Free Surface Potential Flow around Multi-Hulls in Shallow Water Using a Potential Based Panel Method [*1]

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The present paper investigates the shallow water effect on the hydrodynamic characteristics of lifting body such as wave resistance, sinkage and trim using a potential based boundary element method. The surfaces are discretized into flat quadrilateral elements and the influence coefficients are calculated by Morino's analytical formula. The body boundary condition is linearized about the undisturbed position of the body and the free surface condition is linearized about the mean water surface by the systematic method of perturbation. The results of investigation provide a better understanding the effect of hull separation on the wave resistance of catamaran hull. The influence of water depth on trimaran is, in principle, the same as the influence of water depth on mono hull in the sense that the same type of subcritical, critical and supercritical region is recognized. The peak of wave resistance curve and wave pattern at the critical speed check the validity of the computer scheme.

Keywords : *Wave Making Resistance, Lifting Body, Shallow Water, Free Surface, Boundary Element Method, Sinkage and Trim.*

1. Introduction

The prediction of hydrodynamic forces acting on a lifting body plays an important role in the design of its hull form. The catamaran model is composed of two monohulls and the pressure distribution on inner and outer side of each mono hull is different. As a result each mono hull of catamaran configuration behaves like a lifting body. But the trimaran configuration is composed of main hull with two small outriggers. Since the interior flow between outrigger and main hull is different form the exterior flow, the distribution of pressure on inner and outer side of each outrigger is different and only outriggers are considered as lifting bodies. So it is important to know the lifting effect on the hydrodynamic characteristics of such multihulls. Jiang et al.[1)] theoretically investigate the wave making of a fast catamaran moving uniformly in a rectangular shallow-water channel using the mathematical technique of matched asymptotic expansions. The mutual hydrodynamic interaction between two mono hulls is approximated by means of sectional blockage coefficient in cross flow as well as by a suitable Kutta condition at the stern. Millward et al.[2)] have investigated the interference effects and determined the wave making resistance of a number of catamaran hulls in deep water over a range of Froude numbers up to unity for several hull separations ($0.2 < \delta/L < 0.5$) but there is no information available for catamaran in shallow water.

Suzuki et al.[3)] use modified Rankine source method for the prediction of a trimaran hull and then compare the calculated results with the experiments. Bruzzone et al.[4)] have carried out an experimental and theoretical investigation based on Rankine source panel method on various configurations of a Wigley trimaran in deep water. For each condition, resistance, sinkage, trim and wave profiles along longitudinal cuts have been measured. A similar analysis has also been car-

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ried out by Gligorov and Hofman[5] in shallow water to evaluate the wave resistance and wave pattern by a numerical approach based on the theory derived by Lyakhovitsky[6].

Ships such as patrol boats can achieve speeds which may equal or even exceed the critical speed for a particular depth of water and can be classified as moving at high subcritical or supercritical speeds. It becomes important to be able to predict what effect may occur in different water depth at these higher speeds. Ship squat or under keel clearance is one of the important phenomena affecting safe operation of ships.

The present work is an extension of Morino's panel method[7] into the influence of finite depth on the hydrodynamic characteristics of the ship such as wave making resistance, sinkage and trim etc. The body and free surface boundary conditions are linearized about the undisturbed position of the body and mean water level respectively by means of Taylor series expansion. A computer program PAFS (Panel Method Applied to Free Surface) is modified to simulate the shallow water effect and then verified with two multi-hulls. The peak of the wave resistance curve and the wave pattern at the critical speed check the validity of the computer scheme.

2. Mathematical Formulation

Let us consider two co-ordinate systems of which $x'y'z'$ is fixed with respect to the ship and xyz is a steady moving frame of reference with a forward speed U in the positive x-direction. The origin of the co-ordinate system-xyz shown in Fig. 1 is located at the calm water surface. The z-axis is upward and the y-axis extends to starboard. The depth of water is h. The fluid is assumed to be inviscid and incompressible and its motion is irrotational such that the velocity potential of the fluid Φ can be defined as

$$\Phi = Ux + \sum_{n=1}^{\infty} \varepsilon^n \phi_n + \delta(s\varphi_s + t\varphi_t) \qquad (1)$$

where ε and δ are two small parameters, ϕ is the steady perturbation potential in absence of sinkage and trim, φ_s is the steady potential due to unit sinkage, φ_t steady potential due to unit trim. s is the sinkage (positive upward) and t is the trim angle (trim by the stern is positive).

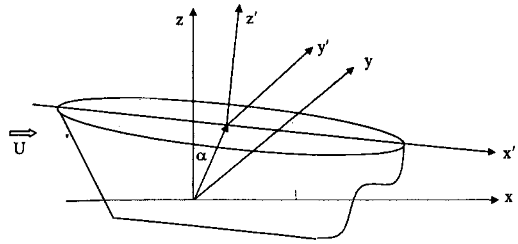


Fig. 1 Definition sketch of a co-ordinate system.

