Forward-Speed Effects on Hydrodynamic Interactions between Twin Hulls of a Catamaran in Waves

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Introduction

Twin-hull motion problems have been studied so far by the strip theory incorporating 2-D exact interaction solutions. This type of method can not account for important 3-D effects in the dissipation of wave energy reflecting between twin hulls and in the drastic change of wave-pattern characteristics with increasing forward speed. Some new approaches have been recently applied to high-speed problems, such as Chapman's type pseudo 3-D theory by Ohkusu & Faltinsen [1], Rankine source method by Kring & Sclavounos [2], and thin-ship theory by Watanabe [3]. However there exists no theory which can bridge a gap between zero and high speeds and can be computed with relative ease. A new theory presented in this paper is meant to serve that purpose; which is based on Newman's unified theory and regarded as an extension of the tank-wall interference problem by Kashiwagi & Ohkusu [4]. Breit & Sclavounos [5] developed a similar slender-ship theory for a catamaran, but their theory is limited to the zero-speed case and seems difficult to extend to the forward-speed case, because the radiation problem is reduced to a set of radiation-diffraction problems.

Theory

The present theory starts with dividing the flow field into inner and outer regions. The inner region is defined as the vicinity of left hull, and the other is the outer region where of importance are the interaction effects of right hull as well as 3-D and forward-speed effects. Thus we take the coordinate system $o\text{-}xyz$ with the origin placed at the center of the left hull, as shown in Fig.1; the separation distance between twin hulls is denoted by D, which is assumed to be of order $O(1)$. The forward speed of the ship is U and the circular frequency of oscillation is ω, with time dependence $\exp(i\omega t)$ understood.

For clarity, the explanation of the theory will be limited to the radiation problem of heave and pitch with each demi-hull assumed transversely symmetric, but there exist no fundamental obstacles to generalizing to other modes of motion and to the case where the demi-hull has no transverse symmetry. The diffraction problem can be treated with the same concept, which will be shown in the presentation.

In the outer region, the radiation potential for the j-th mode ($j=3$ for heave, $j=5$ for pitch) can be expressed in the form

$$\begin{aligned}\phi_j^{(o)}(x,y,z) &= \int_L Q_j(\xi)\left\{G(x-\xi,y,z)+G(x-\xi,y-D,z)\right\}d\xi \\ &\quad + \int_L D_j(\xi)\left\{H(x-\xi,y,z)-H(x-\xi,y-D,z)\right\}d\xi \qquad (1)\end{aligned}$$

where $Q_j(\xi)$ and $D_j(\xi)$ are indeterminate longitudinal distributions of source and doublet, respectively, along the centerline of each demi-hull, $G(x,y,z)$ is the 3-D translating and oscillating source of unit strength and likewise $H(x,y,z)$ is the doublet of unit moment with transverse axis.

The inner expansion of (1) appropriate near the left hull can be shown to be

$$\begin{aligned}\phi_j^{(o)}(x,y,z) \sim\; & Q_j(x)\,G_{2D}(y,z) - (1-Kz)\,\mathcal{L}_S(Q_j,D_j;x)\\ & + D_j(x)\,H_{2D}(y,z) - Ky\cdot\mathcal{L}_A(Q_j,D_j;x)\end{aligned} \tag{2}$$

where

$$\mathcal{L}_S = \int_L Q_j(\xi)\{g_L(x-\xi)+g_R(x-\xi)\}\,d\xi + \int_L D_j(\xi)\,f_R(x-\xi)\,d\xi \tag{3}$$

$$\mathcal{L}_A = \int_L Q_j(\xi)\,f_R(x-\xi)\,d\xi + \int_L D_j(\xi)\{h_L(x-\xi)+h_R(x-\xi)\}\,d\xi \tag{4}$$

Here $G_{2D}(y,z)$ and $H_{2D}(y,z)$ are 2-D Green functions of source and doublet, respectively, and hence $\mathcal{L}_S$ and $\mathcal{L}_A$ represent all the effects of twin-hull interactions, forward speed, and three dimensionality.

Subscript L to the kernel function in (3) and (4) designates the contribution from the left hull and likewise subscript R is from the right hull. It should be emphasized that the source distribution along the right hull gives not only the symmetric but also antisymmetric components and the kernel function of antisymmetric component $f_R(x-\xi)$ is the same as that of symmetric one obtained from the doublet distribution. As clear from (2) to (4), these cross terms play an important role in accounting for the interactions between twin hulls.

Turning to the inner solution, the basic idea of the unified theory inspires us to include both of symmetric and antisymmetric homogeneous components with respect to the center plane of the left hull; that is,

$$\begin{aligned}\phi_j^{(i)}(x;y,z) =\; & \varphi_j(x;y,z) + \frac{U}{i\omega}\widehat{\varphi}_j(x;y,z)\\ & + C_j^S(x)\{\varphi_3(y,z)-\varphi_3^*(y,z)\} + C_j^A(x)\{\varphi_2(y,z)-\varphi_2^*(y,z)\}\end{aligned} \tag{5}$$

where the asterisk means the complex conjugate, and the velocity potentials φ_j and $\widehat{\varphi}_j$ are the particular solutions satisfying the following body boundary condition:

$$\frac{\partial\varphi_j}{\partial N} = N_j \;\; (j=2,3,5), \qquad \frac{\partial\widehat{\varphi}_j}{\partial N} = M_j \;\; (j=3,5) \tag{6}$$

N_j and M_j are slender-body approximations of the j-th component of the normal and so-called m-terms, respectively.

