

# ALTERNATIVE METHODS ON ADDED RESISTANCE OF SHIPS IN REGULAR HEAD WAVES

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## ABSTRACT

Some selected methods for predicting added resistance of ships in regular head waves have been taken for examination. They are: Maruo's method, Maruo-Ishii's method, Gerritsma-Beukelman's method and Strip method. Three series 60 parent form ships of block co-efficient 0.60, 0.70 and 0.80, representing fine, medium and fuller form ship, have been taken for computation. Computed results are then compared with some available experimental results to examine the suitability of the methods employed. Test and examination results focus in head seas which are the most severe for added resistance. Overall prediction shows that Maruo and Gerritsma-Beukelman's method may be applied for reasonable prediction, specially for fine and medium ship forms. On the other hand, all the methods mentioned previously (commonly known as 2-D methods) fail to predict reasonable prediction for the fuller ship forms and that is why a 3-D method, which has a wide range of applicability with respect to hull form and frequency, has been applied for the case of fuller ship form.

**Keywords:** 2-D Methods, Added resistance, Regular Waves, Strip Theory

## 1.0 INTRODUCTION

In the past powering requirement of ships predicted by a tank test was usually the value in a calm sea and considerable power had to be added to this when a ship streaming in a seaway. The increase of the resistance due to the waves encountered in comparison with calm water resistance is called added resistance and it is an important part of ship design due to its enormous economical effect such as fuel economy, maintaining time schedule *etc.* Since experimental study in a model basin is not always possible, so analytical prediction or numerical calculation could be a good alternative to foresee the ship behaviour and could be applied for the evaluation of added resistance in the ship design phase conveniently. The increase of resistance has been recognised for a long time and there were different opinions about the cause of added resistance. Attempts to calculate resistance increase analytically, which is based on its motion in waves, started in late thirties and since then many research works have been undertaken by many researchers to handle this problem of added resistance. Havelock [1] demonstrated that the additional resistance arises due to the phase difference between the ship motion for heaving and pitching and excitation of the waves. Boese [2] derived a formula for added resistance integrating pressure forces over the wetted surface of the ship. Hearn *et. al.*, [3] made a series of computations based on several different theoretical models for the prediction of added resistance advancing in waves. Both near field and far field approaches are presented for added resistance calculation. Kashiwagi [4] derived a formula for added resistance in regular oblique waves based on a 3-D theory. All the theoretical methods are generally tedious and elaborate. They have been treated from several points of view containing some inherent limitations with respect to each other. It is therefore desirable to find out reliable one from available methods which is also the main aim of this paper. Of course,

to examine all the methods in this respect demands huge work and it is not the intention of this paper. However, of numerous methods as developed so far, four methods have been chosen here for examination. They are:

- 1) Maruo's Method
- 2) Maruo-Ishii's Method
- 3) Gerritsma-Beukelman's Method and
- 4) Strip Method.

The reason for choosing these are Maruo's method [5] is widely discussed by many researchers [6-9], Maruo-Ishii's method is regarded as giving better results than Maruo's original work especially in head waves [10], Gerritsma and Beukelman's method is recognised for its simplicity as well as giving better results than others [11] and Strip method is also simple and regarded as giving better results in some cases [8]. An attempt has been made in this paper to predict added resistance of ships in regular head waves by employing above four different methods and scrutiny has been carried out among these methods in order to justify which method would be relatively more reliable than others. These four methods can be treated commonly as 2-D methods. In addition to those 2-D methods, a 3-D method has been also applied for special case.

## 2.0 MOTION RESPONSES WITH A STRIP THEORY

Added resistance has great sensitivity to motion prediction and so accurate prediction of motion is equally important for added resistance theories. In this paper calculation of motion responses is done with New Strip Method (NSM) given in reference [12] which simplifies the 3-D problem to 2-D. This also permits the hull to be divided into a number of transverse section as shown in Figure 1 and the calculation of the sectional added mass and

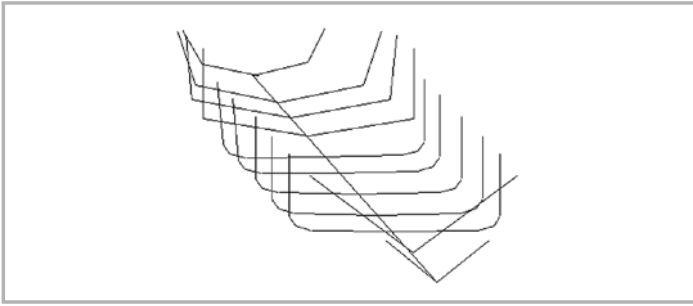


Figure 1: Representation of ship hull by transverse strip along the length of ship

sectional damping are required for the determination of the coefficients of the equations of motion and the exciting force and moments. The hydrodynamic problem consists of determining the added mass and damping for a cylinder of infinite length, floating in water of infinite depth and vertically oscillating in small harmonic motion. To calculate the added mass and damping properties of each section, a mapping is employed which transforms a circle into an arbitrary shape and the said properties of a circle oscillating harmonically in a free surface may be determined with relative ease. Calculations are performed for a range of regular waves and the hydrodynamic coefficients must be provided for each wave frequency and also the heave and pitch motion value together with their correspondent phase relationship. Once motion responses and hydrodynamic properties have been determined by using NSM, the prediction of added resistance can be obtained by using different 2-D methods mentioned above.

