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The effect of lift on the wave-making resistance of multi-hull craft

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A potential based panel method is presented to estimate the wave-making characteristics of multi-hull craft. In order to simulate the lifting potential flow around the sub-hulls, the method adopts mixed source/doublet distributions on the sub-hulls and their wake surface, while sources are distributed on the main hull and the free surface. In this way, the asymmetric flow characteristics of the sub-hull are properly simulated, i.e., a Kutta condition is satisfied at the trailing edge of the sub-hull. Comparison is made between the numerical and model experimental measurements, and a good correlation has been found. The wave-making characteristics and pressure distributions on the sub-hull predicted by the present method can differ from those based on a distribution of sources alone, especially the pressure distributions at the stern of the sub-hulls.
Keywords: Multi-hull craft, lift, panel method, potential flow, wave-making resistance

1. Introduction

Multi-hull ships (catamaran, trimaran, pentamaran, etc.) offer many hydrodynamic and layout advantages, and are attractive options for ship designers. The interference among the sub-hulls and the main hull can lead to optimal position of the sub-hulls relating to the main hull to reduce wave-making resistance. Other advantages are the larger deck area and increased stability. Practical tools for predicting the wave-making resistance performance of these types are desirable for the designers, especially at the initial design stage, where various options are to be evaluated. The most widely used tools for such purposes are based on potential panel methods. In many cases, the sub-hulls experience a lateral lifting force due to the asymmetric flow about the central plane of the sub-hulls; therefore, a Kutta condition should be imposed at the trailing edge. In tackling the steady wave-making problem of multi-hull craft, many researchers have adopted the Kelvin source technique in which the Green function satisfies the linear free surface condition and far-field radiation condition, but is unable to satisfy the Kutta condition at the trailing edge; see, for example,

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Yang, Noblesse, Lohner and Hendrix [1]. In the analysis of a 3D lifting body with a free surface, Lee and Joo [2] used a mixed source and doublet distribution on the body surface and a distribution of sources on the free surface to calculate the wave-making resistance of a catamaran; a Dirichlet-type body boundary condition was used on the body surface. In their formulations, the source strength on body surface was set equal to the component of incoming flow velocity in normal direction to the body surface; the induced velocity of the source distribution on the free surface was not included, and so the body boundary condition was not satisfied exactly. They strongly recommended checking normal velocity component on body surface. Larsson and Janson developed a 3D panel method for yacht and trimaran potential flow [3,4]. In their method, sources and doublets were distributed on the lifting part of the craft. The use of a Neumann boundary condition (where the normal component of velocity is zero) leads to fewer equations than the unknown strengths of source and doublet. In order to achieve closure, the lifting body surface can be divided into strips, essentially parallel to the undisturbed flow direction. At each strip, the doublet strength is assumed constant spanwise and varies linearly with the arc length from the trailing edge of the pressure side around the nose, back to the trailing edge on the suction side. Behind the trailing edge, several wake panels are added along which the doublet strength is constant. The Kutta condition is satisfied by prescribing a direction of the flow immediately behind the trailing edge, where the velocity vector is assumed to be in the bisector plane. Numerically, this is accomplished by specifying the normal to the surface and setting the velocity in this direction to be zero. This turns out to be exactly the same condition as the hull surface condition, so Kutta equations are of exactly the same form as the hull condition. However, a problem arises in calculating the induced velocity of the doublet on the lifting body surface and the Kutta panels. Xie and Vassalos [5] adopted source and doublet distributions on the body surface and source distribution on the free surface to analyse performance of a 3D hydrofoil under a free surface; the doublet strength on the lifting body does not necessarily vary linearly with the arc length. Using an alternative approach, Suzuki, Nakata, Ikehata and Kai [6], and Zou and Soding [7] distributed doublets on the central plane of the lifting body, while sources were distributed on the hull surface. Chen and Liu [8] distributed doublets on a sub-surface inside the lifting body ('de-singularity' method).

