

## Added resistance and parametric roll prediction as a design criteria for energy efficient ships

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**Abstract.** The increased interest in the design of energy efficient ships post IMO regulation on enforcing EEDI has encouraged researchers to reevaluate the numerical methods in predicting important hull design parameters. The prediction of added resistance and stability of ships in the rough sea environment dictates selection of ship hulls. A 3D panel method based on Green function is developed for vessel motion prediction. The effects of parametric instability are also investigated using the Volterra series approach to model the hydrostatic variation due to ship motions. The added resistance is calculated using the near field pressure integration method.

**Keywords:** added resistance; 3D panel method; EEDI; parametric roll

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### 1. Introduction

Ships are the most economic and fuel efficient way to transfer cargo in bulk amount across continents. However, the exhaust gases produced by the ships has long term effects on human health and the ecosystem. The International Maritime Organization (IMO) has been working on prevention of air pollution since 1980. The study on CO<sub>2</sub> and other Green House Gas (GHG) emission from ships was presented in October 2000 and potential technical and operational measures for reduction of GHG were identified. In 2005, regulations have been imposed to control emission of NO<sub>x</sub> and SO<sub>x</sub> gases. In July 2011, IMO made the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) mandatory for all ships over 400 gross tones (at present excluding ships with steam turbine, diesel-electric and hybrid propulsion) built on or after January 2013. The EEDI is a measure of ship energy efficiency in terms of CO<sub>2</sub> emission per capacity mile (g/t\*nm) which must be less than a prescribed value for the specific ship type and size. A reduction factor will be used to implement EEDI in phases to gradually reduce the required limit. To achieve these goals, advancement in the ship hull design, propulsion techniques and alternative energy sources are being investigated.

The propulsive power required for a ship to travel in sea is greatly affected by the added resistance due to waves. Also, the large amplitude roll motion of a vessel increases the fuel

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dimensional panel method based on Green function. The program has been validated successfully for various structures including floating hemisphere, ship and TLP for zero forward speed with WAMIT (Lee 2013). The forward speed case has been further validated against experimental result published by ITTC Seakeeping Committee (1978) for the container vessel S175. The validation results are published in Guha (2012) and Guha and Falzarano (2013).

The ITTC Container ship S175 (Fig. 1) has been chosen for validation of added resistance calculation for various forward speed. The principal particulars of the vessel are given in Table 1. The motion prediction of the vessel is validated against published results (ITTC Seakeeping Committee 1978) and shown in Figs. 2 and 3. The mean drift force is compared with WAMIT results in Fig. 4 and shown to be in good agreement. The added resistance for head sea condition with  $F_n=0.15$  and  $0.25$  are shown in Figs. 5 and 6. The results obtained by the in-house program is labeled as “Numerical” in the presented plots.

Table 1 Principal particulars of the container ship S175

<b>Principal Particulars of S175</b>			
Length between perpendiculars	Lpp	m	175
Breadth	B	m	25.4
Side height	D	m	15.4
Design draught	T	m	9.5
Displacement	$\Delta$	t	24168.76
Vertical centre of gravity(from baseline)	$z_g$	m	9.5
Roll Radius of Gyration	kxx	m	8.33
Pitch Radius of Gyration	kyy	m	42
Yaw Radius of Gyration	kzz	m	35.4