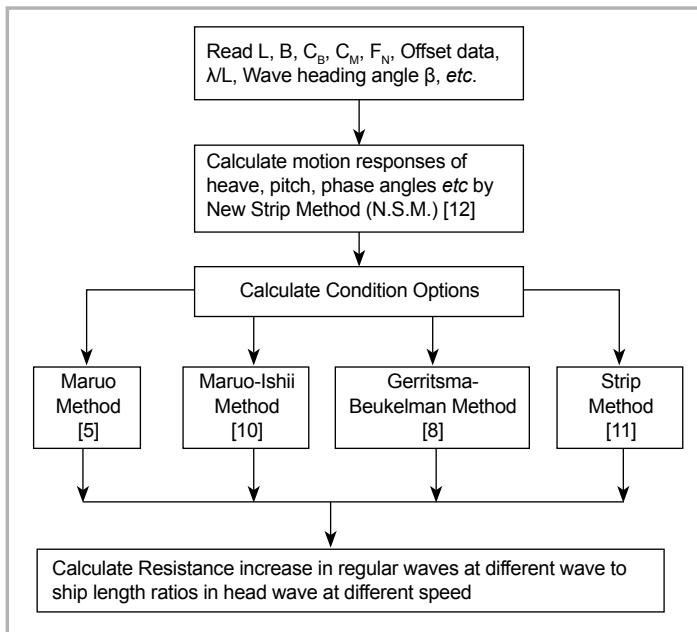


Figure 2: Summary of steps involved for computation of added resistance by 2-D methods

### 3.0 EXPERIMENTAL MEASURE OF ADDED RESISTANCE

The prediction of added resistance by experimental means is always very expensive and time consuming. Experiments of various ship hull forms are usually obtained by two different methods in towing tanks: constant-thrust method and constant-velocity method. In the constant-thrust method, the model is towed by a

constant weight and the resultant speed of the model is measured. The measurement is done, in most cases, by attaching the model to a sub-carriage that can move relative to the main carriage. The towing force is applied to the sub-carriage. In the constant-velocity method, the model is firmly attached to the resistance dynamometer and no speed variations relative to the carriage are possible and the time average of the resistance is measured. Since the added resistance is the difference between the resistance measured in calm water and waves at exactly the same average speed, constant-velocity method is a more direct technique than constant-thrust method, because speed can be controlled directly. The constant thrust method, however, would be applicable in determining the speed loss associated with a constant towing force.

### 4.0 PREDICTION METHODS OF ADDED RESISTANCE

As mentioned earlier, four methods have been employed in this study for computation of added resistance in waves along with 3-D method for special case. A flow charts has been laid out in order to show the summary of steps involved for computation of added resistance. A flow chart has been laid out in Figure 2 in order to show the summary of steps involved for computation of added resistance.

For the numerical computations of 2-D methods, Computer Coding has been developed in Fortran language with some subroutines taken from Kadumatsu [6]. The methods used in the paper are elaborately described in different literatures and here only a brief outline of the methods are given in the following sections:

#### (a) Maruo's Method:

The resistance of ship in the regular waves are first obtained by Maruo [5] and it is a potential flow solution. Here the equations for conservation of energy and momentum have been used to derive a theoretical method for added resistance. This procedure is valid for any wavelength and wave heading, even though it is difficult to apply it from practical point of view. A singularity distribution is used to represent the hull form and wave field potential associated with the regular wave field and the velocity potential of the waves produced by singularities. The velocity potential of a regular wave may be obtained immediately. The hull from singularity distribution may be determined from an approximate distribution such as a center-plane source distribution originally employed by Maruo. Since computation of source integral is very difficult, Maruo use an approximate method. Although these functions mean the distribution of sources on the ship's surface, Maruo consider a point source in each transverse section (as shown in Figure 1) of the ship instead of the actual surface distribution. Thus the source density of the source is replaced by a line distribution and allow the evaluation of the added resistance in terms of the geometric characteristics of the ship described at each section and the measured or computed ship motions. However making the variables non-dimensional, the calculation for added resistance lend themselves to numerical computation and the final expression of Maruo's formula in regular head waves is expressed as:

$$R_{AW} = \frac{4\pi\rho}{l^2} \left( - \int_{-\infty}^{-\kappa} + \int_{-\kappa_1}^{-\infty} \frac{(m + \omega_1)^2 (m + \kappa_1)}{\sqrt{(m + \omega_1)^4 - \kappa_1^2 m^2}} |H(m)|^2 dm \right) \quad (1)$$

$$\kappa = (x_1 + 2\omega_1 + \sqrt{x_1^2 + 4x_1\omega_1}), \nu = \frac{L_{bp}}{2}, \omega_1 = \frac{\omega_e \nu}{U},$$

$$x_1 = \frac{gl}{U^2}, \kappa_1 = \kappa, l = \frac{2\pi l}{\lambda} \quad (2)$$

$$|H(m)|^2 = \frac{B^2 \xi_a^2 U^2}{4\pi} \left[ (\omega_1 + m)^2 \xi_0^2 G_1^2 + (\omega_1 + m)^2 (\kappa_1^2 \psi_0^2 G_3^2) \right. \\ \left. + \kappa_1 x_1 G_3^2 - 2(\omega_1 + m)^2 G_1 G_2 \kappa_1 \xi_0 \psi_0 \sin(\varepsilon_{zw} - \varepsilon_{\theta w} - \alpha + \beta) \right. \\ \left. - 2(\omega_1 + m) G_1 G_3 \sqrt{\kappa_1 x_1} \xi_0 \cos(\varepsilon_{zw} - \alpha + \gamma) \right. \\ \left. - 2(\omega_1 + m) G_2 G_3 \sqrt{\kappa_1 x_1} \psi_0 \sin(\varepsilon_{\theta w} - \beta + \gamma) \right] \quad (3)$$

where,  $G_1, G_2, G_3, \alpha, \beta, \gamma$  are the magnitudes and phase angles of the complex functions,  $\varepsilon_{zw}$  is the phase difference between heave and wave,  $\varepsilon_{\theta w}$  is the phase difference between pitch and wave and  $m$  is the transformation function. Other Symbols have meaning as explained in Nomenclature.

