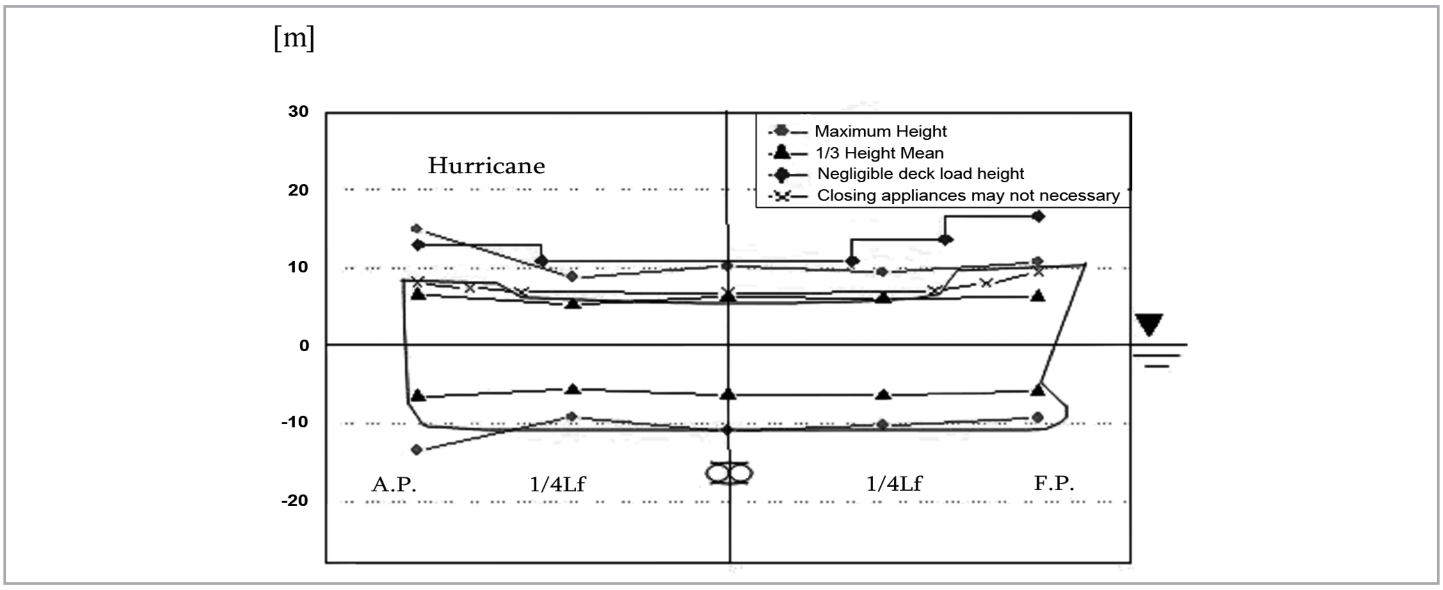

Figure 30: Relative wave height of panamax container ship at heading angle of 165⁰

6.0 CONCLUSIONS

Applying 3-D Source-sink method, numerical study of sea-keeping performances has been performed in this paper. Comparing the present numerical results of Green function for the translating pulsating source located at position (0,0, -1) with the numerical results taken from Malick and Michel [9], it is seen that the present numerical results has given quite satisfactory results both for real and imaginary part of the Green's function and its derivatives. For the case of Series60 ships with C_B=0.70, present numerical calculation has given very good predictions of motion responses for both head and oblique waves compared with the experimental data as well as with other published numerical results taken from Bailey *et al*.[10]. The results provides validity and reliability to the computation of seakeeping problems by present numerical coding. It may be worth to mention here that panels of 800 for discretisation of wetted surface with 380 panels inside the hull for adding a horizontal flat surface slightly immersed have been used to calculate motion responses of this Series60 ship. Comparison of the other hydrodynamic properties of this ship have been shown in Reference [16].

From the numerical result of time domain simulations of relative wave height of ships in short crested irregular sea, it is seen except some exception in hurricane condition, the numerical result of the 1/3 highest mean value is almost below the height at where closing appliances are not necessary as well as corresponding height to the minimum requirement of deck load. This implies that the requirement by the classification society may be reasonable height for weathertight. But the maximum value in most cases is over its height except moderate sea.

From the time domain simulation in short crested irregular wave with a speed of 20 knots (F_n=0.20) particularly for strong gale and hurricane, numerical calculation shows some relative wave height that could be dangerous for overall safety of the ship as bottom slamming is evident in this case. But for the case of reduced speed and different heading angle, we have noticed that overall seakeeping performances have been improved for these conditions as 1/3 height mean value of relative wave height has been reduced considerably .

The concept of relative wave height can be used to assess the added resistance of ship in waves, for example, added resistance prediction by Gerritsma's method. ■

NOMENCLATURE

a_{ij}	Frequency-dependent added mass
b_{ij}	Damping coefficient matrices
B	Breadth of ship (m)
B_n	Non-linear damping coefficient (only for roll)
β	Heading angle
C_B	Block coefficient of ship
C_{ij}	Hydrostatic restoring coefficient
d	Draught of ship (m)
F_n	Froude number
$\overline{F}_i$	Wave exciting forces and moments
R_{ij}	Retardation function matrix
g	Gravitational acceleration (ms^{-2})
G	Green's function
k	Wave number
L	Length of ship (m)
M_{ij}	Inertia matrix
m_{ij}	Frequency independent added mass matrix
n	Components of normal vector
P	Arbitral point in fluid
ρ	Density of water (ton s^2m^{-4})
Q	Point on body surface
r	Distance from hull boundary surface
ε_{mn}	Random phase of elementary wave
r_g	Distance from C.G of ship
S_H	Hull surface
T^i_{mn}	Complex Transfer function of exciting force
X_j	Complex motion amplitude in *j-th* mode
x_g	Centre of gravity of ship in x -axis
(x_p, y_p, z_p)	Coordinate at the arbitral point of ship
ς_A	Amplitude of incident wave (m)
ϕ_I	Diffraction potential
σ_j	Strength of source distributed over hull
ϕ_j	Radiation potential
ϕ_T	Total potential
ϕ_0	Steady potential
ϕ_w	Incident wave potential
ϕ	Unsteady potential
$\dot{\omega}$	Constant frequency chosen arbitrarily
ω	Frequency of wave
ω_e	Frequency of encounter (rad./s)
z_r	Relative wave height (m)

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PROFILE

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