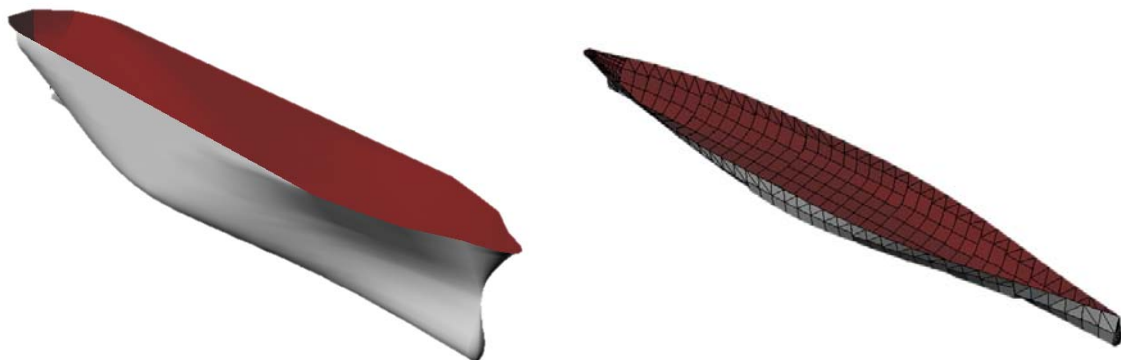


Fig. 1 Hull form (Left) and panel mesh(right) of S175ContainerShip

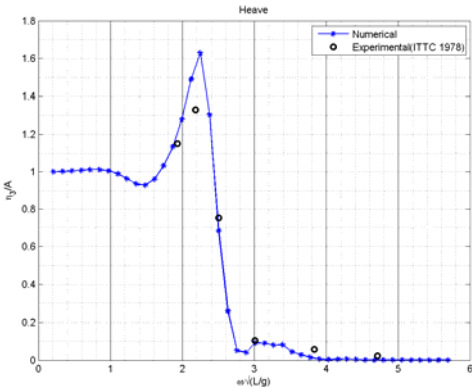


Fig. 2 Comparison of heave response of S175 container ship at  $F_n=0.275$  and  $\beta=180$  deg

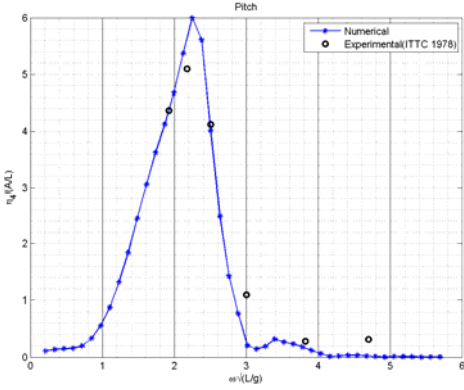


Fig. 3 Comparison of pitch response of S175 container ship at  $F_n=0.275$  and  $\beta=180$  deg

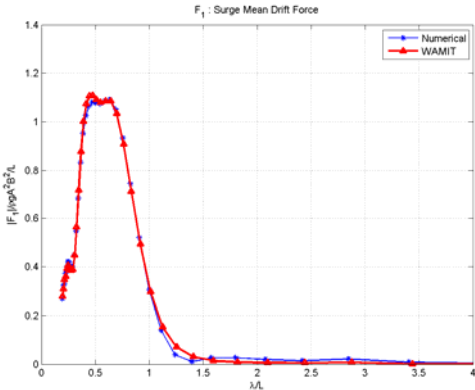


Fig. 4 Surge mean drift force comparison with WAMIT for  $F_n=0$

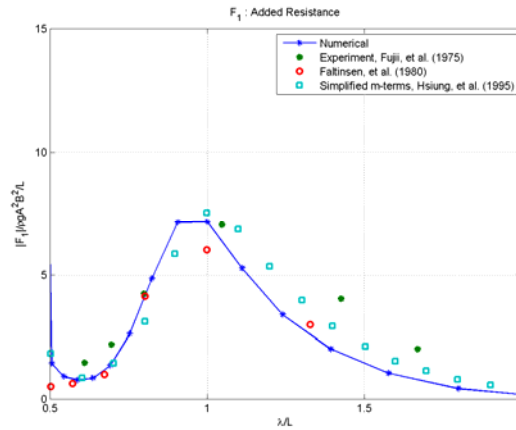


Fig. 5 Added Resistance for S175 at  $F_n=0.15$  for wave heading  $\beta=180$  deg

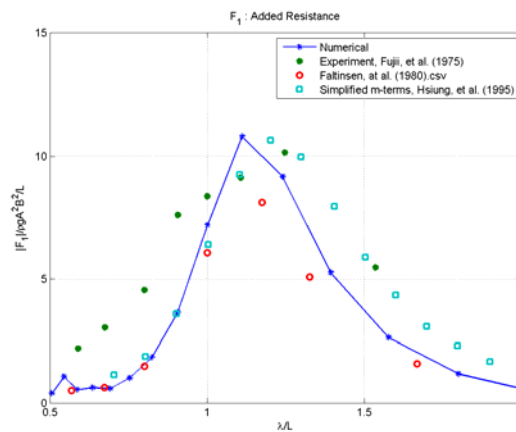


Fig. 6 Added Resistance for S175 at  $F_n=0.25$  for wave heading  $\beta=180$  deg

### 3. Parametric roll assessment

The problem of parametric roll of ships is quite old and has been widely investigated by researchers all over the world. For a long time it was believed that parametric roll was a severe phenomenon experienced mostly by fishing vessels in the following sea conditions.