### (b) Maruo-Ishii's Method:

Maruo and Ishii [10] considerably simplified the original integral representation of Maruo's expression by using a high frequency assumption and shows that if the singularity distribution on the centerline of a ship is known, the resistance increase can be calculated. Singularity distribution on the centerline of a ship can be obtained in two dimensions where the velocity potential can be expressed by the relative vertical velocity between the fluid and the section of the ship. For longitudinal motion, only the relative vertical velocity is considered and horizontal component is neglected. The final form of expression for added resistance in regular head waves is given as:

$$R_{AW} = 8 \pi^2 \rho \int_{-\infty}^{\infty} |M(x)|^2 \left[ k - \frac{d\delta(x)}{dx} \right] dx \quad (4)$$

$$\text{Where, } |M(x)| = \frac{g\bar{A}|V|}{4\pi\omega_e^2} \quad (5)$$

$M(x)$  is the 2D strength of the periodic source,  $V$  is the relative vertical velocity of the section. In order to determine  $M(x)$ , we must obtain  $V$  and in the case without advance of speed,  $V$  is considered to be the kinematic relative velocity of a section to the fluid, but in the case with advance speed the effect of the change of the section shape must be considered. Applying the momentum theory to the flow in the section,  $V(x)$  can be written according to New Strip Method [12]:

$$V(x) = \frac{1}{B(x)} \left( i\omega_e + U \frac{\delta}{\delta x} \right) (B(x)(Z_G - x\theta - \zeta_w)) \quad (6)$$

Where  $B(x)$  is the width of each section at the water plane,  $Z_G$  is the vertical displacement of the center of gravity,  $\theta$  is the angle of rotation about the transverse axis through the center of gravity and  $\zeta_w$  is the elevation of the water surface due to incident waves. Other Symbols are explained in Nomenclature.

### (c) Gerritsma and Beukelman's Method:

The added resistance of a moving ship can be interpreted to be a result of the damping waves radiated away from the ship hull. This principle was used by Gerritsma and Beukelman [11] to compute added resistance by calculating the energy flux radiated from the hull. This approach is least rigorous and very simple.

According to this approach the quantity of energy flux  $E$  radiated from an oscillating ship during one period of wave encounter  $T_e$  in case of regular longitudinal bow waves is given by

$$E = \int_0^{T_e} \int_0^L b' V_z^2 dx dt \quad (7)$$

Where,

$$b' = (b_n - U \frac{\delta a_n}{\delta x}) \& V_z = z - (x - x_G) \theta + U\theta - \zeta^* + U\delta\zeta^*/\delta x \quad (8)$$

$$\zeta^* = \zeta \left( 1 - \frac{k}{y_{wl}} \int y_z e^{kz} dz \right) \quad (9)$$

In this expression  $y_z$  is the half width of any longitudinal section and  $y_{wl}$  is the half width of the design waterline at longitudinal section.

Gerritsma and Beukelman have shown that the added work of the ship is proportional to the radiated energy, *i.e.*,

$$E = R_{AW}(U + c)T_e = \lambda.R_{AW}$$

Equating Equations (7) and (10), we get

$$R_{AW} = \frac{k}{y_{wl}} \int_0^{T_e} \int_0^L b' V_z^2 dx dt = \int_L \frac{k}{2\omega_e} (b_n - U \frac{\delta a_n}{\delta x}) V_{za}^2 dx \quad (11)$$

Coefficients  $a_n$  and  $b_n$  in this formula can be determined by means of NSM [12]

### (d) Strip Method:

In the Strip method of calculation, the underwater portion of the hull is divided into a number of sections or strips. The flow is assumed two dimensional and the interactions between the strips or section are neglected. This method is similar to that of Gerritsma and Beukelman. However the difference between the two methods is observed in the size of divergences waves energy and in the term giving the effect of forward speed [8].

The non-dimensional expression for added resistance by Strip method has been expressed as follows:

$$K_w = C'_{11} \zeta_0^2 + C'_{22} \psi_0^2 + C'_{33} + C_{12c} \zeta_0 \psi_0 \cos \varepsilon_{\theta z} + C_{13c} \zeta_0 \cos \varepsilon_{zw} \\ + C_{13s} \zeta_0 \sin \varepsilon_{zw} + C_{23c} \psi_0 \cos \varepsilon_{\theta w} + C_{23s} \psi_0 \sin \varepsilon_{\theta w} \quad (12)$$

$$C'_{11} = \frac{\pi/p}{8(B/L)^2 \omega_L^2} \int_{-1}^1 \bar{A}_S^2 d\zeta \quad (13)$$

$$C'_{22} = \frac{(\pi/p)^3}{8(B/L)^2 \omega_L^2} \int_{-1}^1 (\zeta - \zeta_G)^2 \bar{A}_S^2 d\zeta \quad (14)$$

$$C'_{33} = \frac{(\pi/p)^3}{8(B/L)^2 \omega_L^2} \int_{-1}^1 \bar{A}_S^2 e^{-2kd} m d\zeta \quad (15)$$

$$C_{12c} = \frac{(\pi/p)^2}{4(B/L)^2\omega_L^2} \int_{-1}^1 (\xi - \xi_G) \bar{A}_S^2 d\zeta \quad (16)$$

$$C_{13c} = \frac{(\pi/p)}{4(B/L)^2\omega_L^2} \int_{-1}^1 \bar{A}_S^2 e^{-kd} m \cos(\pi/p)\zeta d\zeta \quad (17)$$

$$C_{13s} = \frac{(\pi/p)}{4(B/L)^2\omega_L^2} \int_{-1}^1 \bar{A}_S^2 e^{-kd} m \sin(\pi/p)\zeta d\zeta \quad (18)$$

$$C_{23c} = \frac{(\pi/p)^2}{4(B/L)^2\omega_L^2} \int_{-1}^1 \bar{A}_S^2 e^{-kd} m (\xi - \xi_G) \cos(\pi/p)\zeta d\zeta \quad (19)$$

$$C_{23s} = \frac{(\pi/p)^2}{4(B/L)^2\omega_L^2} \int_{-1}^1 \bar{A}_S^2 e^{-kd} m (\xi - \xi_G) \sin(\pi/p)\zeta d\zeta \quad (20)$$

$$\bar{A}_S^2 = \bar{A}^2 - 0.5 Fn\omega_L^3 (B/L)^2 \delta(C_0 K_4 \eta^2) / \delta\zeta \quad (21)$$

Symbols have meaning as explained in Nomenclature.

**(e) 3-D Method:**

3-D numerical model is based on distribution of sources on the submerged surface of the ship for solving the linearised boundary value problems associated with potential flow around a ship moving in waves at forward speed. An integral equation is given either for the source strength or for the velocity potential in the domain of the ship surface. The Green function, defined as velocity potential of a pulsating source located at a some point, must satisfy the linearised free surface condition and the radiation condition. To obtain the solution, the surface has been discretised by number of panels as shown in Figure 14 and replace the integral equation by a finite system of linear equations.

