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Prediction of excess resistance of ships by 3-D near field approach and its comparison with some alternative methods

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ABSTRACT: Second-order forces have been widely investigated using 2-D methods since the early 60's and more recently also using 3-D methods. The present work uses near field approach of 3-D Green Function method as well as some alternative 2-D methods for calculating the second order forces or excess resistance in waves. In this paper, results for excess resistance using both 3-D near field approach and 2-D methods are presented and compared with other published data and experimental measurement. The application of present 3-D approach to sea keeping problems of some complex geometry like Series 60 hull and a bulk carrier ship demonstrates that 3-D near field approach is valid in predicting added resistance of ship in waves and also provides better results in many cases particularly for blunt shaped slow speed vessel.

KEY WORDS: Second order force, Ship motion, Near-field approach, Momentum conservation method.

1 INTRODUCTION

Accurate prediction of second order force or excess resistance in waves is an important part of ship performance due to its economic implications in terms of selection of engine power, fuel consumption and route time evaluation. This is why design offices consider this problem of excess resistance from the early stage of design. Usually performance evaluation of a ship in a seaway is based on the calm water resistance without properly considering the weather conditions prevailing in the operating route. Based on the tradition or experience of similar ship sailing on the same route, the magnitude of excess resistance is often considered as 10%-30% of calm water resistance. Excess resistance in waves can be determined from model tests or analytical methods. Model experiments are carried out in regular or irregular head seas and excess resistance is measured as the difference between the time average resistance in waves and the calm water resistance measured at the same speed. On the other hand there are two major analytical approaches to estimate excess resistance due to waves. One is far-field method based on the momentum-conservation theory proposed by Maruo [1] and the other approach is a near field method by integrating pressures on the body surface. For many past years, the former approach has been widely applied due to its simplicity and efficiency, which has no need to compute hydrodynamic pressure on the complicated body surface. Recently due to rapid growth of computer technology, the near field method is being acclaimed as an alternative method. In this paper near field approach of 3-D Green Function method has been applied for solving seakeeping problems in the frequency domain. Although, the mathematical formulation of the Green function method have been well established, but the numerical solutions have been presented in limited circumstance by many authors. The present study uses Kelvin singularity with translating and pulsating Green function presented by Wehausen and Laitone [2] and Inglis & Price [3]. Hess & Smith [4] method is applied to obtain the density of the singularities distributed over the hull surface. A computer code has been developed to solve the problem in seakeeping such as frequency dependent hydrodynamic coefficients, motion responses etc. The motion response is then used to calculate total potential & its derivatives for the prediction of second order forces of a ship in waves. Before applying this numerical calculation to real ship form, computer code has been validated using Lewis form mathematical model. All computed results of this mathematical model using 3-D methods are compared with available experimental results. After validation of present code, some real form ships like Series 60 ship form of C_B=0.6,0.7 & 0.80 and a fat bulk carrier ship have been taken for numerical computation of excess resistance using 3-D near field method. Furthermore, the numerical computation has been extended to simple 2-D methods in order to compare the same results with 3-D near field method. Finally on the basis of numerical results of different types of real ship form, some conclusions regarding the sensitivity of ship form on the prediction of excess resistance of ships in waves.

2 THEORETICAL BACKGROUND

2.1 Boundary value problem

The adoption of potential theory is a typical approach to tackle the seakeeping problems. When a floating body moving with forward velocity U through an incompressible ideal fluid is under wave excitation, the boundary value problem for velocity potential can take the following form:

$$\nabla^2\phi_0 = 0 \text{ and } \nabla^2\phi = 0 \text{ in fluid domain} \quad (1)$$

The body hull boundary conditions,

$$\frac{\partial \phi_j}{\partial n} = n_j - Um_j \text{ (for j=1-6) } \& \quad \frac{\partial \phi_7}{\partial n} = -\frac{\partial \phi_w}{\partial n} \quad (2)$$