Many researchers tried analyzing this phenomenon. Neves and Rodríguez (2007) used a third order coupled model to analyze the parametric roll of a fishing vessel and compared it with the experimental results. Spyrou (2011) suggested a simple analytical criteria for parametric rolling in the following sea conditions. Other researchers who have studied the parametric roll in following seas include Belenky *et al.* (2008), Gamo *et al.* (2005) and PérezRojas and Abad (2003).



However, later it was realized that the problem was also severe for fine form ships like containerships in head waves. In October 1998, the containership APL China encountered extreme weather which resulted in severe loss of cargo. A detailed investigation France *et al.* (2003) of this incident revealed that the primary cause of the catastrophe was the parametric rolling of the ship. After this revelation the research community's interest in parametric rolling of post-Panamax containerships in head seas was aroused.

A lot of researchers have investigated this problem and have come up with different assessments and possible solutions to the problem. Neves and Rodríguez (2007) modeled the problem as a coupled multi degree of freedom problem and has analyzed the effects of coupling between heave and pitch on roll motions. Neves and Rodríguez (2006) also developed a third order coupled model to capture the effect of softening stiffness term and compared against experiments. Paulling (2011) provided a synopsis of the research being performed in the field of parametric roll of ships. He also suggested the use of a few simplified approaches.

Bulian (2005) suggested analytical approximations to evaluate the GM in regular waves and used them to perform simulations in regular waves and compared them against simulations using a GZ look up table to include the quasi-statically calculated stiffness into the roll motion simulations (Bulian 2006). Later Bulian *et al.* (2006) investigated the effect of parametric roll in irregular seas (Bulian *et al.* 2008). Spyrou (2011) (Spyrou *et al.* 2008) has suggested the development of probabilistic framework to come up with analytical criteria for parametric roll.

Moideen (2010) has looked at the development of 3-D stability charts by Spyrou (2011) (Spyrou *et al.* 2008) suggested the development of. including the non-linear damping as a function of roll amplitude in regular waves (Moideen *et al.* 2012). Umeda *et al.* (2012) and Hashimoto and Umeda (2012) performed time domain simulations with calculating the Froude Krylov and diffraction forces up to the instantaneous waterline at each time step and compared them against experimental time series. Belenky *et al.* (2003) performed time domain simulations and checked the ergodicity of these simulations.

However, a unanimous criteria for parametric roll in head seas has not yet been provided by IMO. In this paper we look at two specific methods of analysis for parametric roll in regular and irregular waves.

### 3.1 Equation of motion

We begin with the single degree of freedom roll equation of motion as shown in Eq. (11).

$$(I + A(\omega))\ddot{\phi} + B(\omega)\dot{\phi} + B_q\dot{\phi}|\dot{\phi}| + C(t, \phi) = 0 \quad (11)$$

where

$I$  is the mass moment of inertia of the ship

$A(\omega)$  is the frequency dependent added moment of inertia

$B(\omega)$  is the frequency dependent linear damping

$B_q(\omega)$  is the frequency dependent quadratic damping

$C(t, \phi)$  is the roll restoring moment of the ship

$\phi$  is the instantaneous roll angle

### 3.1.1 Roll restoring moment

The restoring term in Eq. (11) can be expressed in terms of the instantaneous roll restoring arm GZ as in Eq. (12)

$$C(t, \phi) = \rho g \nabla_d GZ(t, \phi) \quad (12)$$

Due to the symmetry of the ship about the centerline, the GZ curve may be assumed to be an odd polynomial function of the instantaneous roll angle. The most simplest case is to consider the linear approximation as shown in Eq. (13)

$$GZ(t, \phi) = GM(t)\phi \quad (13)$$

Where  $GM(t)$  is the time varying metacentric height. In the case of following or head seas, the underwater hull form and the water plane area change as the wave passes along the ship. This change will result in the variation of GZ with time. The coefficient  $GM(t)$  captures the variation of the under water hull form with time. The resulting roll equation of motion is given by Eq. (14).

$$(I + A(\omega))\ddot{\phi} + B(\omega)\dot{\phi} + B_q\dot{\phi}|\dot{\phi}| + \rho g \nabla_d GM(t)\phi = 0 \quad (14)$$

If the excitation does not consist of a single frequency, then the added mass must be replaced by infinite frequency added mass and the radiation damping by a convolution integral of the roll velocity by an impulse response function. However in this paper, based upon experience and in order to simplify, this effect is neglected and the added mass and radiation damping are assumed to have a constant value equal to their value at the natural frequency of the system.