The potential Φ satisfies the Laplace equation

$$\nabla^2\Phi = 0 \text{ in the fluid domain } V \qquad (2)$$

The fluid domain V is bounded by hull surface S_H, free surface S_F, wake surface S_W, sea bottom S_B and the surface at infinity.

2.1 Body Boundary Condition

The boundary condition on the hull surface can be expressed as

(a) Problem without the effect of sinkage and trim
$\nabla\phi_1 \cdot n = -Un_x$ and $\nabla\phi_2 \cdot n = 0$
in which $n = n_x i + n_y j + n_z k$ is the unit normal vector on the surface and is positive into the fluid.

(b) Problem with the effect of sinkage and trim
$\nabla\varphi_s \cdot n = m_3$ and $\nabla\varphi_t \cdot n = m_5$
with
$m_1 i + m_2 j + m_3 k = -(n \cdot \nabla)W$
$m_4 i + m_5 j + m_6 k = -(n \cdot \nabla)(x \times W)$
and $W = U + \nabla\phi_1$

2.2 Free Surface Boundary Condition

The free surface condition is nonlinear in nature and should be satisfied on the true free surface which is unknown and can be linearized as a part of the solution using perturbation method. For second order approximation the velocity potential and the wave elevation can be written as

$$\begin{aligned} \Phi &= Ux + \varepsilon\phi_1 + \varepsilon^2(\phi_2 + s\varphi_s + t\varphi_t) \\ \zeta &= \varepsilon\zeta_1 + \varepsilon^2(\zeta_2 + s\zeta_s + t\zeta_t) \end{aligned} \qquad (3)$$

Using Taylor's series expansion in equation (3), the free surface boundary condition can be obtained as

$$\varepsilon \; : \; \phi_{1xx} + K_0\phi_{1z} = 0 \quad \text{on} \quad z = 0 \qquad (4)$$

$$\varepsilon^2 \; : \; \phi_{2xx} + K_0\phi_{2z} = f(\phi_1) \quad \text{on} \quad z = 0 \qquad (5)$$

$$f(\phi_1) = -\frac{1}{U}\frac{\partial}{\partial x}({\phi_{1x}}^2 + {\phi_{1y}}^2 + {\phi_{1z}}^2) - \zeta_1\frac{\partial}{\partial z}(\phi_{1xx} + K_0\phi_{1z})$$

The free surface boundary conditions due to sinkage and trim can be written as

$$\varepsilon^2 : \phi_{sxx} + K_0\phi_{sz} = 0 \quad \text{on} \quad z = 0 \tag{6}$$

$$\varepsilon^2 : \phi_{txx} + K_0\phi_{tz} = 0 \quad \text{on} \quad z = 0 \tag{7}$$

2.3 Kutta Condition

For the steady lifting flow problem, the potential jump across the wake surface S_W is the same as the circulation around the body and is constant in the streamwise direction.

$$(\Delta\phi)_{on\,S_w} = \phi^+ - \phi^- = \Gamma$$

A kutta condition is required at the trailing edge to uniquely specify the circulation.

2.4 Sea Bottom Condition

The vertical velocity component on the flat bottom surface is zero so that

$$\left.\begin{array}{ll} \varepsilon : \nabla\phi_1 \cdot n = 0 & \varepsilon^2 : \nabla\phi_2 \cdot n = 0 \\ \varepsilon^2 : \nabla\varphi_s \cdot n = 0 & \varepsilon^2 : \nabla\varphi_t \cdot n = 0 \end{array}\right\} \quad \text{on} \quad z = -h \tag{8}$$

2.5 Radiation Condition

Finally it is necessary to impose a condition that there are no waves far upstream of the ship and the waves always travel downstream. The radiation condition is satisfied numerically as discussed in later.

2.6 Calculation of Sinkage and Trim

The fluid pressure acting on the instantaneous wetted surface S_H during oscillatory motions of the ship can be written by Bernoulli's equation

$$p - p_\infty = \frac{1}{2}\rho(U^2 - \nabla\Phi\cdot\nabla\Phi) - \rho g z$$

The pressure at any point on the wetted surface S_H can be expressed in terms of the pressure at the corresponding point of the surface S_0 at mean water level:

$$[p-p_\infty]_{S_H} = \left[1 + (\alpha\cdot\nabla) + \frac{1}{2}(\alpha\cdot\nabla)^2 + \cdots\right][p-p_\infty]_{S_0}$$