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 can be expressed as Wehausen and Laitone [13]:

$$\Phi_j(P) = -\frac{1}{4\pi} \left( \iint_{S_H} G(P,Q) \sigma_j(Q) ds + \frac{U^2}{g} \oint_{CH} G(P,Q) \sigma_j(Q) n_1 dl \right) \quad (21)$$

Where, contour integral (2nd term) is over the intersection of the hull surface  $S_H$  and the free surface. The numerical technique of detailed derivation is not the scope of the paper and so omitted in this paper.

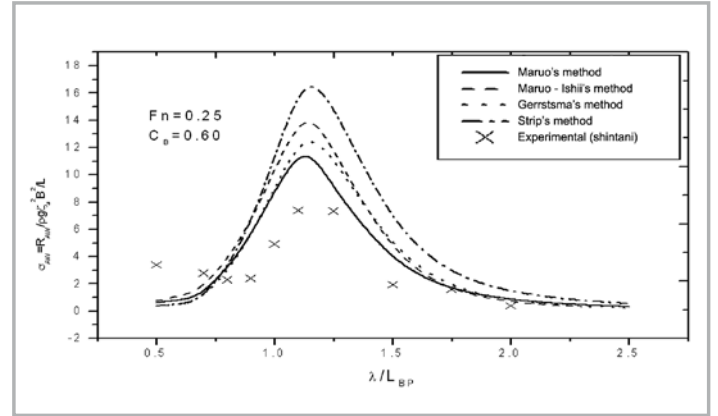
**Table 1: Principal particulars of Series 60 ships**

Ship Particulars	Ship-1	Ship-2	Ship-3
Length, $L_{BP}$ (m)	121.95	121.95	121.95
Beam, $B$ (m)	16.26	17.42	18.76
Draft, $d$ (m)	6.504	6.97	7.51
L/B ratio	7.50	7.00	6.50
B/d ratio	2.50	2.50	2.50
Block Coefficient, $C_B$	0.60	0.70	0.80
Displacement,(Tonnes)	7931.55	10622.4	14079.2
LCB,% LBP from Amidship	1.5Aft	0.5Aft	2.5Forward

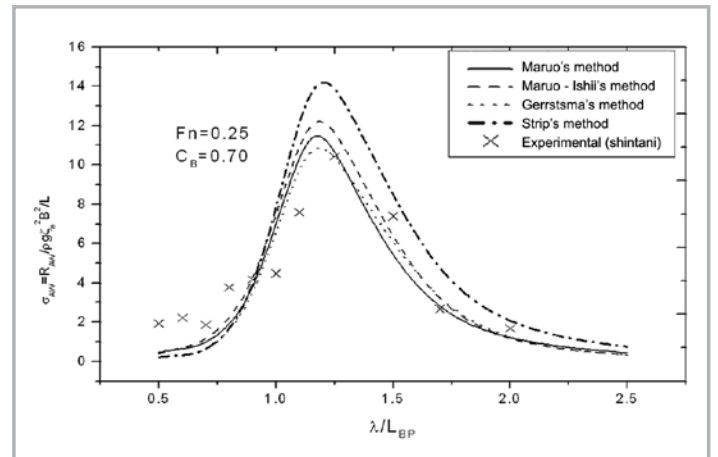
**5.0 RESULTS AND DISCUSSIONS**

For the examination of the methods employed, three Series 60 parent form ships (fine, medium and fuller form ships) have been taken for computation. The principal particulars of these parent form ships are given in Table 1.

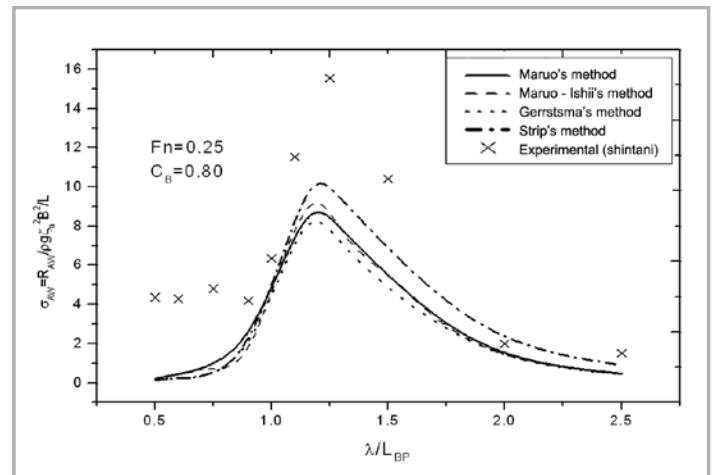
In order to determine the suitability of the employed methods, it is necessary to compare the results obtained by individual method with the experimental ones.



**Figure 3: Non dimensional added resistance for different methods for series 60 ship-1 with  $C_B = 0.60$  in head waves,  $\beta = 180^\circ$**



**Figure 4: Non dimensional added resistance for different methods for series 60 ship-2 with  $C_B = 0.70$  in head waves,  $\beta = 180^\circ$**



**Figure 5: Non dimensional added resistance for different methods for series 60 ship-3 with  $C_B = 0.80$  in head waves,  $\beta = 180^\circ$**

Figure 3 has been introduced to make a comparison of the results obtained by different methods with that of experimental results for ship-1. It represents the added resistance coefficient in head waves, drawn as a function of wave length-ship length ratio at Froude number of 0.25. From this figure, it is seen that the agreement between computed results and experimental ones is satisfactory at higher wave to ship length ratios especially when  $\lambda/L_{BP} > 1.7$ . On the other hand at low wavelength to ship length ratios below 0.6 computed results by all methods are lower than experimental ones and in the region between  $0.9 > \lambda/L_{BP} > 1.3$ , the computed results are higher than experimental ones. However in the case of Maruo's method, the discrepancy is relatively less while in the case of Strip method, the discrepancy is quite high especially in the intermediate region ( $0.9 > \lambda/L_{BP} > 1.3$ ). It may be noted that experimental results have been taken from Shintani [8].