The free surface condition

$$\left(-i\omega_e\phi_j - U\frac{\partial \phi_j}{\partial x}\right)^2 + g\frac{\partial \phi_j}{\partial z} = 0 \text{ at z = 0} \quad (3)$$

Where, $(n_1, n_2, n_3) = \overline{N}$ are the components of normal vector, & $(n_4, n_5, n_6) = (\bar{r} - \overline{r_g}) \times \overline{N}$ are the components of normal vector with respect to rotational motion $(\bar{r} - \overline{r_g})$, $\bar{r}$ is distance from the hull boundary surface of the ship, $\bar{r}_g$ is distance from the C.G of the ship, $\omega_e = \omega - kU\cos\chi$, frequency of encounter, $k = \omega^2/g$ is wave number, g = gravitational acceleration.

Further,

$$(m_1, m_2, m_3) = \overline{m} = (\overline{n}.\nabla)\nabla(x + \frac{1}{U}\phi_0) \quad (4)$$

$$(m_4, m_5, m_6) = \bar{r} \times \overline{m} = \bar{r} \times \overline{m} - \nabla(x + \frac{1}{U}\phi_0) \quad (5)$$

The potential field can be written as

$$\phi_T = -Ux + \phi_0 + \phi e^{-i\omega t} \quad (6)$$

Where, ϕ_0 is a time independent potential field due to ship steady forward motion and ϕ is the periodic potential field due to the ship's oscillatory motions which can be expressed as follows:

$$\phi = \phi_w + \phi_7 + \sum_{j=1}^{6} -i\omega_e \overline{X}_j \phi_j \quad (7)$$

where ϕ_j is the radiation potential due to the j-th mode of motion and $\overline{X}_j$ is the complex motion amplitude in j-th mode. The cases j=1,2,3,4,5 & 6 correspond to surge, sway, heave, roll, pitch, and yaw, respectively. Again, ϕ_w is the incident wave potential that can be expressed as,

$$\phi_w = -\frac{i\zeta_A\omega}{k}e^{kz}e^{ik(x\cos\chi + y\sin\chi)} \quad (8)$$

The potential function ϕ can be obtained by introducing a singularity distribution over the hull boundary surface. If $\sigma_j(Q)$ is considered as the strength of source distributed over the hull boundary surface at point Q then the potential ϕ_j at any point P inside the fluid can be expressed as:

$$\varphi_j(P) = -\frac{1}{4\pi}\left[\iint_{S_H} G(P,Q)\sigma_j(Q)\mathrm{d}s + \frac{U^2}{g}\oint_{C_H} G(P,Q)\sigma_j(Q\right. \quad (9)$$

Where, *G(P,Q)* represent the velocity potential at the field point *P(x,y,z)* due to a source at the point *Q(x,y,z)* and the second term of Eqn.(9) is the contour integral over the intersection of the hull surface S_H and the free surface. Detailed numerical technique of solving velocity potential has been given in [5].

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 :

$$F_{ij} = \rho\iint_s\left(\omega_e^2\overline{X}_j\varphi_j + i\omega_e U\overline{X}_j\frac{\partial\varphi_j}{\partial x}\right)n_i\mathrm{d}s \quad (10)$$

Added mass and damping coefficients are obtained by:

$$a_{ij} = -\rho\,\mathrm{Re}\iint_s\left(\varphi_j + i\frac{U}{\omega_e}\frac{\partial\varphi_j}{\partial x}\right)n_i\mathrm{d}s \quad (11)$$

$$b_{ij} = -\rho\omega_e\,\mathrm{Im}\iint_s\left(\varphi_j + i\frac{U}{\omega_e}\frac{\partial\varphi_j}{\partial x}\right)n_i\mathrm{d}s \quad (12)$$