In the analysis of hydrodynamic performance of multi-hull craft, the source distribution only method has a relatively simple mathematical formulations, however, this method is unable to satisfy Kutta condition (with finite velocity at the trailing edge of the sub-hulls). The prescript distribution of doublet (linear distribution along the arc length of the lifting bodies) may be not suitable for general 3D flow cases. While the method of distributing doublets on the central plane of the lifting body is appropriate for thin lifting body cases. In the present paper, a potential based panel method is developed to predict wave-making characteristics of multi-hull craft. The free surface boundary condition is linearised for the double-body flow potential. The total velocity potential is split into the double body flow and the disturbance flow potential. On the surface of lifting body (sub-hulls), a Dirichlet-type boundary condition is applied to a distribution of sources and doublets. A distribution of doublets alone is deployed on the wake surface of the sub-hulls, whereas sources are distributed on the main hull surface and on the free surface. Numerical results of a catamaran are compared with some published model test experimental measurements, a good agreement has been found. Some numerical predictions are presented for two trimaran configurations; these are compared against those using a distribution of sources. It is found that wave-making characteristics and pressure distributions on the sub-hulls predicted with the two methods are different, especially pressure distribution at the stern part of the sub-hulls.

2. Mathematical formulations

Potential flow theory will be used in the present study, which means that the fluid is ideal and incompressible and the flow is irrotational. A right-hand coordinate system 0-xyz is assumed, located on the craft advancing at forward speed U, xy-plane is on the undisturbed water surface; z-axis is positive upward, see Fig. 1. The velocity potential, $\Phi(x, y, z)$, satisfies Laplace equation and the following boundary conditions:

$$g\frac{\partial\Phi}{\partial z} + \frac{1}{2}\nabla\Phi\cdot\nabla(\nabla\Phi\cdot\nabla\Phi) = 0 \quad \text{on } z = \varsigma(x, y), \tag{1}$$

$$\frac{\partial\Phi}{\partial n} = 0 \quad \text{on } S_h \text{ and } S_b, \tag{2}$$

$$\nabla\Phi < \infty \quad \text{on the trailing edge of } S_b, \tag{3}$$

$$\Phi = -xU \quad \text{far upstream}, \tag{4}$$

where S_h and S_b are the main hull and the sub-hull surfaces, respectively. Equation (3) is the Kutta condition. The free surface flow problem formulated above is

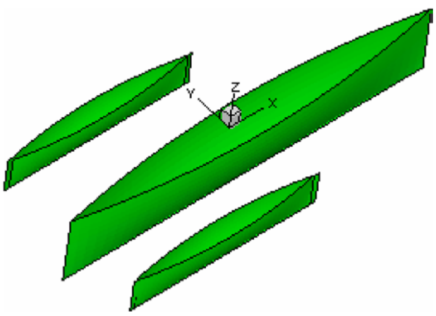


Fig. 1. Coordinate system.

nonlinear, due to the free surface boundary condition and the unknown position of the corresponding boundary. In the present study, the velocity potential is split into the double body flow (ϕ) and the disturbance flow (φ) potentials:

$$\Phi(x, y, z) = \phi(x, y, z) + \varphi(x, y, z). \tag{5}$$

It is assumed that the disturbance flow is much less than the double body flow. The nonlinear free surface condition (1) is expanded on the free surface corresponding to the double body flow, and it is further expanded at the undisturbed free surface (i.e., $z = 0$). The linearised free surface condition is therefore:

$$\begin{aligned}&\nabla\phi \cdot \nabla(\nabla\phi \cdot \nabla\varphi) + \frac{1}{2}\nabla\varphi \cdot \nabla(\nabla\phi \cdot \nabla\phi) + g\varphi_z - \phi_{zz}\nabla\phi \cdot \nabla\varphi \\ &\quad = -\frac{1}{2}\nabla\phi \cdot \nabla(\nabla\phi \cdot \nabla\phi) - \frac{1}{2}\phi_{zz}(U^2 - \nabla\phi \cdot \nabla\phi).\end{aligned} \tag{6}$$

The solution of the double body flow can be written in terms of velocity potentials due to the disturbances of the main hull and the sub-hulls, and the incoming flows:

$$\phi(x, y, z) = \phi_h(x, y, z) + \phi_b(x, y, z) + \phi_\infty. \tag{7}$$

Sources are distributed on the main hull surface; sources/doublets are distributed on the sub-hull surface and doublets are distributed on the wake surface as well. These velocity potentials are expressed as:

$$\phi_h(x, y, z) = \iint_{S_h} \frac{\sigma_0}{r}\,\mathrm{d}s, \tag{8}$$

$$\begin{aligned}\phi_b(x, y, z) = {} & \frac{1}{4\pi}\iint_{S_b}\left[\frac{1}{r}\frac{\partial\phi_b}{\partial n} - \phi_b\frac{\partial}{\partial n}\frac{1}{r}\right]\mathrm{d}s \\ & - \frac{1}{4\pi}\iint_{S_w}\left[(\phi_b^+ - \phi_b^-)\frac{\partial}{\partial n}\frac{1}{r}\right]\mathrm{d}s\end{aligned} \tag{9}$$