Non-dimensionalizing the roll equation of motion Eq. (14) by the transformations given in Eq. (15) is given by Eq. (16)

$$\begin{aligned} \omega_0 &= \sqrt{\frac{\rho g \nabla_d GM_0}{I + A(\omega_0)}} & \tau &= \omega_0 t \\ \frac{d}{dt}() &= \omega_0 \frac{d}{d\tau}() & \bar{\phi} &= \frac{\phi}{\phi_v} \\ \zeta &= \frac{B(\omega_0)}{2(I + A(\omega_0))\omega_0} & \zeta \delta_q &= \frac{B_q \phi_v}{I + A(\omega_0)} \\ GM(t) &= GM_0 + \partial GM(t) & \zeta \gamma(t) &= \frac{\partial GM(t)}{GM_0} \end{aligned} \quad (15)$$

where

$GM_0$  is the calm water metacentric height of the vessel

$\partial GM(t)$  is the variation in  $GM$  from the calm water case due to the presence of waves and body motions

$\omega_0$  is the natural frequency of roll in calm water condition

$\tau = \omega_0 t$  is the rescaled time

$\phi_v$  is the angle of vanishing stability of the calm water GZ

$\bar{\phi}$  is the roll angle nondimensionalized by  $\phi_v$

$$\ddot{\bar{\phi}} + 2\zeta\dot{\bar{\phi}} + \zeta\delta_q\dot{\bar{\phi}}|\dot{\bar{\phi}}| + (1 + \zeta\gamma(\tau))\bar{\phi} = 0 \quad (16)$$

Dropping the bar, the roll equation of motion can be expressed as Eq. (17)

$$\ddot{\phi} + \phi = \zeta(-2\dot{\phi} - \delta_q\dot{\phi}|\dot{\phi}| - \gamma(\tau)\phi) \quad (17)$$

### 3.2 Parametric roll in irregular seas

Unlike for the regular wave case, there is no simple analytical solution available for the irregular wave case. Even the analytical methods that do exist have a lot of assumptions which reduce their practical use for analyzing response in severe sea states. Thus the only widespread method of analysis is to perform time domain simulations for Eq. (17).

In order to perform a time domain simulation, it is necessary to correctly estimate the variation of linear stiffness  $\gamma(\tau)$  in irregular waves. In this section, the variation in GM with time shall be derived as a Volterra series based on the works of Hua *et al.* (1999) and Moideen (2010) (Moideen *et al.* 2013).

The local breadth  $B$ , sectional moment about the keel  $M$  and the sectional area  $A$  at a section  $x$  and draft  $T(x)$  are expressed as Taylor series expansion of the sectional draft change  $z$  as shown in Eq. (18)

$$\begin{aligned} B(x, T(x) + z) &= B(x, T(x)) + c_1(x)z + \frac{1}{2!}c_2(x)z^2 + \dots \\ M(x, T(x) + z) &= M(x, T(x)) + d_1(x)z + \frac{1}{2!}d_2(x)z^2 + \dots \\ A(x, T(x) + z) &= A(x, T(x)) + e_1(x)z + \frac{1}{2!}e_2(x)z^2 + \dots \end{aligned} \quad (18)$$

where

$$\begin{aligned} c_1(x) &= \frac{\partial B}{\partial z}(x, T(x)) & c_2(x) &= \frac{\partial^2 B}{\partial z^2}(x, T(x)) \\ d_1(x) &= \frac{\partial M}{\partial z}(x, T(x)) & d_2(x) &= \frac{\partial^2 M}{\partial z^2}(x, T(x)) \\ e_1(x) &= \frac{\partial A}{\partial z}(x, T(x)) & e_2(x) &= \frac{\partial^2 A}{\partial z^2}(x, T(x)) \end{aligned} \quad (19)$$

and so on

The metacentric height GM for any ship is given as in Eq. (20).

$$GM = BM + KB - KG \quad (20)$$

The metacentric radius BM and vertical center of buoyancy KB at any instantaneous position are given by Eqs. (21) and (22) respectively.

$$BM = \frac{1}{12\nabla_d} \int_L B^3(x, T(x) + r(x)) dx \quad (21)$$

$$KB = \frac{1}{\nabla_d} \int_L M(x, T(x) + r(x)) dx \quad (22)$$

where

$T(x)$  is the local draft at station  $x$  of the ship in calm water

$r(x)$  is the relative wave elevation (including the effects of heave and pitch) at station  $x$  of the ship.