α is the oscillatory displacement of the ship and will be obtained from the transformation of the co-ordinate system as $(tz',\ 0,\ s - tx')$. It is assumed that the displacement α is so small that the second order terms may be neglected. The hydrodynamic forces (k =1, 2, 3 indicates surge, sway and heave) and moments (k = 4, 5, 6 indicates rolling, pitching and yawing) in the k-th direction can be represented by

$$F_k = -\int(p - p_\infty)n_k dS \approx F_k^0 + sF_k^s + tF_k^t \tag{9}$$

$$F_k^0 = \rho\int\left\{\frac{1}{2}(W^2 - U^2) + W\cdot\nabla\phi_2\right\}n_k dS$$

$$F_k^s = \rho\int\left\{W\cdot\nabla\varphi_s + \frac{1}{2}\frac{\partial}{\partial z}W^2\right\}n_k dS$$

$$F_k^t = \rho\int\left\{W\cdot\nabla\varphi_t + \frac{1}{2}(z'\frac{\partial}{\partial x} - x'\frac{\partial}{\partial z})W^2\right\}n_k dS$$

Suppose the ship responds to these forces and experiences a sinkage s defined as the downward vertical displacement at $x = 0$ and trim t defined as the bow up angle of rotation about $x = 0$. Now the following equations are obtained from the static equilibrium of forces:

$$F_3 = \rho g\int_{-L/2}^{L/2}(s - tx)f_w(x)dx \tag{10}$$

$$= s\rho g\int_{-L/2}^{L/2} f_w(x)dx - t\rho g\int_{-L/2}^{L/2} f_w(x)xdx$$

$$F_5 = -\rho g\int_{-L/2}^{L/2}(s - tx)f_w(x)xdx \tag{11}$$

$$= -s\rho g\int_{-L/2}^{L/2} f_w(x)xdx + t\rho g\int_{-L/2}^{L/2} f_w(x)x^2dx$$

$fw(x)$ is the width of the water plane area at the still water level and L denotes the length of the ship. Combining equations (9), (10) and (11) following relations are obtained

$$\begin{aligned} s(F_3^S - H_0) + t(F_3^t + H_1) &= -F_3^0 \\ s(F_5^S + H_1) + t(F_5^t - H_2) &= -F_5^0 \end{aligned}$$

These are two simultaneous equations from which we can get the value of s and t. The symbols are defined as follows

$$H_0 = \rho g\int_{-L/2}^{L/2} f_w(x)dx, \quad H_1 = \rho g\int_{-L/2}^{L/2} f_w(x)xdx$$

$$H_2 = \rho g\int_{-L/2}^{L/2} f_w(x)x^2dx$$

2.7 Resistance and Wave profile

The wave resistance can be calculated by integration of the pressure over the area of the hull up to mean water level and including the calculated waterline as follows:

$$R_w = -\int[\frac{1}{2}\rho(U^2-\nabla\Phi\cdot\nabla\Phi)-\rho gz]n_x dS-\frac{1}{2}\rho g\oint_{w1}\zeta^2 n_x dl$$

The equations of the wave elevation can be obtained from equation (3) as

$$\begin{aligned}\zeta_1 &= -\frac{U}{g}\phi_{1x}\\ \zeta_2 &= -\frac{U}{g}\phi_{2x}-\frac{U}{g}\zeta_1\phi_{1xz}-\frac{1}{2g}(\phi_{1x}{}^2+\phi_{1y}{}^2+\phi_{1z}{}^2)\\ \zeta_s &= -\frac{U}{g}\varphi_{sx}\\ \zeta_t &= -\frac{U}{g}\varphi_{tx}\end{aligned}$$

3. The Boundary Element Method

3.1 Integral Equation and its Discretization

Applying Green's second identity to the velocity potential ϕ and the Green's function G, Laplace's equation can be transformed into an integral equation as

$$\begin{aligned}4\pi E\phi(p) &= \sum_{j=1}^{N_H}\int_{S_H}\phi(q)\frac{\partial G}{\partial n_p}dS-\sum_{j=1}^{N_H}\int_{S_H}\frac{\partial\phi(q)}{\partial n_q}GdS\\ &+ \sum_{j=1}^{N_W}\int_{S_W}\Delta\phi(q)\frac{\partial G}{\partial n_p}dS\\ &+ \sum_{j=1}^{N_B}\int_{S_B}\phi(q)\frac{\partial G}{\partial n_p}dS-\sum_{j=1}^{N_F}\int_{S_F}\frac{\partial\phi q}{\partial n_q}GdS\\ E &= 1/2 \quad \text{on } S_H, S_B, S_W\\ &= 1 \quad \text{on } S_F\end{aligned}$$

The Green function that satisfies the Laplace equation is $G = (1/R + 1/R')$. R is the position vector between the field point p and the point of singularity q on the surface and R' is the image of R. N_H, N_F, N_W and N_B are the number of elements in the hull surface, free surface, wake surface and sea bottom respectively. The integral over such an element is calculated according to Morino's analytical formula[8] based on the assumption of quadrilateral hyperboloidal element. Thus a set of linear equations for first order approximation is obtained as follows:

$$[A]\mathbf{x} = [B]Un_{\mathbf{x}} + [C]\nabla\phi_1$$

[A], [B] and [C] are the matrices built up by the Green's function and its derivatives. **x** is the matrix formed by the strengths of sources and dipoles respectively. In order to satisfy the radiation condition the second derivatives of velocity potential in the left hand side of free surface conditions (4) and (5) are computed by Dawson's upstream finite difference operator[9]. The circulation $\nabla\phi_1$ is unknown and will be obtained as described in the next section.