and $\phi_\infty = -xU$, where S_w is the wake surface of the sub-hulls, ϕ_b^+ and ϕ_b^- are the velocity potentials of suction side and pressure side of the trailing edge of S_b. When the field point is on the sub-hull surface, (9) becomes:

$$\begin{aligned}&2\pi\phi_b + \iint_{S_b - S_\varepsilon}\left[\phi_b\frac{\partial}{\partial n}\frac{1}{r}\right]\mathrm{d}s + \iint_{S_w}\left[(\phi_b^+ - \phi_b^-)\frac{\partial}{\partial n}\frac{1}{r}\right]\mathrm{d}s \\ &\quad + \iint_{S_b}\frac{\partial\phi_h}{\partial n}\frac{1}{r}\,\mathrm{d}s = \iint_{S_b}\frac{Un_x}{r}\,\mathrm{d}s,\end{aligned} \tag{10}$$

where S_ε is a small part of the sub-hull surface surrounding the field point and the following body boundary condition on the sub-hull

$$\frac{\partial \phi_h}{\partial n} + \frac{\partial \phi_b}{\partial n} + \frac{\partial \phi_\infty}{\partial n} = 0 \quad \text{on } S_n \tag{11}$$

has been used. The disturbance flow potential consists of potentials due to disturbance from the main hull, the sub-hull and the free surfaces:

$$\varphi(x, y, z) = \varphi_h(x, y, z) + \varphi_b(x, y, z) + \varphi_{\mathrm{F}}(x, y, z). \tag{12}$$

Sources are distributed on the main hull and the free surface, and sources and doublets are distributed on the sub-hull surface:

$$\varphi_h(x, y, z) = \iint_{S_h} \frac{\sigma_h}{r}\,\mathrm{d}s, \tag{13}$$

$$\begin{aligned}\varphi_b(x, y, z) = {} & \frac{1}{4\pi}\iint_{S_b}\left[\frac{1}{r}\frac{\partial \varphi_b}{\partial n} - \varphi_b \frac{\partial}{\partial n}\frac{1}{r}\right]\mathrm{d}s \\ & - \frac{1}{4\pi}\iint_{S_w}\left[(\varphi_b^+ - \varphi_b^-)\frac{\partial}{\partial n}\frac{1}{r}\right]\mathrm{d}s,\end{aligned} \tag{14}$$

$$\varphi_{\mathrm{F}}(x, y, z) = \iint_{S_{\mathrm{F}}} \frac{\sigma_F}{r}\,\mathrm{d}s. \tag{15}$$

The body boundary conditions for the disturbance flow are

$$\frac{\partial \varphi_h}{\partial n} + \frac{\partial \varphi_b}{\partial n} + \frac{\partial \varphi_{\mathrm{F}}}{\partial n} = 0 \quad \text{on } S_b \text{ and } S_h. \tag{16}$$

Again, when the field point is on the sub-hull surface, (14) becomes

$$\begin{aligned}& 2\pi\varphi_b + \iint_{S_b - S_\varepsilon}\left[\varphi_b \frac{\partial}{\partial n}\frac{1}{r}\right]\mathrm{d}s + \iint_{S_w}\left[(\varphi_b^+ - \varphi_b^-)\frac{\partial}{\partial n}\frac{1}{r}\right]\mathrm{d}s \\ & \quad + \iint_{S_b}\frac{\partial \varphi_h}{\partial n}\frac{1}{r}\,\mathrm{d}s + \iint_{S_b}\frac{\partial \varphi_{\mathrm{F}}}{\partial n}\frac{1}{r}\,\mathrm{d}s = 0,\end{aligned} \tag{17}$$

where the body boundary condition (16) is used. Panel grids on the free surface are defined by equations $y = y(x)$ and $x =$ constant in the longitudinal ($\vec{L}$) and transverse ($\vec{T}$) directions respectively. The following relations exist for the partial derivates on the free surface:

$$\begin{cases} f_x = \dfrac{1}{L_x} f_{\mathrm{L}} - \dfrac{L_y}{L_x} f_{\mathrm{T}}, \\ f_y = f_{\mathrm{T}}, \end{cases} \tag{18}$$