The vertical center of gravity KG at any instantaneous position including the effect of pitch motion is given by Eq. (23). The second term in Eq. (23) takes into account the lowering of the keel point due to the pitching of the vessel.

$$KG = \frac{1}{\nabla_d} \int_L A(x, T(x) + r(x))(KG_0 + x(\eta_5 - \alpha_{trim})) dx \quad (23)$$

where

$\eta_5$  is the instantaneous pitch angle

$\alpha_{trim}$  is the static trim of the vessel in calm water

$KG_0$  is the vertical center of gravity in the calm water condition

Substituting Eqs. (21)-(23) into Eq. (20) leads to Eq. (24)

$$\begin{aligned} \partial GM = & \frac{1}{\nabla_d} \int_L \left( \frac{B^3(x, T(x) + r(x))}{12} + M(x, T(x) + r(x)) \right. \\ & \left. - A(x, T(x) + r(x))(KG_0 + x(\eta_5 - \alpha_{trim})) \right) dx \\ & - GM_0 \end{aligned} \quad (24)$$

Substituting Eq. (18) into Eq. (24) leads to Eq. (25)

$$\partial GM = \sum_i \partial GM_i \quad (25)$$

where

$$\begin{aligned}
 \partial GM_1 &= \frac{1}{\nabla_d} \int_L \left[ \frac{B^2(x, T(x))c_1(x)}{4} + d_1(x) - KG_0 e_1(x) \right] r(x) dx \\
 \partial GM_2 &= \frac{1}{\nabla_d} \int_L \left[ \frac{3B^2(x, T(x))c_2(x) + 3B(x, T(x))c_2^2(x)}{12} + d_2(x) \right. \\
 &\quad \left. - KG_0 e_2(x) \right] r^2(x) dx - \frac{1}{\nabla_d} \int_L x e_1(x) \eta_5 r(x) dx
 \end{aligned} \tag{26}$$

and so on

In other words, the various orders of GM variations can be expressed as Eq. (27).

$$\partial GM(t) = \sum_i \left[ \int_L G_i(x) r^i(x, t) dx + \int_L R_{i-1}(x) r^{i-1}(x, t) dx \right] \tag{27}$$

where

$$\begin{aligned}
 G_1(x) &= \frac{1}{\nabla_d} \left[ \frac{B^2(x, T(x))c_1(x)}{4} + d_1(x) - KG_0 e_1(x) \right] \\
 G_2(x) &= \frac{1}{\nabla_d} \left[ \frac{3B^2(x, T(x))c_2(x) + 3B(x, T(x))c_2^2(x)}{12} + d_2(x) \right. \\
 &\quad \left. - KG_0 e_2(x) \right] \\
 G_3(x) &= \frac{1}{\nabla_d} \left[ \frac{3B^2(x, T(x))c_3(x) + 6B(x, T(x))c_1(x)c_2(x) + c_1^3(x)}{12} \right. \\
 &\quad \left. + d_3(x) - KG_0 e_3(x) \right]
 \end{aligned} \tag{28}$$

$$\begin{aligned}
 R_1(\omega, x) &= -\frac{x e_1(x) \eta_5(\omega)}{\nabla_d} \\
 R_2(\omega, x) &= -\frac{x e_2(x) \eta_5(\omega)}{\nabla_d}
 \end{aligned} \tag{29}$$

The surface wave elevation can be considered as a Fourier Series shown in Eq. (30)

$$\eta(x, t) = \frac{1}{2} \sum_{n=1}^N a_n \left[ e^{i(k_n x - \omega_n t + \beta_n)} + e^{-i(k_n x - \omega_n t + \beta_n)} \right] \tag{30}$$