The other derivatives of the velocity potentials with respect to x and y (ϕ_x, ϕ_y) are evaluated after approximating the distribution of velocity potential by a quadratic equation passing through the potentials at the centroids of three adjacent panels. This method of numerical differentiation is proposed by Yanagizawa[10]. For the evaluation of ϕ_n the velocity potential are calculated at three different positions along the normal direction and the same procedure is applied to get the derivative with respect to n as described earlier.

The matrix of linear system of equations is solved by LU decomposition method. The advantage of using LU technique is that we only need to partition LU in one time for first order problem and subsequently we will apply it for higher order problems. Therefore, the CPU time can be saved.

3.2 Implementation of Pressure Kutta Condition

In this section we shall discuss the implementation of the pressure Kutta condition at the trailing edge of the lifting body. The perturbation velocity potential on the boundary surface is discretized as follows:

$$[A]\mathbf{x} = [B]Un_{\mathbf{x}} + [C]\nabla\phi_{1m} \tag{12}$$

The quantity $\Delta\phi_{1m}$ represents the jump in the potential at the m-th wake strip and will be determined by applying the Kutta condition at the trailing edge of the body.

The Kutta condition requires that the velocity at the trailing edge of the body be finite. In the numerical formulation of the problem, we will implement the Kutta condition by requiring that the pressure at the upper and lower control points be equal and this can be expressed as

$$\Delta p_m = p_m^U - p_m^L = 0 \quad \text{for} \ m = 1...M \tag{13}$$

where, M is the number of elements at the trailing edge of the body. A direct solution of the resulting system of equations (12) and (13) is difficult due to the non-linear character of the equation (13). Therefore, an iterative solution algorithm[11] is employed. At the k-th iteration, we solve the linear system of equations (12) with the values of $\Delta\phi_m^{(k)}$ determined from the $(k-1)^{th}$ iteration. The values of $\Delta p_m^{(k)}$ are given by equation (13), with the values of the pressures P_m^U and P_m^L determined from Bernoulli's equation. If $\Delta p_m^{(k)}$ is not equal to zero with the desired tolerance ($\varepsilon = 1 \times 10^{-5}$), we proceed to another iteration with $\Delta\phi_m^{(k+1)}$ determined as follows:

$$[\Delta\phi]^{k+1} = [\Delta\phi]^k - [J]^{-1}[\Delta p]^k \tag{14}$$

where

$$[\Delta p] = [\Delta p_1, \ \Delta p_2 \ \cdots\cdots \ \Delta p_M]^T$$

$$[\Delta\phi] = [\Delta\phi_1, \ \Delta\phi_2 \ \cdots\cdots \ \Delta\phi_M]^T$$

and $[J]^{-1}$ is the inverse of the Jacobian matrix, the elements of which are defined as

$$J_{ij} = \left[\frac{\partial(\Delta p_i)}{\partial(\Delta\phi_j)}\right] \begin{cases} i & = 1 \cdots M \\ j & = 1 \cdots l \end{cases}$$

with the values of the partial derivatives approximated numerically as:

$$\frac{\partial(\Delta p_i)}{\partial(\Delta\phi_j)} \approx \frac{\Delta p_i^{(\beta)} - \Delta p_i^{(0)}}{\Delta\phi_j^{(\beta)} - \Delta\phi_j^{(0)}}$$

where $\Delta p_i^{(0)}$ corresponding to the initial guess $\Delta\phi_j^{(0)}$ and $\Delta p_i^{(\beta)}$ corresponding to $\Delta\phi_j^{(\beta)}$, a perturbation to the initial guess defined as

$$\Delta\phi_j^{(\beta)} = (1-\beta)\Delta\phi_j^{(0)} \quad l = j$$

and

$$\Delta\phi_l^{(\beta)} = \Delta\phi_l^{(0)} \qquad \text{for } l \neq j$$

where β is a very small number which can be 0.01. The initial guess $\Delta\phi_m^{(0)}$ is taken as the difference of the potentials at the upper and lower control points at the trailing edge of the body.

$$\Delta\phi_m^{(0)} = \phi_m^{(U)} - \phi_m^{(L)}$$

The initial guess is therefore the original Morino's Kutta condition.