where f is a field function (e.g., velocity components), (L_x, L_y) are directional cosines of the longitudinal curvature axis, $\vec{L}$. The free surface boundary condition, (6) can be re-written as

$$A_1(\varphi_x)_{\mathrm{L}} + A_2(\varphi_x)_{\mathrm{T}} + A_3(\varphi_y)_{\mathrm{T}} + H_1\varphi_x + H_2\varphi_y + g\varphi_z = G_2, \qquad (19)$$

where $H_1 = 2\phi_x\phi_{xx} + 2\phi_y\phi_{xy} - \phi_x\phi_{zz}$, $H_2 = 2\phi_x\phi_{yx} + 2\phi_y\phi_{yy} - \phi_y\phi_{zz}$, $A_1 = \phi_x\phi_x/L_x$, $A_2 = 2\phi_x\phi_y - \phi_x\phi_x L_y/L_x$, $A_3 = \phi_y\phi_y$, g is the acceleration due to gravity, and

$$\begin{aligned} G_2 = & -\phi_x\phi_x\phi_{xx} - \phi_x\phi_y\phi_{yx} - \phi_x\phi_y\phi_{xy} - \phi_y\phi_y\phi_{yy} \\ & -\frac{1}{2}(U^2 - \phi_x^2 - \phi_y^2). \end{aligned} \qquad (20)$$

Once the double body flow problem has been solved, coefficients A_1, A_2, A_3, H_1, H_2 and G_2 can be calculated at each control point of the free surface panels with the numerical schemes described below.

3. Numerical method

The method of Hess and Smith [9] is used to solve the unknown source strength on the main-hull (σ_0) and the unknown velocity potential (doublet strength, ϕ_b) on the sub-hull of the double body flow problem. The body surfaces are divided into a number of panels in the longitudinal and girthwise directions, on each of which the strengths of source/doublet are constant. At the trailing edge, because of the unknown doublet strength on the wake surface, a Morino-type of Kutta condition [10] is applied, and the doublet strengths on the wake surface are determined in terms of values on the null points of the adjacent panels by a one-sided three-point finite difference scheme [5]. In this way, (10) yields *NB* equations for the unknowns, where *NB* is the total number of panels on the sub-hull. An additional *NH* equations are obtained by applying a Neumann-type boundary condition on the main-hull, where *NH* is the total number of panels on the main hull surface. The problem is now closed. The solution of the equations generates the source distribution on the main hull and the doublet distribution on the sub-hull of the double-body flow.

For the disturbed flow, the approach for applying the body boundary condition on the main hull and sub-hulls is the same as that of for the double-body flow. Discretizing (17) yields *NB* equations for the unknowns. Applying the body boundary condition (16) on the main hull surface then gives an additional *NH* equations.

In order to discretize the free-surface boundary condition, Dawson's established 4-point upwind difference scheme [11] is used to calculate longitudinal derivates on the free surface; the lateral and vertical derivatives are calculated by a 3-point difference scheme:

$$\begin{cases} (f_{\mathrm{L}})_{i,j} = \alpha_{i,j} f_{i,j} + \beta_{i,j} f_{i-1,j} + \gamma_{i,j} f_{i-2,j} + \delta_{i,j} f_{i-3,j}, \\ (f_{\mathrm{T}})_{i,j} = a_{i,j} f_{i,j-1} + b_{i,j} f_{i,j} + c_{i,j} f_{i,j+1}, \end{cases} \tag{21}$$

where $\alpha, \beta, \gamma, \delta; a, b, c$ are coefficients of the finite difference schemes. Discretizing (19) and making use of the above finite difference schemes, one equation will be obtained for each control point on the free surface:

$$\sum_{k=1}^{NB} P_{k,i_x,i_y} \varphi_{b,k} + \sum_{j=1}^{NH} Q_{j,i_x,i_y} \sigma_{h,j} + \sum_{j_x=1}^{NX} \sum_{j_y=1}^{NY} R_{j_x,j_y;i_x,i_y} \sigma_{\mathrm{F},j_x,j_y} = G_{2,i_x,i_y}, \tag{22}$$