Figure 4 repeats Figure 3 for ship-2 with block coefficient 0.70. It is seen from this figure that the discrepancies between computed results and results obtained experimentally have been reduced compared to the previous Figure 3, although there are discrepancies at lower wavelength to ship length ratios for all the methods.

Figure 5 repeats Figure 3 for ship-3 with block coefficient 0.80. Here overall agreement between theoretical and experimental is

very poor particularly at low wavelength to ship length ratios for all methods.

It may be noted here that a comparison of computed results with experimental results for a fixed Froude number 0.25 is shown in Figures 3 to 5. This trend may or may not be followed in the case of other Froude number. Comparison was made between the computed results with the experimental results for the case of wide variation of speed. Figures 6 to 13 have been introduced for that purposes. It is worth to mention here that experimental results shown in the figures, are due to Sibul and Gerritsma and have been taken from Beck [7], where the experimental results represent the mean curve drawn through experimental points.

Figure 6 through Figure 9 represent the added resistance coefficient of Series 60 ship with  $C_B=0.60$  obtained by four theoretical methods employed as well as those by experimental ones as a function of Froude numbers at four wave to ship length ratios with each figure representing for a particular wave to ship length ratio in head waves.

Figure 10 through Figure 13 repeat Figure 6 through Figure 9 the same for Series 60 ship with  $C_B=0.80$ .

Figure 6 shows at low Froude numbers (less than 0.13 approximately) experimental results under predict the added resistance than all employed theoretical methods. But, for relatively higher Froude numbers (greater than 0.13

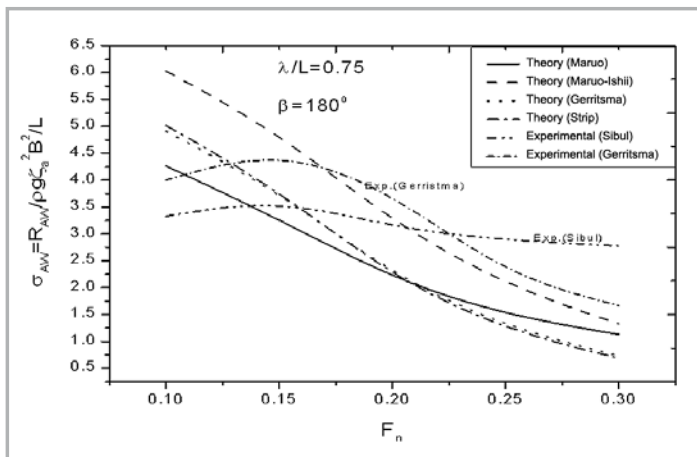


Figure 6 : Added resistance coefficient as a function of Froude number at  $\lambda/L = 0.75$  for series 60 ship-1 with  $C_B = 0.60$  in head waves,  $\beta = 180^\circ$

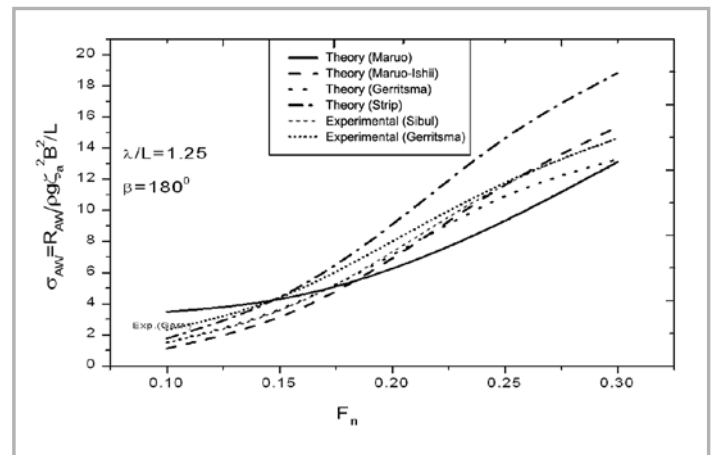


Figure 8: Added resistance coefficient as a function of Froude number at  $\lambda/L = 1.25$  for series 60 ship-1 with  $C_B = 0.60$  in head waves,  $\beta = 180^\circ$

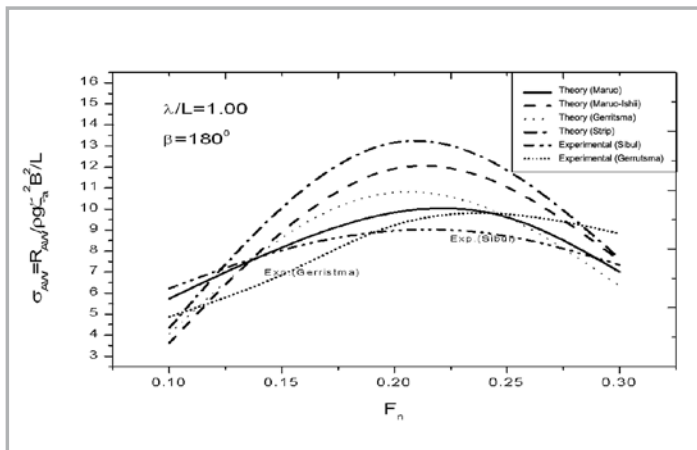


Figure 7: Added resistance coefficient as a function of Froude number at  $\lambda/L=1.00$  for series 60 ship-1 with  $C_B = 0.60$  in head waves,  $\beta = 180^\circ$