4. Discussion of Results

To investigate the shallow water effect on wave resistance and wave pattern around multihulls, the method has been tested for catamaran and trimaran hulls. For both catamaran and trimaran configurations we choose Wigley hull form having the equation for its hull surface:

$$y(x,z) = \frac{B}{2}\left(1 - \frac{z^2}{T^2}\right)\left(1 - \frac{4x^2}{L^2}\right)$$

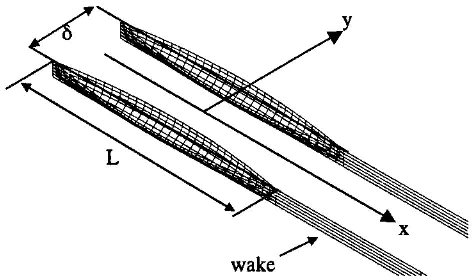
B and T are the vessel width and draft respectively. The principal particulars for the Wigley hull are shown in Table 1.

Table 1 Principal particulars of the wigley hull.

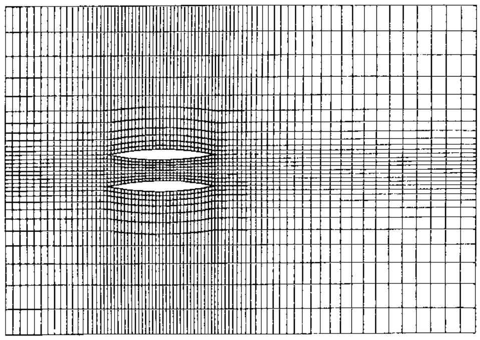
Parameter	Wigley Hull
L/B	10
B/T	16
C_B	0.444
C_M	0.667

4.1 Catamaran Hull

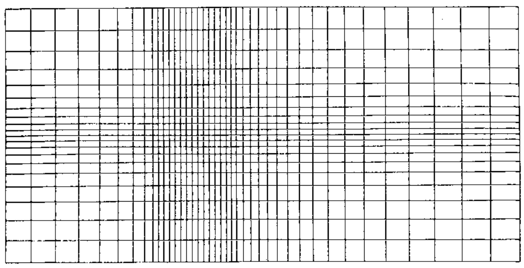
The first numerical example is the catamaran hull. The catamaran configuration is composed of two monohulls and must be considered as a lifting body due to the difference in pressure on inner and outer side of each mono hull. The panel arrangement for the catamaran model is shown in Fig. 2. The number of panels on one half of the computational domain is 30 × 5 × 2 on the body surface, 80 × 15 on the free surface, 5 on each wake strip and 40 × 10 on the sea bottom respectively. In Fig. 3 the wave profile (2nd order approximation, free sinkage and trim) on inner side of the catamaran hull is significantly lower than that of the outer side. This difference is mainly due to the wave interference effects and is exaggerated by the influence of water depth. The wave making resistances at various water-depth to draft ratios, h/T are plotted in Fig. 4. Fixed condition means not to take into account the effect of sinkage and trim into computation and free condition as reversed. The resistance increases up to the critical speed and then again decreases. Fig. 5 also shows the comparison of wave resistance and indicates broadly similar trends to those of the published mono hull results such as Tarafder et al[12]. It should be noted that some difficulty is encountered in acquiring satisfactory data at the narrowest hull separation (distance between the central lines



(a) Distribution of panels on body and wake surface

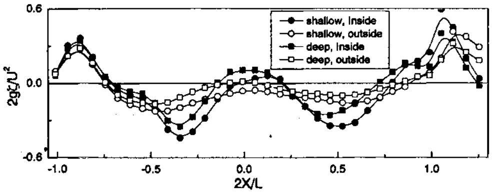


(b) Distribution of panels on free surface

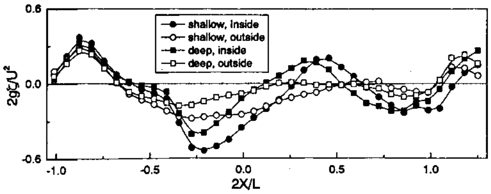


(c) Distribution of panels on sea bottom

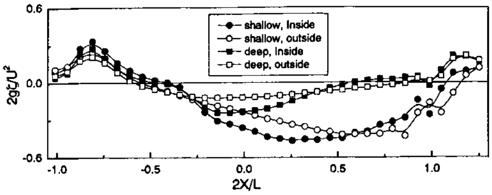
Fig. 2 Panel arrangement for a catamaran model.



(a) Wave profile at F_n=0.289



(b) Wave profile at F_n=0.332



(c) Wave profile at F_n=0.40

Fig. 3 Wave profile around a catamaran hull ($\delta/L = 0.2$) in deep and sub-critical depth, $h/T = 2.8$.

of the two mono hulls) to ship length ratio, $\delta/L = 0.2$. This may be due to substantial wave breaking between the two mono hulls. The results also indicate that higher separation ratios, δ/L give a smaller wave interference with humps and hollows located at lower Froude numbers. Beneficial wave interference is found at about $Fn = 0.37$ to 0.46 whilst adverse effects are found both side of this speed range. The wave interference can effectively be neglected above a particular speed that is dependent on hull separation. This is an interesting and important result since it suggests that, for higher speed designs, the choice of hull spacing may be based on other requirements such as sea keeping performance without incurring significant penalties in calm water resistance.