Assuming the effect of heave and pitch of the vessel, the relative wave elevation can be expressed as in Eq. (31)

$$\begin{aligned}
r(x, t) &= \frac{1}{2} \sum_{n=1}^N a_n [e^{i(k_n x)} - \eta_3(\omega_n) + x\eta_5(\omega_n)] e^{i(-\omega_n t + \beta_n)} \\
&+ \frac{1}{2} \sum_{n=1}^N a_n [e^{-i(k_n x)} - \overline{\eta_3}(\omega_n) + x\overline{\eta_5}(\omega_n)] e^{-i(-\omega_n t + \beta_n)}
\end{aligned} \tag{31}$$

where

$\eta_3(\omega)$  is the heave complex RAO

$\eta_5(\omega)$  is the pitch complex RAO

The relative wave elevation can further be expressed as shown in Eq. (32)

$$r(x, t) = \frac{1}{2} \sum_{n=1}^N a_n [v(\omega_n, x) e^{-i(\omega_n t - \beta_n)} + \overline{v}(\omega_n, x) e^{i(\omega_n t - \beta_n)}] \tag{32}$$

where

$$\begin{aligned}
v(\omega_n, x) &= [e^{i(k_n x)} - \eta_3(\omega_n) + x\eta_5(\omega_n)] \\
\overline{v}(\omega_n, x) &= [e^{-i(k_n x)} - \overline{\eta_3}(\omega_n) + x\overline{\eta_5}(\omega_n)]
\end{aligned} \tag{33}$$

Similarly the pitch time series can also be expressed as a Fourier Series as in Eq. (34)

$$\eta_5(t) = \frac{1}{2} \sum_{n=1}^N a_n [\eta_5(\omega_n) e^{-i(\omega_n t - \beta_n)} + \overline{\eta_5}(\omega_n) e^{i(\omega_n t - \beta_n)}] \tag{34}$$

Substituting Eqs. (28), (29), (32) and (34) into Eq. (27) gives the first and second order GM transfer functions. The first order transfer function and the corresponding 1<sup>st</sup> order GM variation is given by Eqs. (35) and (36) respectively.

$$\begin{aligned}
f_1(\omega) &= \int_L G_1(x) v(\omega, x) dx \\
\overline{f_1}(\omega) &= \int_L G_1(x) \overline{v}(\omega, x) dx
\end{aligned} \tag{35}$$

$$\partial GM_1(t) = \sum_{n=1}^N a_n [f_1(\omega_n) e^{-i(\omega_n t - \beta_n)} + \overline{f_1}(\omega_n) e^{i(\omega_n t - \beta_n)}] \tag{36}$$

Similarly, the second order transfer function and second order GM variation are given by Eqs. (37) and (38) respectively.

$$\begin{aligned}
 u_2(\omega_m, \omega_n) &= \int_L [G_2(x)v(\omega_m, x)v(\omega_n, x) + R_2(\omega_m, x)v(\omega_n, x)]dx \\
 \bar{u}_2(\omega_m, \omega_n) &= \int_L [G_2(x)v(\omega_m, x)\bar{v}(\omega_n, x) + R_2(\omega_m, x)\bar{v}(\omega_n, x)]dx \\
 v_2(\omega_m, \omega_n) &= \int_L [G_2(x)\bar{v}(\omega_m, x)v(\omega_n, x) + \bar{R}_2(\omega_m, x)v(\omega_n, x)]dx \\
 \bar{v}_2(\omega_m, \omega_n) &= \int_L [G_2(x)\bar{v}(\omega_m, x)\bar{v}(\omega_n, x) + \bar{R}_2(\omega_m, x)\bar{v}(\omega_n, x)]dx
 \end{aligned} \tag{37}$$

$$\begin{aligned}
 \partial GM_2(t) &= \sum_{m=1}^M \sum_{n=1}^N a_m a_n \{u_2(\omega_m, \omega_n)e^{-i[(\omega_m+\omega_n)t-\beta_m-\beta_n]} \\
 &\quad \bar{u}_2(\omega_m, \omega_n)e^{-i[(\omega_m-\omega_n)t-\beta_m+\beta_n]}\} + \\
 &\quad \sum_{m=1}^M \sum_{n=1}^N a_m a_n \{v_2(\omega_m, \omega_n)e^{i[(\omega_m-\omega_n)t-\beta_m+\beta_n]} \\
 &\quad \bar{v}_2(\omega_m, \omega_n)e^{i[(\omega_m+\omega_n)t-\beta_m-\beta_n]}\}
 \end{aligned} \tag{38}$$

Thus  $\gamma(t)$  in Eq. (37) can be expressed as Eq. (39)

$$\gamma(t) = \frac{\partial GM}{GM_0} = \frac{\partial GM_1(t) + \partial GM_2(t)}{GM_0} \tag{39}$$

Where  $\partial GM_1(t)$  and  $\partial GM_2(t)$  are obtained from Eqs. (36) and (38) respectively. Transforming the time scale in  $\gamma(t)$  and substituting into Eq. (17), multiple time domain simulations for various sea states can be performed to evaluate the susceptibility of the hull form to parametric roll in irregular long crested seas.