Wave exciting forces and moments can be obtained by

$$\overline{F}_i = -i\rho\omega_e e^{-i\omega_e t}\iint\left\{(\varphi_w + \varphi_7) + i\frac{U}{\omega_e}\frac{\partial(\varphi_w + \varphi_7)}{\partial x}\right\}n_i\mathrm{d}s \quad (13)$$

(1)

2.2 Formulation of second order force by near field approach

By using Bernoulli's equation and Taylor expansion, pressure can be evaluated and the second order force is provided by integrating second order pressure over the body surface. The fluid motion can be described by means of expansion of velocity potential assuming motion to be small parameter ε :

$$\Phi = \Phi_1 + \Phi_2 + O(\varepsilon^3)$$
$$\Phi_1 = O(\mathcal{E}) \ \& \ \Phi_2 = O(\varepsilon^2) \tag{14}$$

The force on the body can be expressed as:

$$F_k = F_k^{(0)} + F_k^{(1)} + F_k^{(2)} + O(\varepsilon^3) \tag{15}$$

Where,

$$F_k^{(0)} = -\iint_{s_b} \rho g z n_k \, ds, \tag{16}$$

$$F_k^{(1)} = \iint_{s_b} -\rho \frac{\partial \varphi_1}{\partial t} n_k \, ds \tag{17}$$

$$F_k^{(2)} = -\iint_{S_b} \left[\rho \frac{\partial \varphi_2}{\partial t} + \rho \frac{(\nabla \varphi_1)^2}{2} \right] n_k \mathrm{d}s - \iint_{\Delta S_b} \left[\rho g z + \rho \frac{\partial \varphi_1}{\partial t} \right] n_k \mathrm{d}s \tag{18}$$

S_b denotes the wetted surface of the body under the mean water line, ΔS_b varies with time due to wave elevation and n is the outward unit normal vector on the surface of the body.

Neglecting second order hydrostatic reaction forces due to second order displacement under the influence of the mean second order wave exciting force, it can be seen that second order pressure is derived from second order potential in the Bernoulli's equation and the interaction between the ship motion and the gradient of the first-order pressure. In this paper, the second order potential is neglected since it will not contribute to the mean second order excess resistance or drift force or moment. Thus, excess resistance can be expressed as:

$$F_k = -\iint_{s_b} \rho \frac{\nabla \phi_1 . \nabla \phi_1^*}{4} n_k ds + \oint_{MWL} \frac{1}{4} \frac{\rho}{g} \left[\frac{\partial \phi_1}{\partial t} \right]^2 n_k ds \tag{19}$$

3 VALIDATION STUDY

For the validation of 3-D numerical code, a Lewis form mathematical model, whose principal particulars are shown in Table 1, has been taken. Fig.1 shows the distribution of panels for the numerical calculation. The numerical results of hydrodynamic coefficients at Froude no. 0.2 given by 3-D Green function method are compared with experimental results as well as other numerical results based on the Slender ship theory [6]. Fig.2 to Fig.5 show non-dimensional added mass & damping coefficient for heave and pitch mode & these figures depict relatively good agreement between experimental and the present 3-D numerical calculations for wide range of frequencies although there are some discrepancies between the experimental and other numerical results in the low frequency range specially for heave and pitch added mass coefficient. The present numerical calculation seems to give better prediction than slender ship theory. Figs 6-7 show the numerical calculation of exciting forces and moments in head waves and generally the numerical value of exciting force and moment remain more or less same in spite of changing forward speed. The reason may be that the Froude-Krylov forces or moments are the dominant contributions to the wave exciting forces in head sea. The present numerical calculation shows overall very good agreement with the experimental results.