where [**P**], [**Q**], [**R**] are the matrix coefficients, for example

$$\begin{aligned} Q_{j;i_x,i_y} = {} & A_1 \boldsymbol{\alpha}_{i_x,i_y} \mathrm{WHX}_{i_x,i_y;j} + A_1 \boldsymbol{\beta}_{i_x,i_y} \mathrm{WHX}_{i_x-1,i_y;j} \\ & + A_1 \boldsymbol{\gamma}_{i_x,i_y} \mathrm{WHX}_{i_x-2,i_y;j} + A_1 \boldsymbol{\delta}_{i_x,i_y} \mathrm{WHX}_{i_x-3,i_y;j} \\ & + A_2 a_{i_x,i_y} \mathrm{WHX}_{i_x,i_y-1;j} + A_2 b_{i_x,i_y} \mathrm{WHX}_{i_x,i_y;j} \\ & + A_2 c_{i_x,i_y} \mathrm{WHX}_{i_x,i_y+1;j} + A_3 a_{i_x,i_y} \mathrm{WHY}_{i_x,i_y-1;j} \\ & + A_3 b_{i_x,i_y} \mathrm{WHY}_{i_x,i_y;j} + A_3 c_{i_x,i_y} \mathrm{WHY}_{i_x,i_y+1;j} \\ & + H_1 \mathrm{WHX}_{i_x,i_y;j} + H_2 \mathrm{WHY}_{i_x,i_y;j} + g \mathrm{WHZ}_{i_x,i_y;j}, \end{aligned} \tag{23}$$

where $(\mathrm{WHX}_{i_x,i_y;j}; \mathrm{WHY}_{i_x,i_y;j}; \mathrm{WHZ}_{i_x,i_y;j}) = \overrightarrow{\mathbf{WH}}_{i_x,i_y;j}$, and

$$\begin{aligned} \overrightarrow{\mathbf{WH}}_{i_x,i_y;j} = {} & \nabla \iint_{\Delta S_{h,j}} \left(\frac{1}{r_{i_x,i_y;j}} \right) \mathrm{d}s \\ & + \sum_{k=1}^{NB} \left(\vec{n}_k \cdot \nabla \iint_{\Delta S_{h,j}} \frac{\mathrm{d}s}{r_{k,j}} \right) \left(-\frac{1}{4\pi} \nabla \iint_{\Delta S_{b,k}} \frac{\mathrm{d}s}{r_{i_x,i_y;k}} \right). \end{aligned} \tag{24}$$

Solution of the combined equations obtained from control points on the main hull, sub-hulls and the free surface will be the source strengths on the main hull, doublet strengths on the sub-hull and source strengths on the free surface panels of the disturbance flow.

Once the velocity potential has been solved, the velocity distribution on the main hull are calculated by:

$$\vec{\mathbf{v}}_h = \nabla \phi_\infty + \nabla(\phi_b + \varphi_b) + \nabla(\phi_h + \varphi_h) + \nabla \varphi_{\mathrm{F}} \quad \text{on } S_h. \tag{25}$$

While velocity distribution on the sub-hull is calculated in the following manner:

$$\begin{aligned}\vec{\mathbf{v}}_b &= \nabla\boldsymbol{\phi}_\infty + \nabla(\boldsymbol{\phi}_b + \boldsymbol{\varphi}_b) + \nabla(\boldsymbol{\phi}_h + \boldsymbol{\varphi}_h) + \nabla\boldsymbol{\varphi}_{\mathrm{F}} \\ &= v_{bn}\vec{\mathbf{n}} + v_{be1}\vec{\mathbf{e}}_1 + v_{be2}\vec{\mathbf{e}}_2 \quad \text{on } S_b,\end{aligned} \tag{26}$$

where $(\vec{\mathbf{n}}, \vec{\mathbf{e}}_1, \vec{\mathbf{e}}_2)$ are the unit vector on the sub-hull surface, $\vec{\mathbf{n}}$ is the normal direction, $\vec{\mathbf{e}}_1$ and $\vec{\mathbf{e}}_2$ are the tangential vector components. Therefore $v_{bn} = 0$ and

$$\left\{\begin{aligned} v_{be1} &= \big(\nabla\phi_\infty + \nabla(\phi_h + \varphi_h) + \nabla\varphi_{\mathrm{F}}\big)\cdot\vec{\mathbf{e}}_1 \\ &\quad + \big(\nabla(\phi_b + \varphi_b)\cdot\vec{\mathbf{e}}_1\big), \\ v_{be2} &= \big(\nabla\phi_\infty + \nabla(\phi_h + \varphi_h) + \nabla\varphi_{\mathrm{F}}\big)\cdot\vec{\mathbf{e}}_2 \\ &\quad + \big(\nabla(\phi_b + \varphi_b)\cdot\vec{\mathbf{e}}_2\big)\end{aligned}\right. \quad \text{on } S_b. \tag{27}$$