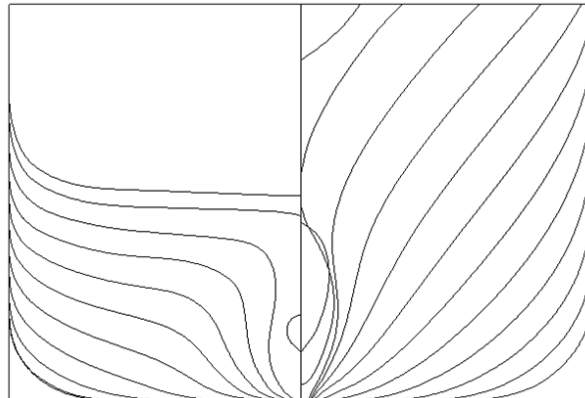


Fig. 7 Body Plan of C11 hull form

### 3.3 Example: APL China hull form

In this section, above method of Volterra series is applied to a modified hull form of APL China. The details of the ship are given in Table 2. The body plan of the hull form is shown in Fig. 7.

A simulation of the ship in a Bretschneider Spectrum of significant wave height of  $H_s = 5\text{m}$  and modal period of  $T_m = 13.16\text{ sec}$  has been performed. The absolute value of the 1<sup>st</sup> order transfer function is shown in Fig. 8. The second order transfer functions are shown in Fig. 9. The second order GM variation is observed to be much smaller than the first order GM variation. However, it was found that the first order GM variational ways has a zero mean and is not enough to model the asymmetric GM variation always the calm water  $GM_0$ . The second order GM variation has a non-zero mean component which captures the asymmetric behavior more accurately.

The resulting wave elevation, GM variation and roll motion time series are shown in Figs. 10-12. Fig. 12 shows the roll motion time series to have approximately twice the period of the excitation which demonstrates the Mathieu type behavior in the irregular seas. The effect of second order transfer function should not be confused with a 2<sup>nd</sup> order roll phenomenon as the second order transfer function only relates to the modeling of an asymmetric variation of GM about the calm water GM.

Table 2 Particulars of the C11 Pram Hull form

Particulars (Units)	Value
Length between Pependiculars ( $m$ )	255.302
Breadth ( $m$ )	40
Depth ( $m$ )	29.25
Draft Aft ( $m$ )	11.5
Draft Fwd ( $m$ )	11.5
Displacement from Maxsurf ( $m^3$ )	$6.74 \times 10^4$
Displacement (tonnes)	$6.9085 \times 10^4$
Displacement (kgs)	$6.9085 \times 10^7$
KG ( $m$ )	18.374
GM ( $m$ )	1.965
Roll Gyradius ( $m$ )	16.73
Roll Inertia ( $kgm^2$ )	$1.93365 \times 10^{10}$
Roll Added Inertia ( $kgm^2$ )	$4.49590 \times 10^9$
Natural Period of Roll ( $sec$ )	26.58
Natural Frequency of Roll ( $rad/sec$ )	0.2364



### 4. Conclusions

Two different approaches to improve the EEDI of a ship have been proposed. The first is to predict added resistance of a ship in forward speed efficiently. A near field pressure integration method is used using a 3D panel method program to predict the added resistance. The hull form can be optimized for better EEDI based on the added resistance prediction.

The second approach is to reduce the ship motion in irregular seas so as to enable the ship to operate for most of its voyage at its design speed. Two methods have been proposed for prediction of parametric roll of ship in both regular and irregular seas.

The regular wave method utilizes Floquet theory, and the irregular wave method is based on a Volterra series approach. These two methods will help determine the magnitude of roll motion in regular and irregular seas. Based on these, the hull form can be effectively optimized to reduce its susceptibility to parametric roll and hence improve the EEDI of the vessel.