The interference effects on running sinkage and trim of catamaran hulls are given in Figs. 6 and 7. The significant trim interference occurs only at the high speed region. The overall results and trends are in broad agreement with the mono hull data. The computed contour of wave pattern (2nd, free) around catamaran hull is shown in Fig. 8. As can be seen in Fig. 8(a) diverging waves are radiating from bow together with transverse waves following behind the stern of ship. The Kelvin angle increases as the speed of the ship increases and reaches its maximum value at the critical speed. As this critical condition in Fig. 8(b), the wave making effect is concentrated in a single crest at the bow and very pronounced wave crest are created

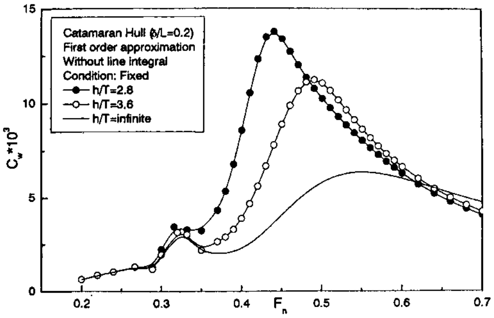


Fig. 4 Wave making resistance of catamaran hull ($\delta/L = 0.2$).

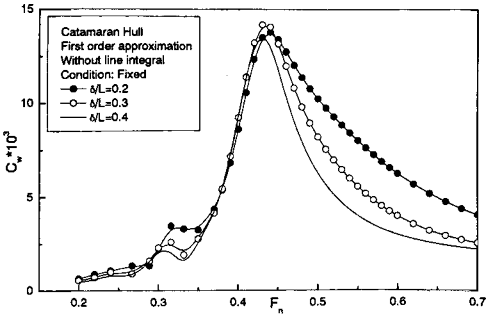


Fig. 5 Wave making resistance of catamaran hull at $h/T = 3.6$.

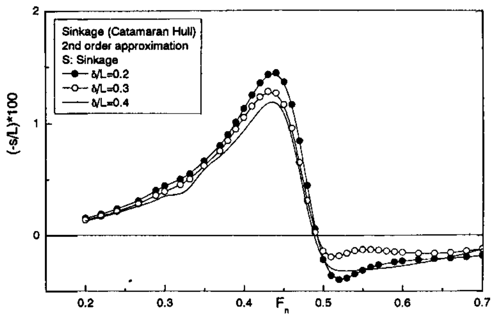


Fig. 6 Sinkage of catamaran hull at $h/T = 3.6$.

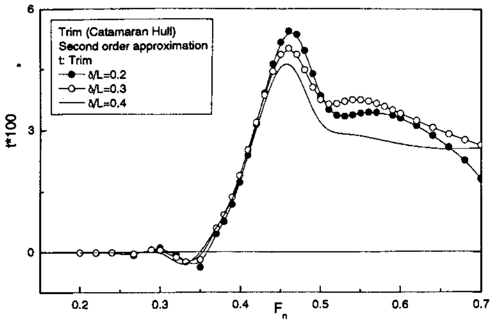
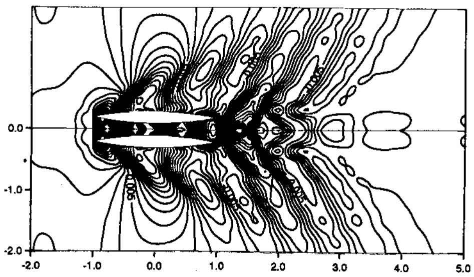
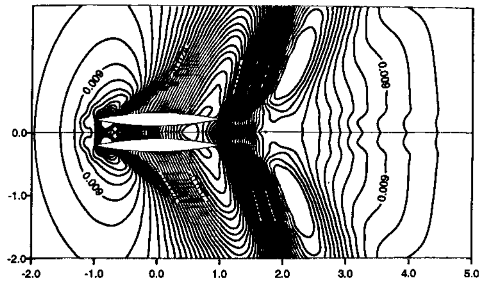


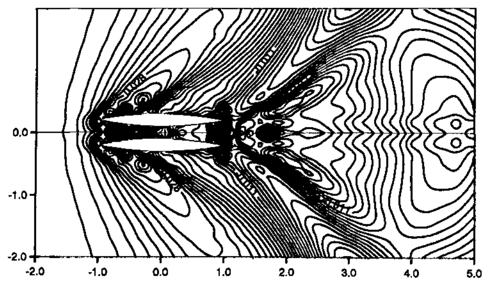
Fig. 7 Trim of catamaran hull at $h/T = 3.6$.