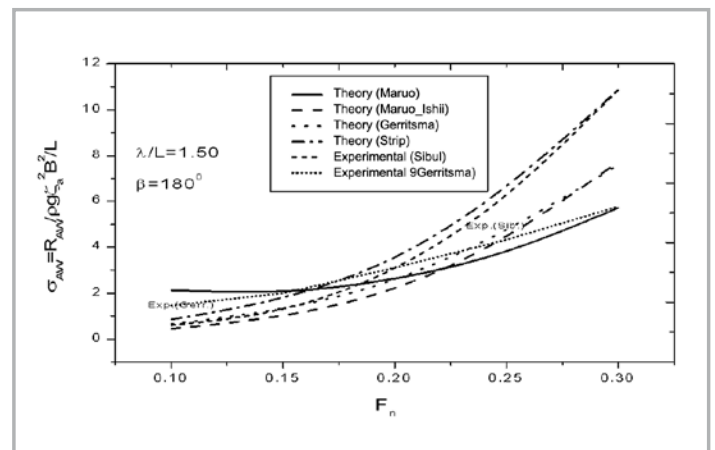


Figure 9: Added resistance coefficient as a function of Froude number at  $\lambda/L = 1.50$  for series 60 ship-1 with  $C_B = 0.60$  in head waves,  $\beta = 180^\circ$



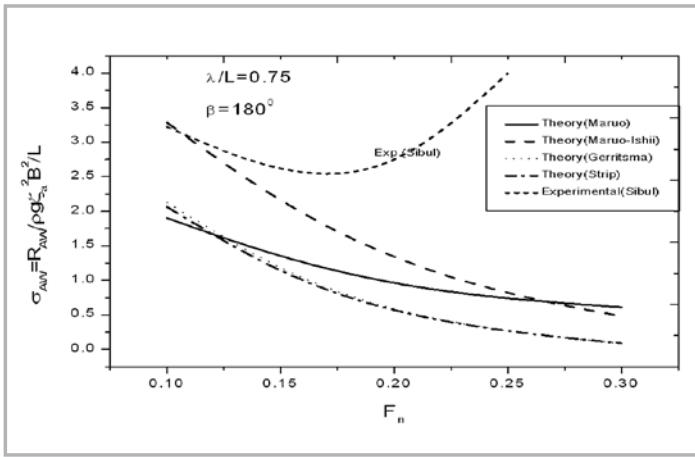


Figure 10: Added resistance coefficient as a function of Froude number at  $\lambda/L = 0.75$  for series 60 ship-3 with  $C_B = 0.80$  in head waves,  $\beta = 180^\circ$

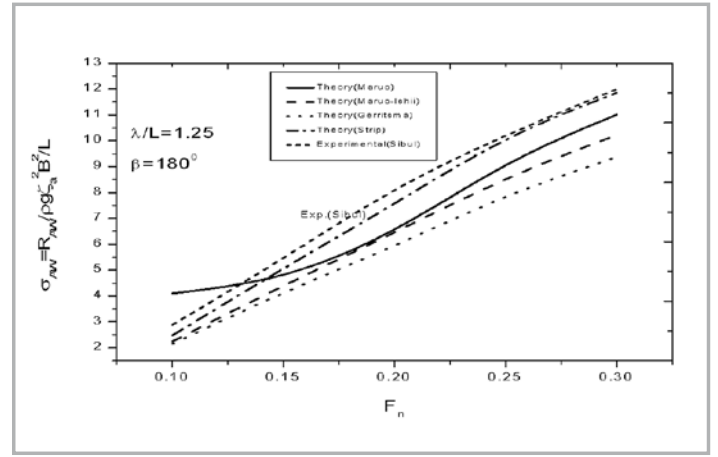


Figure 12: Added resistance coefficient as a function of Froude number at  $\lambda/L = 1.25$  for series 60 ship-3 with  $C_B = 0.80$  in head waves,  $\beta = 180^\circ$

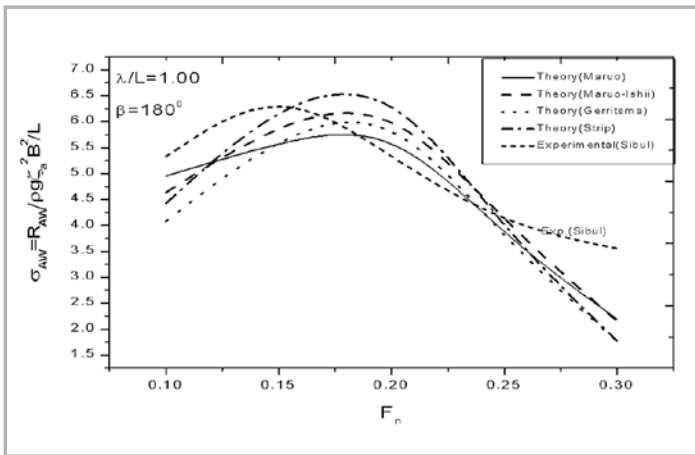


Figure 11: Added resistance coefficient as a function of Froude number at  $\lambda/L = 1.00$  for series 60 ship-3 with  $C_B = 0.80$  in head waves,  $\beta = 180^\circ$

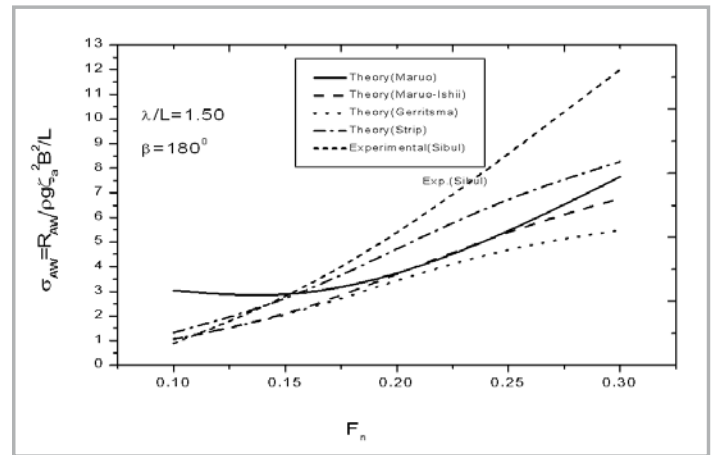


Figure 13: Added resistance coefficient as a function of Froude number at  $\lambda/L = 1.50$  for series 60 ship-3 with  $C_B = 0.80$  in head waves,  $\beta = 180^\circ$

approximately) the situation is just opposite to the previous results, especially when the theoretical results are compared with the experimental ones due to Sibul. The discrepancy between theoretical and experimental results may be due to the fact that at lower wave to ship length ratio all linearised theories fail to predict motion data accurately and this is the inherent limitation of the motion data predicted theoretically, for example Beck [7]. Overall Maruo-Ishii's method is seen to give the better prediction at higher Froude number ( $>0.15$  approx.) especially when comparison is made with the experimental results due to Gerritsma. However, theoretical results obtained by Maruo, Gerritsma and Strip method give similar results when compared to each other. Again discrepancy between experimental results due to Sibul and Gerritsma may be due to the fact that there might be variation in results from laboratory to laboratory due to instrumental inaccuracies and techniques adopted [6]. Moreover the experimental curves represent the mean line drawn through experimental points. It may be mentioned here that the motion amplitudes and phase angles are necessary input for calculation of added resistance by all the theories of added resistance, which has a considerable impact on the results of added resistance as mentioned earlier.