The first terms in the right-hand side of (27) are calculated directly, while the second terms are calculated numerically by a finite difference scheme [5]. The non-dimensional dynamic pressure coefficient on the main hull and the sub-hull surface is:

$$C_p(x, y, z) = (1 - \vec{\mathbf{v}}\cdot\vec{\mathbf{v}}/U^2) \quad \text{on } S_h \text{ and } S_b \tag{28}$$

and the wave-making resistance:

$$R_w = -\frac{1}{2}\rho U^2 \iint_S C_p n_x \,\mathrm{d}s \quad \text{for } S_h \text{ and } S_b. \tag{29}$$

The non-dimensional coefficient of wave-making resistance is defined as $C_w = 2R_w/\rho U^2 S_0$, where S_0 stands for the mean wetted surface area of the main hull or the sub-hull. The wave surface elevation is calculated by

$$\varsigma(x, y) = \frac{1}{2g}(U^2 - \nabla\Phi\cdot\nabla\Phi) \quad \text{on } S_{\mathrm{F}} \tag{30}$$

and the non-dimensional free surface elevation is defined as $\tilde{\varsigma}(x, y) = 2g\varsigma/U^2$.

4. Numerical results and discussion

Some numerical convergence tests were carried out to establish appropriate panels for both the hull and the free surface boundaries. A Wigley hull catamaran was selected to test the present method. The Wigley hull form is defined as:

$$y = \pm\frac{B}{2}\left(1 - \frac{z^2}{T^2}\right)\left(1 - \frac{4x^2}{L^2}\right), \tag{31}$$

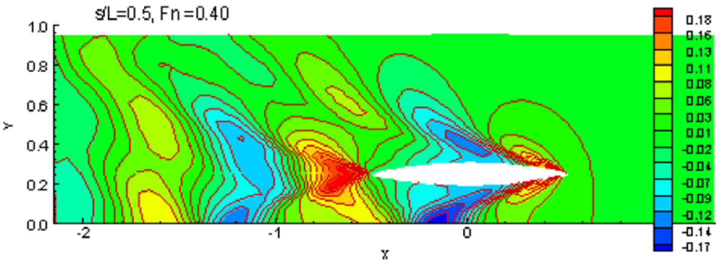


Fig. 2. Wave pattern of the catamaran.

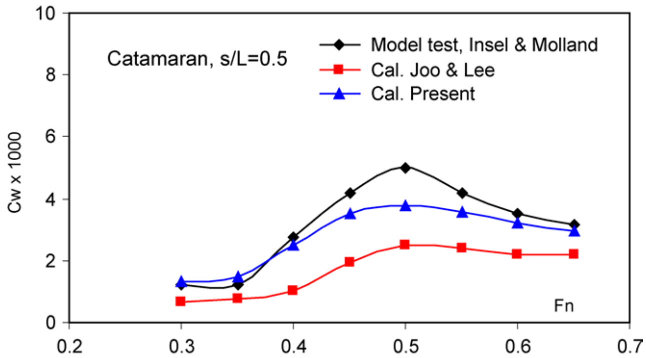


Fig. 3. Comparison of wave-making resistance of a catamaran.

where L, B, T are the length, beam and draft of the hull, respectively. The distance between the demi-hulls was $s/L = 0.5$, where L is the craft length. Figure 2 indicates the wave pattern at a Froude number $Fn = 0.40$. The predicted wave-making resistance coefficients are shown in Fig. 3. The experimental results of Insel and Molland [12] and the numerical results of Lee and Joo [2] are also plotted in Fig. 3. It can be seen that the present predictions show better agreement with model tests than those of Lee and Joo. As indicated previously, the reason may be because the hull surface boundary condition was not satisfied exactly.