Table 1: Particulars of Lewis form model

Length	L (m)	4.0
Breadth	B (m)	0.50
Depth	D (m)	0.40
Draft	d (m)	0.25
Displacement	Δ (m^3)	0.25
Block Coeff.	C_B	0.50
Prismatic Coeff.	C_P	0.60
Midship Coeff.	C_M	0.833
L/B Ratio	-	8.0

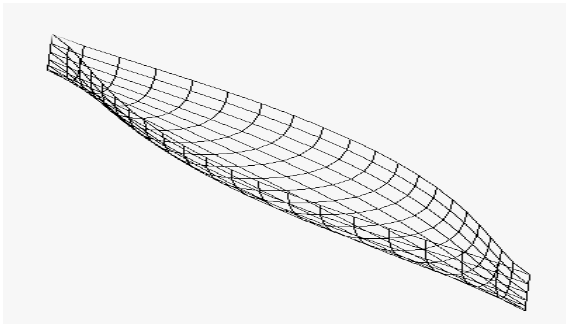

Fig.1 Panel distribution of Lewis-form ship

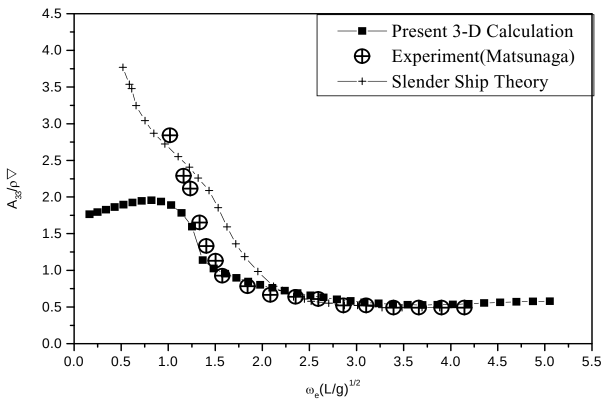

Fig. 2 Heave added mass coefficient at Fn=0.20

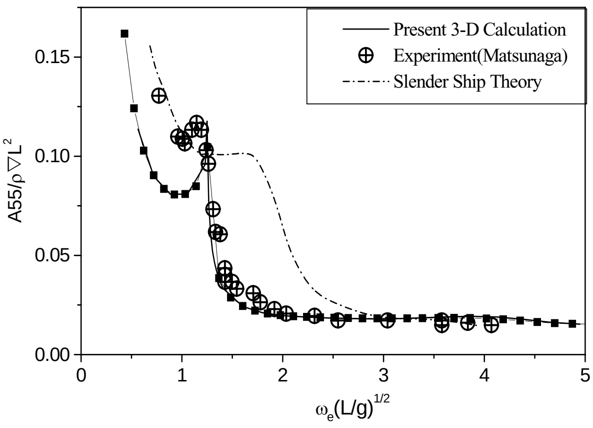

Fig. 3 Pitch added mass coefficient at Fn=0.20

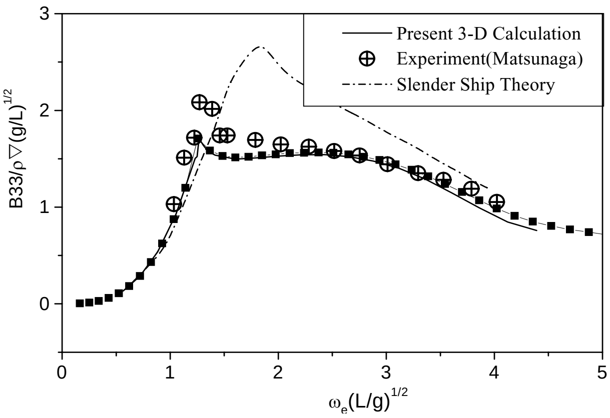

Fig. 4 Heave damping coefficient at Fn=0.20

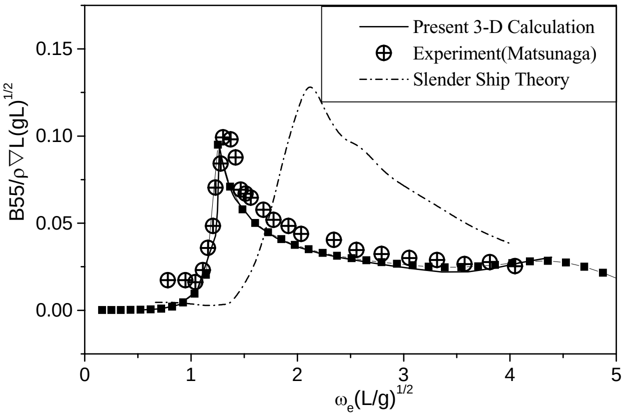

Fig. 5 Pitch damping coefficient at Fn=0.20

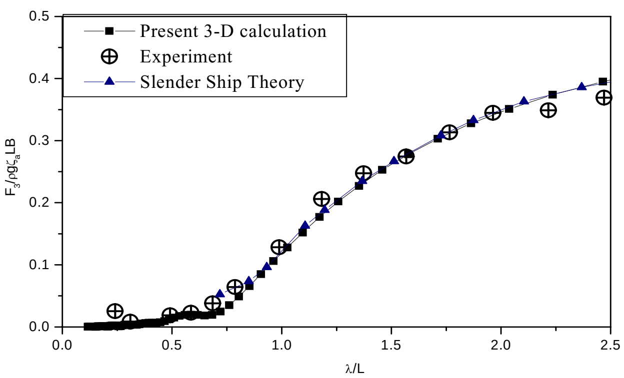

Fig. 6 Heave exciting force coefficient at Fn=0.20 in head waves

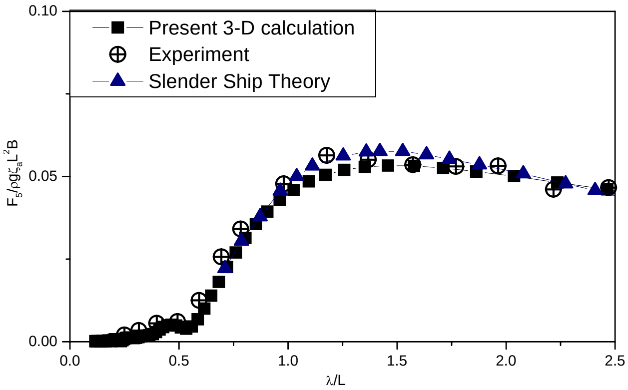

Fig. 7 Pitch exciting force coefficient at Fn=0.20 in head waves

4 NUMERICAL RESULT AND DISCUSSION

Different floating bodies have been considered for calculating excess resistance of ships in waves using 3-D near field method. The numerical results have been compared with experimental data as well as other 2-D approaches like conservation of momentum approach given by Maruo and radiated energy approach given by Gerritsma & Beukelmen. The excess resistance R_{AW} has been non-dimensionalzed according to following:

$$\sigma_{AW} = \frac{R_{AW}}{\rho g (B^2 / L) \zeta^2}$$

It may be mentioned here that while calculating motion responses in case of 2-D approaches, New Strip Method (NSM) has been used and detailed numerical techniques has been given in [7] and experimental data had been taken from the reference [8-10].

4.1 The Series 60 ship

Series 60 ships of C_B=0.60, 0.70 & 0.80 have been taken for numerical calculation in head waves. Also, these different range of hull form will show the effect of hull fullness on excess resistance prediction. From the Figs 8-10, it is seen that present numerical calculation show better agreement 2-D based momentum conservation or radiated energy method specially around the resonance region where 2-D methods usually over-predict the value largely. As shown in Fig.10, for higher wave length to ship length ratio, excess resitance is underestimated by a factor of 2 especially for series 60 ship of C_B=0.80.