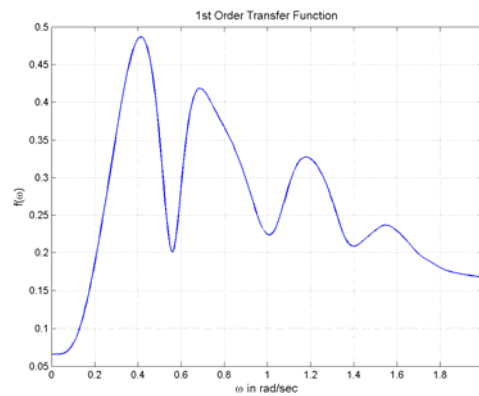


Fig. 8 The 1st order transfer function for GM variation  $\partial GM_1$

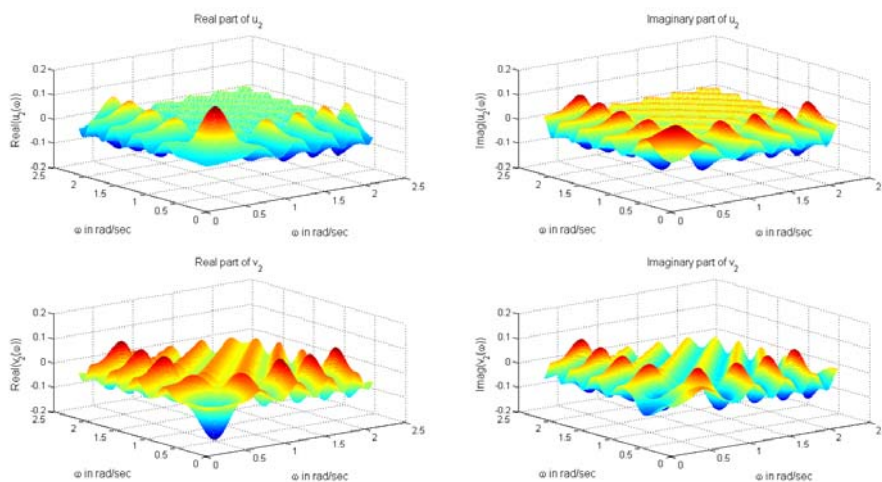


Fig. 9 The 2<sup>nd</sup> order transfer function for GM variation  $\partial GM_2$

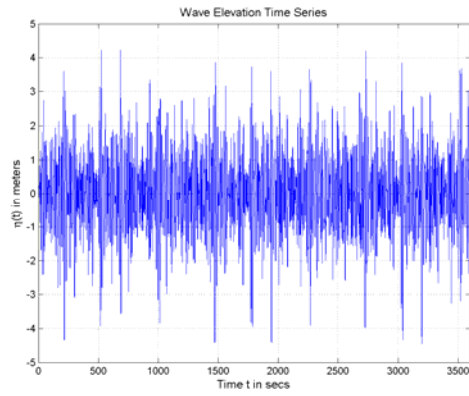


Fig. 10 Wave elevation time series

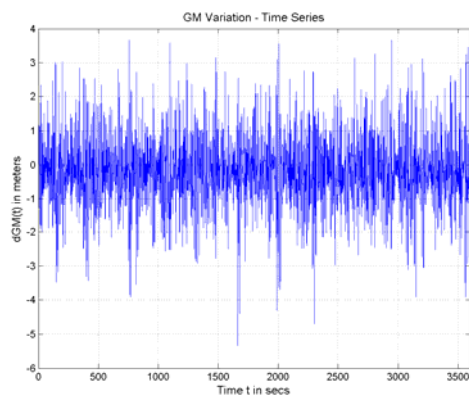


Fig. 11 Variation of GM from calm water condition in waves

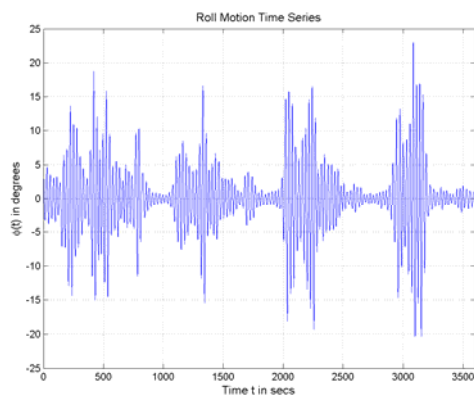


Fig. 12 Roll motion time series

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