(a) Wave pattern at F_h= 0.794 (F_n=0.332)



(b) Wave pattern at F_h= 0.980 (F_n=0.41)



(a) Wave pattern at F_h=1.195 (F_n=0.50)

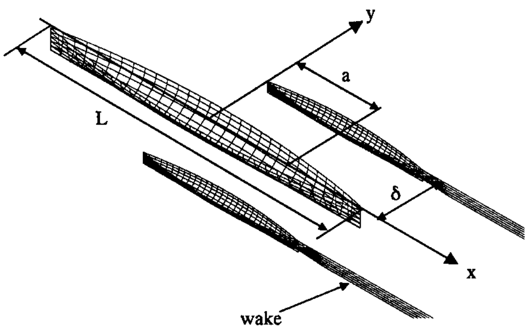
Fig. 8 Wave pattern around catamaran hull ($\delta/L = 0.20$) at $h/T = 2.8$.

at the stern. At the supercritical speed in Fig. 8(c), the wave pattern now consists only of diverging wave and transverse wave is going to be disappeared.

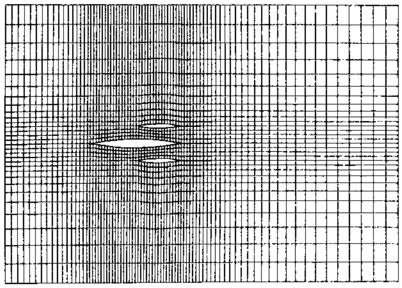
4.2 Trimaran Hull

The trimaran model is composed of main hull with two small outriggers. Since the interior flow between outrigger and main hull is different form the exterior flow, pressure distribution on each side of outrigger is inconsistent. Because of this reason, outriggers must be considered as lifting bodies and the wave making characteristics may be altered by their lifting effect. The principal particulars of main hull are two times longer and wider than those of outriggers.

The trimaran configuration is chosen by arranging

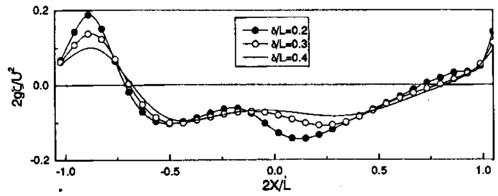


(a) Distribution of panels on body and wake surface

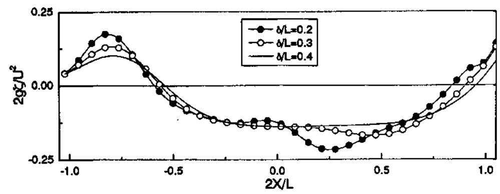


(b) Distribution of panels on free surface

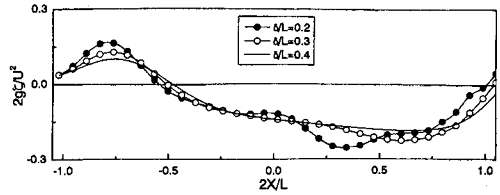
Fig. 9 Panel arrangement for a trimaran model.



(a) Wave profile at F_n=0.289



(b) Wave profile at F_n=0.37



(c) Wave profile at F_n=0.40

Fig. 10 Comparison of calculated wave profile on the trimaran main hull ($a/L = 0.0M$) in deep and at $h/T = 3.2$.

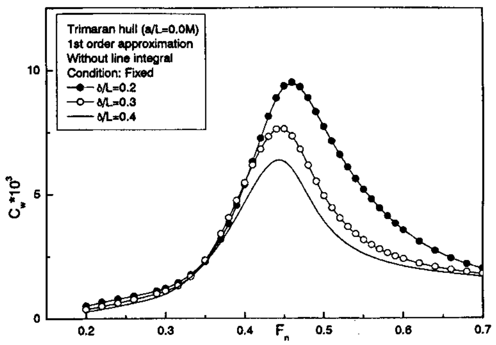


Fig. 11 Wave making resistance of trimaran hull ($a/L = 0.0M$) at $h/T = 3.2$.

the symmetry plane of the outrigger at a distance δ/L = 0.20, 0.30 and 0.40 (L is the length of the main hull) respectively from the symmetry plane of the main hull. For the trimaran (δ/L = 0.20), three longitudinal positions are assumed by placing the midship section of the outrigger at a distance a/L=0.0, 0.25 forward and 0.25 aft from the midship section of the main hull. These transverse locations of the outrigger are written in the graph as a/L=0.0M, 0.25F and 0.25A respectively.

Fig. 9 gives the panel arrangement of trimaran model. The number of panels on one half of the computational domain is $30 \times 5 \times 3$ on body surface, 80×15 on free surface and 5 on each wake strip respectively. The bottom surface shown in Fig. 2(c) is also used in the present case.

The dependence on Froude number is qualitatively same in the sense that the same type of sub-critical, critical and supercritical region is recognized.