4.2 The ore / bulk carrier ship

The present numerical calculation has been tested for the fat ship of following particulars:

Items	Ship	Model
L_{PP} /m	285.0	2.9113
B /m	50.0	0.5118
d /m	18.5	0.1890
Lcb (% L_{PP})	-3.83	-3.83
C_B	0.829	0.829

The numerical results of excess resistance co-efficient for this ship have been shown in Figs.11~13 for different Froude no. with head sea condition. Comparison of the present calculation with towing tank results as well as numerical results given by semi 3-D theory [11] have also been shown. For slower speed case as shown in Fig.11, the present 3-D near field method overestimated the experimental data especially for the case of shorter wave to ship length ratio. For Froude no. 0.10, present numerical calculation slightly under-predict the experimental value, but overall agreement is better than 2-D based momentum conservation method & semi 3-D theory. For the case of Froude no. 0.15, the present numerical result follows the trend of the experimental data although underpredict the peak value as shown in Fig.13. It is quite surprising to see that numerical results shift the peak value with the increase of Froude no., but this trend is not evident for the case of experimental data.

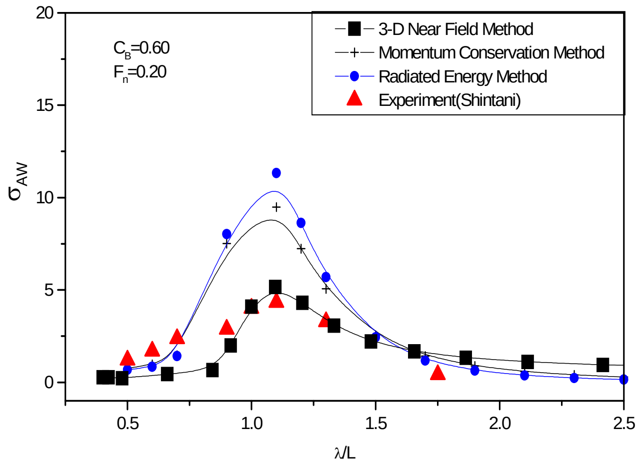

Fig. 8 Excess resistance co-efficient of Series 60 ship with C_B=0.60 at Fn=0.2 in head sea

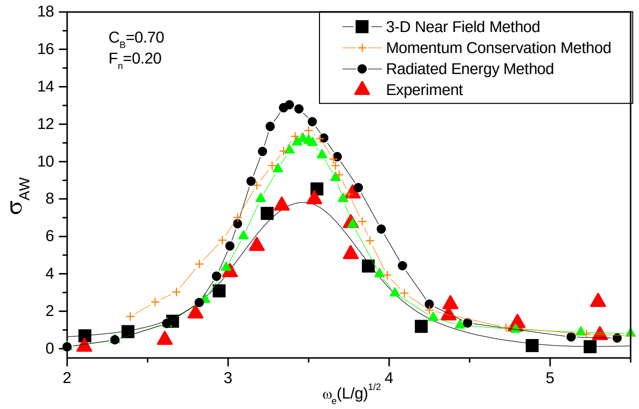

Fig. 9 Excess resistance co-efficient of Series 60 ship with C_B=0.70 at Fn=0.2 in head sea

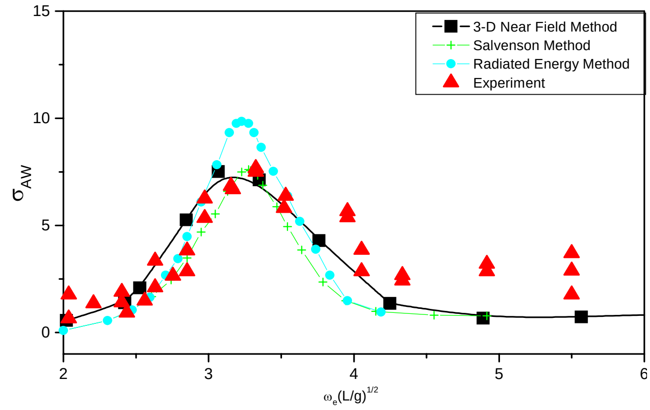

Fig.10 Excess resistance co-efficient of Series60 ship with C_B=0.80 at Fn=0.165 in head sea