Some numerical calculations are also carried out for a trimaran, whose main hull and sub-hulls (outriggers) were the Wigley hull. The length ratio of the main hull and the sub-hull was $L/L_s = 3$, with the longitudinal position of the sub-hull at $x_s = -0.333L$, aft of the centre of the main hull; the separation between the central planes of the sub-hulls was $s = 0.4L$; this configuration is denoted as Trimaran_A. Figure 4 shows the panels on the main hull, the sub-hull and the free surface. Figure 5 is a sample of the wave pattern (non-dimensionalized wave elevation) for $Fn = 0.35$. Figure 6 shows the wave-making resistance coefficients. Results for the two methods are shown: distributions of sources and doublets, and sources only. In the former method, sources and doublets are distributed on the sub-hulls with doublets on the wake surface, while sources are distributed on the main hull and the free surface;

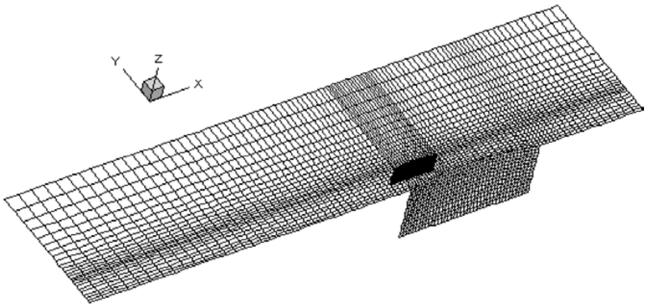


Fig. 4. Panel distribution for a trimaran model.

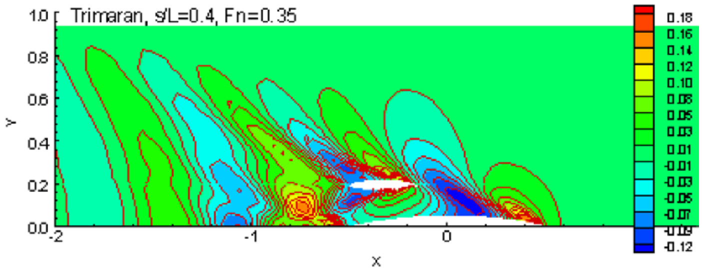


Fig. 5. Wave pattern of trimaran_A at $Fn = 0.35$, $s/L = 0.4$.

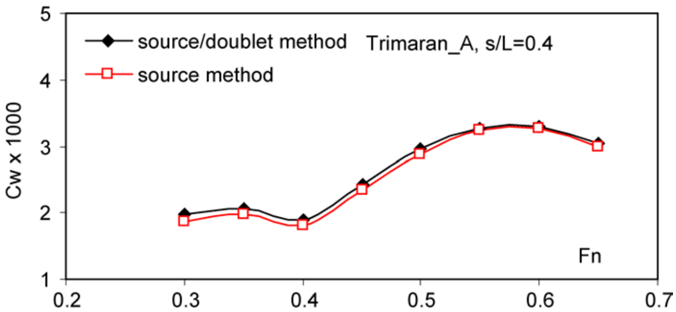
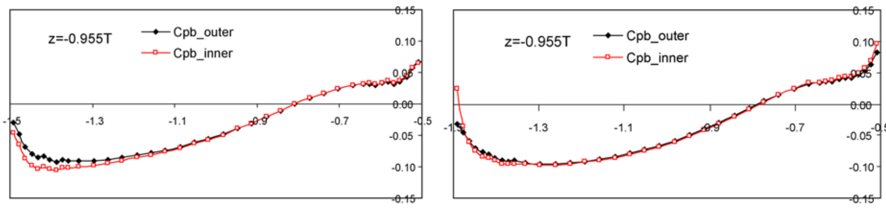


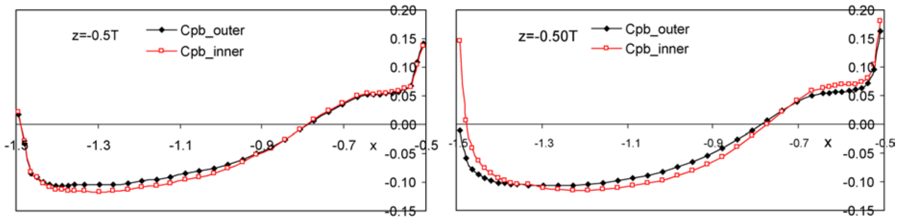
Fig. 6. Wave-making resistance of trimaran_A.

in the latter method, sources are deployed on the sub-hull, the main hull and the free surfaces. It can be seen that the predicted wave-making resistances by the two methods are very close in this case. Selected pressure distributions on the sub-hulls are shown in Figs 7–9. On the aft end of the sub-hull surface, pressure on the inner surface differs much from that on the outer side under the source distribution method. With the source/doublet distribution method, pressures on each side tally well, this is due to the Kutta condition is applied at the trailing edge of the outriggers. A possible