Figure 7 shows overall poor agreement between the experimental and employed theories particularly at the operating speed range of vessels ( $F_n = 0.16-0.25$ ). One possible

explanation for the discrepancy of the experimental results with the theoretical ones may be due to the motion data used for added resistance theories. In this study, motions data have been obtained by employing New Strip Theory (NSM) which, may give large values of motion amplitudes particularly at wave to ship length ratio 1.00, and this is reflected by the theoretical curve for added resistance being too high when compared with experimental ones. But overall Maruo's and Gerritsma-Beukelman's method give good agreement with the experimental results compared to other methods.

Figures 8 and 9 show overall good agreement among the results obtained by employed theories methods and experimental ones, although there are some discrepancies between them. The discrepancy may be attributed due to discrepancy in motion results. It may be noted that added resistance results are very much dependent upon accurate motion data as mentioned earlier. So the discrepancy would have been minimised if experimental motion data could have been used for calculation of added resistance. In the present study, motion data have been obtained by Ordinary Strip Method as mentioned earlier. Similar observations have been made by Beck [7]. Moreover, there may be variation in experimental results from laboratory to laboratory [6]. In Figure 7, Maruo-Ishii's and Gerritsma-Beukelman's method are seen to give close agreement compared to other methods especially when computation is made

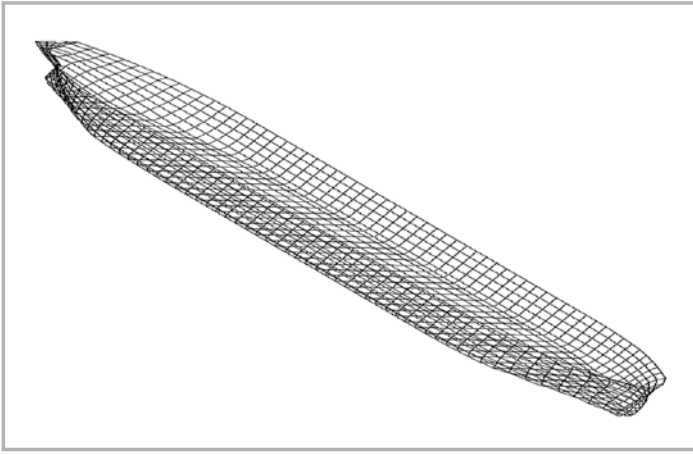


Figure 14: Typical discretisation of wetted surface of fuller form ship

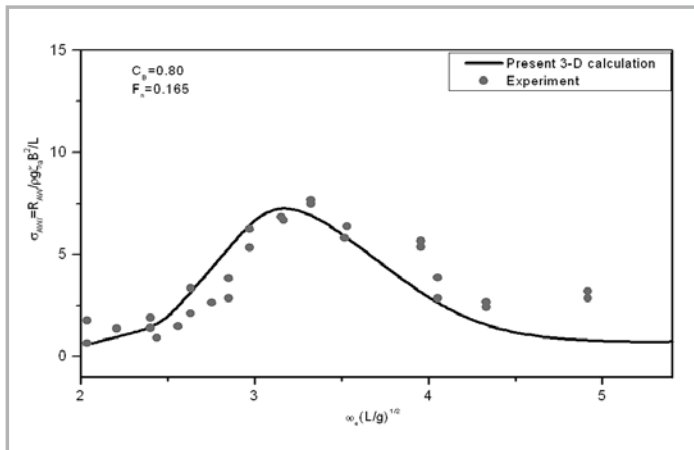


Figure 15: Non dimensional added resistance for different methods for series 60 ship-3 with  $C_B = 0.80$  in head waves,  $\beta = 180^\circ$

with experimental results due to Sibul. On the other hand in Figure 9, Maruo's method is seen to give better agreement than other methods. When comparison is made, the experimental results due to Gerritsma and Strip method is seen to give better agreement compared to experimental results due to Sibul.

Figure 10 depicts very poor agreement almost through out the entire range of ship speed between employed theories and experimental results. This may be due to the fact that almost all theories of added resistance are based on some slender ship assumptions which fail to account for the back scattering of the incident waves, *i.e.*, added resistance due to wave reflection especially for ships of fuller forms at low wavelength-ship length ratios. Similar phenomenon have also been observed by Fujii-Takahashi [14] and Beck [7].

Figure 11 shows all the employed methods under predict the added resistance than experimental results at lower Froude number ( $<0.18$  approximately) and at higher Froude number ( $>0.25$  approximately), but over predict in the intermediate range *i.e.* ( $F_n = 0.18\sim 0.23$  approximately). Overall Maruo's theory [10] and Gerritsma-Beukelman's theory [11] give better agreement in the intermediate range ( $F_n = 0.18\sim 0.23$ ).

Figures 12 and 13 show that all the four methods slightly under predict the added resistance compared to the experimental results. But, overall Strip method gives better prediction through out the entire range of Froude numbers. Maruo's method is seen to over predict the experimental results in the lower Froude numbers.