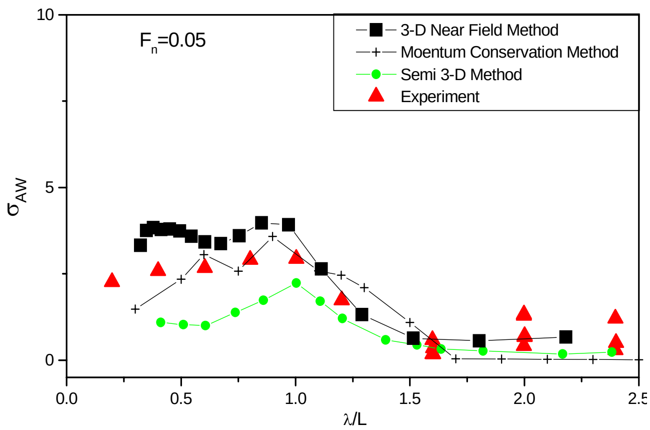

Fig.11 Excess resistance co-efficient of bulk-carrier ship at Fn=0.05 in head sea

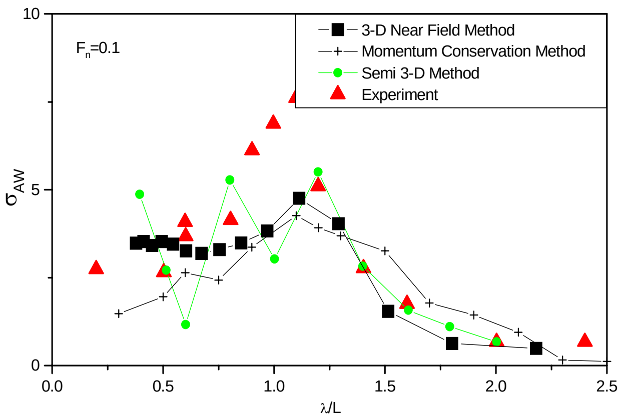

Fig.12 Excess resistance co-efficient of bulk-carrier ship at Fn=0.1 in head sea

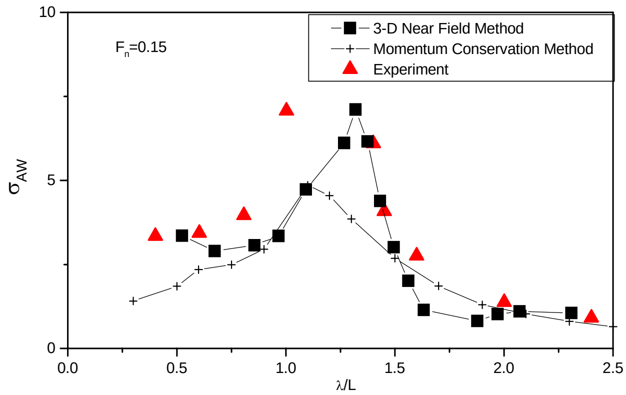

Fig.13 Excess resistance co-efficient of bulk-carrier ship at Fn=0.15 in head sea

5 CONCLUSIONS

Excess resistance of ships in waves has been calculated in this paper using 3-D near field approach. While validating the numerical results with the experimental results for the case of Lewis form ship, overall very good agreement has been found. For numerical results of Series60 ships with CB=0.6, 0.7 & 0.80 in head waves for different forward speed, it is seen that the present 3-D naear field approach gives better prediction than classical 2-D approaches, especially around resonance region where 2-D approaches generally over-predict the experimental value. For a low-speed blunt bulk carrier ship, the present numerical prediction of excess resistance gives reasonable prediction for head sea. And overall, present 3-D numerical calculation gives better prediction than the numerical results of semi 3-D & 2D based theory for the case of fuller form ship, although computational time for present 3-D case is much bigger compared two Semi 3-D or 2-D methods

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