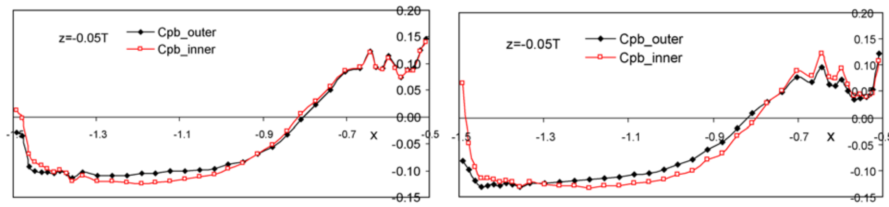
(a) (b)

Fig. 7. Pressure distribution on the sub-hull of trimaran_A for $s/L = 0.6$, $Fn = 0.30$; (a) source/doublet method; (b) source method.



(a) (b)

Fig. 8. Pressure distribution on the sub-hull of trimaran_A for $s/L = 0.6$, $Fn = 0.30$; (a) source/doublet method; (b) source method.



(a) (b)

Fig. 9. Pressure distribution on the sub-hull of trimaran_A for $s/L = 0.6$, $Fn = 0.30$; (a) source/doublet method; (b) source method.

reason for the good agreement between both methods of calculating wave-making resistance is that the net force may mask differences between the forces on various elements. (The two methods also produce different lateral forces for the sub-hulls). It is therefore suggested that a distribution of both sources and doublets should be used for accurate predictions of the pressure distribution on the hull.

The second example was a trimaran with Wigley demi-hulls as its outriggers. In this case, length of the outriggers was $L_s = L/3$, with a separation between the outriggers of $s = 0.34L$; this is referred to as Trimaran_B. Figure 10 shows the wave-making resistances predicted with the two methods. It can be clearly seen that

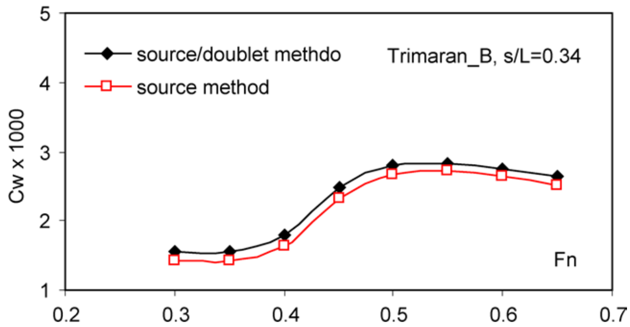


Fig. 10. Wave-making resistance of trimaran_B.

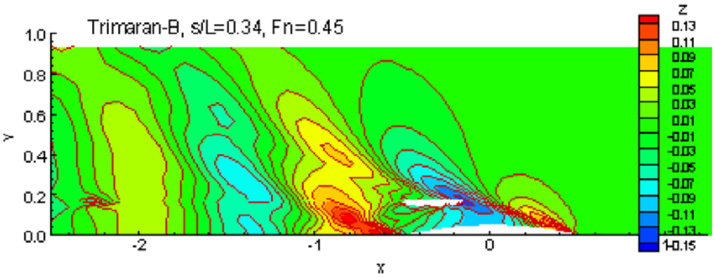


Fig. 11. Wave pattern of trimaran_B at $Fn = 0.45$.

the wave-making resistance predicted by the source method is less than that predicted by the source/doublet method. This is not surprising in view of the vortex-induced resistance which is included in the latter case. Figure 11 shows an example of the wave pattern at $Fn = 0.45$.

5. Concluding remarks

In the present paper, a potential based panel method is presented to predict wave-making characteristics of multi-hull craft. In order to take into account the effect of lateral lift generated by the sub-hulls, a mixed source/doublet distribution has been utilised, i.e., sources and doublets distributed on the sub-hulls, doublets on the wake surface, and sources on the main hull and non-wake free surface. Comparison with model test measurements strongly suggests the validity and accuracy of the present approach. The widely-used method based on a distribution of sources alone was less accurate. It is appreciated that only two configurations of trimaran have been investigated, and so more extensive calculations are needed before stronger claims can be confirmed. Further work should also include free-running craft (high-speed craft), for which the effect of sinkage and trim may be important, but which has not been considered in the present study.

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