Figure 14 shows the typical grid modelling of wetted surface area of a fuller form ship used for the numerical calculation and it is well understood that the smaller panel size will be desired to model the hull shape perfectly. But one of the major concerns of using more panels to represent the hull is the CPU-time. CPU-time for calculating the 3-D potential problem consists of two components: one is setting up of the matrix element and the other is solving the matrix equation and first one is proportional to the number of nodes or number of elements to represent the hull. So suitable panel division is a compromise between the modeling the hull geometry accurately and the constraint of increasing CPU-time [15]. Figure 15 shows the numerical results of Series60 ship of block coefficient 0.80 which represent fuller-form ship, and here present 3-D numerical method provide a good approximation of the added resistance of ship in waves with respect to experimental results [16].

## 5.0 CONCLUSION

From the results and analysis, the following conclusions may be drawn:

- (1) Added resistance predicted by a given method may vary considerably depending on the method used for obtaining ship motions. Comparison of different methods does not therefore provide a useful guidance. The method of calculating the added resistance of a ship in waves is therefore a matter of choice
- (2) The present examination suggests that of the four methods employed in head waves, the method by Maruo, Maruo-Ishii and Gerritsma-Beukelman provide reasonable predictions, especially in the range of wave length to ship length ratios from 0.8~1.5 approximately for fine and medium ship forms. On the other hand Strip's method provides reasonable predictions at wave length to ship length ratios greater than 1.25 for full ship forms. But all the methods fail to predict at small wavelengths especially for full ship forms.
- (3) All the methods have some limitations and so it may be concluded that the practical method for calculating resistance increase with sufficient accuracy is not available yet. But overall prediction shows that Maruo and Gerritsma-Beukelman's method may be applied for reasonable prediction, specially for fine and medium ship forms.
- (4) As expected, 3-D Green function method seems to give better prediction for fuller-form ship, but computational volume and CPU-time are very much higher than any 2-D approaches. ■

## NOMENCLATURE:

$\bar{A}$	amplitude of radiation wave/ heave amplitude
$b_n$	two-dimensional sectional damping coefficient
$B$	ship beam
$c$	Wave celerity
$C_B$	block coefficient
$C_M$	midship section coefficient
$C_0 K_4$	added mass of the section
$dm$	mean draft(sectional area/water line breadth)

$F_n$	Froude number
$g$	acceleration due to gravity
$G$	Green's function
$m$	Transformation function
$n$	Components of normal vector
$P$	Arbitrary point in fluid
$Q$	Point on body surface
$L_{BP}$	ship length
$L.C.B.$	Longitudinal Center of Buoyancy
$R_{AW}$	added resistance
$U$	ship speed
$\kappa$	wave number
$\sigma_{AW}$	added resistance coefficient
$\zeta_a$	incident wave amplitude
$\beta$	angle between mean wave direction and ship heading
$\xi$	non-dimensional x-axis
$\eta$	non-dimensional water line breadth
$\zeta_o$	non-dimensional amplitude of heave
$\psi_o$	non-dimensional amplitude of pitch
$x_G$	x co-ordinate of center of gravity
$p$	ratio of wave to ship length
$\varepsilon$	phase angle
$\varepsilon_{zw}$	phase difference between heave and wave
$\varepsilon_{\theta z}$	phase difference between pitch and heave
$\rho$	mass density of water
$\omega_e$	frequency of encounter
$\omega_L$	non-dimensional circular frequency of encounter
$\lambda$	wavelength

- [5] Maruo, H. (1963). "Resistance increase in waves." Society of Naval Architects of Japan (SNAJ), 60th Anniversary Series, Vol.8
- [6] Baree, M.S. (2000). "Added resistance of ships in waves." Research Report, Ship Design Laboratory, Yokohama National University, Japan, May.
- [7] Beck, R.F. (1967). "The Added Resistance of Ships in Waves." Department of Naval Architecture and marine Engineering, MIT, Report 67-9.
- [8] Shintani Atsushi. (1973). "Some notes on approximate methods of the calculation of resistance increase of ships in wave." Journal of Kansai Soc. of Naval Arch., Japan, No.150.
- [9] Storm-Tejsen *et. al.* (1973). "Added Resistance in Waves." Transactions of the Society of Naval Architects and Marine Engineers, Vol. 81.
- [10] Maruo, H. and Ishii, T. (1976). "Calculation of Added Resistance in Head Waves by Means of a Simplified Formula." Journal of the Society of Naval Architects of Japan, Vol.140.
- [11] Gerritsma, J., Beukelman, W. (1972). "Analysis of the Resistance Increase in Waves of a Fast Cargo Ship." Appendix 5 of the Report of the Seakeeping Committee, Proc. Proc., 13th ITTC, Vol.2, pp171-185.
- [12] Tasai, F. and Takagi, M. (1969). "Theory and Calculation of Ship Responses in Regular Waves." the First Symposium on Seaworthiness of Ships, the Society of Naval Architecture of Japan (in Japanese).
- [13] Wehausen, J.Y. and Laitone (1960). "Surface Waves." *Hundbuck der Physic*, Vol 9, Springer, pp 446-778.
- [14] Fujii H., and Takshashi T. (1975). "Experimental Study on Resistance Increase of a Ship in Regular Oblique Waves." 14th ITTC, Seakeeping Committee, pp.351-360.
- [15] Zakaria, N. M .G. (2006). "A design aspect on the seakeeping performances of ships by 3-D Green function method with forward speed." Doctoral Thesis, Dept. of Environmental & System Sciences, Yokohama National University, Japan, March.
- [16] Salvansen, N. (1978). "Added resistance of ships in waves, journal of hydronautics, Vol.12, no.1.

## REFERENCES

- [1] Havelock, T.H. (1942). "The Damping of Heaving and Pitching Motion of a Ship" *Philosophical Magazine*, Vol.33, pp.666-673.
- [2] Boese, P. (1970). "Eine einfache methode zur berechnung der wind-erstansersshohung eines schiffes im seegang". *Schiffstechnik* 17(86).
- [3] Hearn, G.E., Tong, K.C. and Lau, S.M. (1987). "Hydrodynamic Models and their Influence on Added Resistance Predictions". *International Symposium on Practical Design of Ships and Mobile Units (PRADS)* pp 302-316.
- [4] Kashiwagi, Masashi. (1992). "Added resistance, wave-induced steady sway force and yaw moment on an advancing ship." *Journal Ship technology research Schiffstechnik*, vol. 39, February.

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