The interference effect of running sinkage and trim is shown in Figs. 13 and 14. A steep increase of resistance is connected to the similar increase of sinkage and trim. Sinkage reaches its maximum value earlier

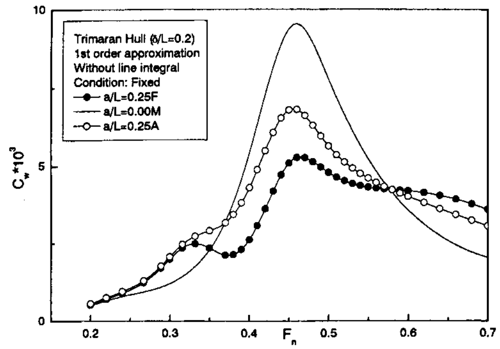


Fig. 12 Wave making resistance of trimaran hull ($\delta/L = 0.2$) at $h/T = 3.2$.

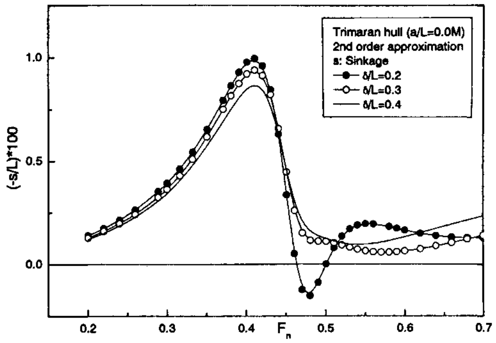


Fig. 13 Sinkage of trimaran hull at $h/T = 3.2$.

than the resistance and trim. The computed contour of wave pattern (2nd, free) around trimaran hull is shown in Fig. 15 and seems to display an acceptable correspondence.

5. Conclusion

The present paper has successfully put forward a numerical approach to predict the shallow water effect on the wave making resistances of multihulls. The following conclusion can be drawn from the present numerical analysis:

The wave making resistance as well as the Kelvin angle increases as the speed of the ship increases and reaches its maximum value at the critical speed. At higher speeds the interference between two similar mono hulls when brought together in a catamaran configuration is so small that for $\delta/L = 0.4$ it can be ignored. $\delta/L = 0.4$ appears to be a separation ratio that can be realistically adopted in practice and designers may be encouraged by a minimal effect. The influence of water depth on trimaran is, in principle, the same

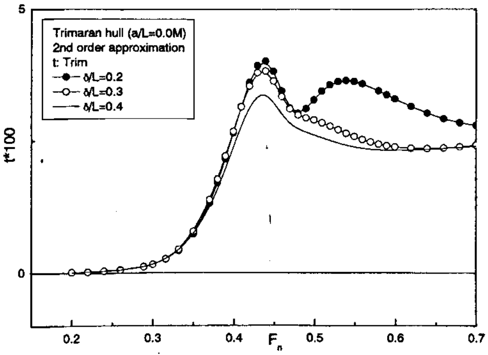


Fig. 14 Trim of trimaran hull at $h/T = 3.2$.

as the influence on mono hull in the sense that the same type of critical and the supercritical region can be recognized.

The theory provides a useful design tool at the preliminary design stage for screening suitable combinations of hull parameters and hull configuration.

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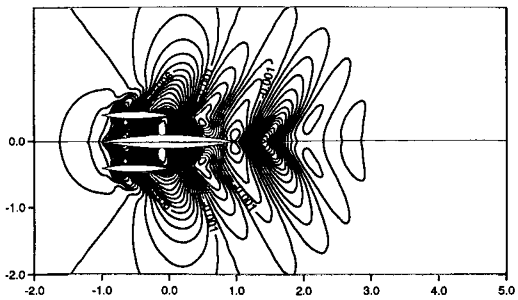
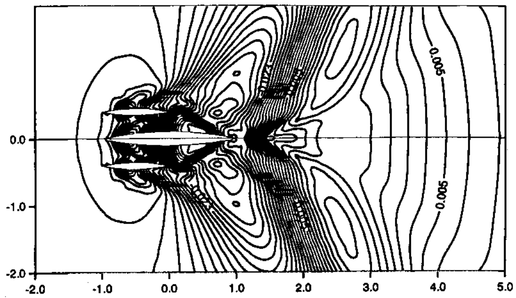
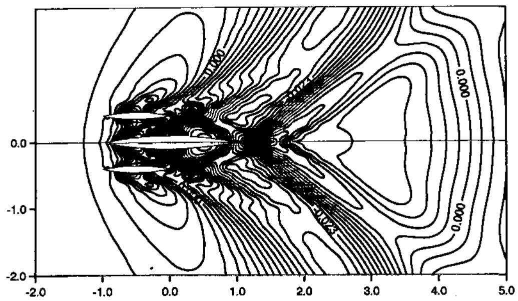


(a) wave pattern at F_h=0.742 (F_n=0.332)



(b) Wave pattern at F_h=0.983 (F_n=0.44)



(c) Wave pattern at F_h=1.12 (F_n=0.50)

Fig. 15 Wave pattern around trimaran hull ($\delta/L = 0.2$ & $a/L = 0.25F$) at $h/T = 3.2$.

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