The outer expansion of (5) takes the form

$$\begin{aligned}\phi_j^{(i)}(x;y,z) \sim\; & \Big[\sigma_j + \frac{U}{i\omega}\widehat{\sigma}_j + C_j^S\{\sigma_3-\sigma_3^*\}\Big]\,G_{2D}(y,z)\\ & + 2i\,C_j^S\,\sigma_3^*\,e^{-Kz}\cos Ky\\ & + C_j^A\{\mu_2-\mu_2^*\}\,H_{2D}(y,z) + 2i\,C_j^A\,\mu_2^*\,e^{-Kz}\sin Ky\end{aligned} \tag{7}$$

where σ_j, $\widehat{\sigma}_j$, and μ_j are 2-D Kochin function equivalent to the complex amplitude of outgoing waves, and C_j^S and C_j^A are unknown at this stage.

Matching requirement between (2) and (7) in an overlap region gives the following relations:

$$Q_j = \sigma_j + \frac{U}{i\omega}\widehat{\sigma}_j + C_j^S\{\sigma_3-\sigma_3^*\} \tag{8}$$

$$\mathcal{L}_S = -2i\,C_j^S\cdot\sigma_3^* \tag{9}$$

$$D_j = C_j^A\{\mu_2-\mu_2^*\} \tag{10}$$

$$\mathcal{L}_A = -2i\,C_j^A\cdot\mu_2^* \tag{11}$$

Eliminating C_j^S from (8)-(9) and C_j^A from (10)-(11) gives the coupled integral equations for the outer source strength Q_j and doublet strength D_j, in the form

$$\left.\begin{aligned} Q_j - \frac{i}{2}(\sigma_3/\sigma_3^* - 1)\mathcal{L}_S(Q_j, D_j; x) &= \sigma_j + \frac{U}{i\omega}\widehat{\sigma}_j \\ D_j - \frac{i}{2}(\mu_2/\mu_2^* - 1)\mathcal{L}_A(Q_j, D_j; x) &= 0 \end{aligned}\right\} \tag{12}$$

Eq.(12) is one of the new results presented in this paper.

With solutions of Q_j and D_j from (12), the coefficients of inner homogeneous component can be readily obtained from (8) and (10), thereby completing the inner solution. It is noteworthy that with increasing forward speed or with increasing separation distance at a constant speed, $\mathcal{L}_A$ tends to zero and $\mathcal{L}_S$ becomes independent of D_j; in this case $D_j = 0$ from (12) and $C_j^A = 0$ from (10), thereby the hydrodynamic interaction becomes zero and the first equation in (12) will be identical to that of Newman's unified theory for a monohull ship.

Using the inner solution of the velocity potential, the added-mass and damping coefficients in the j-th direction on the left hull can be computed as follows:

For $j = 3$ (heave), 5 (pitch)

$$\begin{aligned} A_{jk}^L + B_{jk}^L/i\omega = &- \rho \int_L dx \int_{S_H} \left(N_j - \frac{U}{i\omega}M_j\right)\left\{\varphi_k + \frac{U}{i\omega}\widehat{\varphi}_k\right\} d\ell \\ &- \rho \int_L C_k^S(x)\, dx \int_{S_H} \left(N_j - \frac{U}{i\omega}M_j\right)\{\varphi_3 - \varphi_3^*\}\, d\ell \end{aligned} \tag{13}$$

For $j = 2$ (sway), 4 (roll), 6 (yaw)

$$A_{jk}^L + B_{jk}^L/i\omega = -\rho \int_L C_k^A(x)\, dx \int_{S_H} \left(N_j - \frac{U}{i\omega}M_j\right)\{\varphi_2 - \varphi_2^*\}\, d\ell \tag{14}$$

It should be emphasized that the transverse side force or connecting moment can be calculated from the antisymmetric part of the homogeneous component; which is crucial in the strength design of a catamaran.

Numerical results and comparison with experiments

To validate the theory, computations were performed firstly for the zero-speed case of twin half-immersed spheroids with $B/L = 1/8$ and $D/B = 2$, which is the same as those in Breit & Sclavounos [5]. The result of heave added mass is shown in Fig.2 and compared with independent results by 3-D panel method and conventional strip theory using 2-D interaction solutions. The agreement with 3-D panel method seems virtually perfect.

Next, comparisons are made with experiments conducted at Froude numbers 0.15 and 0.3 using a catamaran model with $B/L = 1/6$ and $D/B = 2$, transverse sections of which are represented by the Lewis form. An example of these comparisons is shown in Fig.3, which is heave added-mass and damping coefficients. The agreement is favorable except for slight discrepancies near the frequency at which the interactions between twin hulls are resonant. We note that the separation distance $D/L = 1/3$ is small considering the assumption of the present theory $D/L = O(1)$. However the same degree of agreement as in Fig.3 is found in other modes and for Froude number 0.3.

The experiments for the wave-exciting force were also conducted and the results were compared with numerical results. The diffraction theory is different a little from the radiation theory explained here, although the basic concept is the same. The wave-exciting force is computed not only from the diffraction-theory solution but also from the forward-speed version of Haskind-Newman's relation; these will be presented in the Workshop.

References

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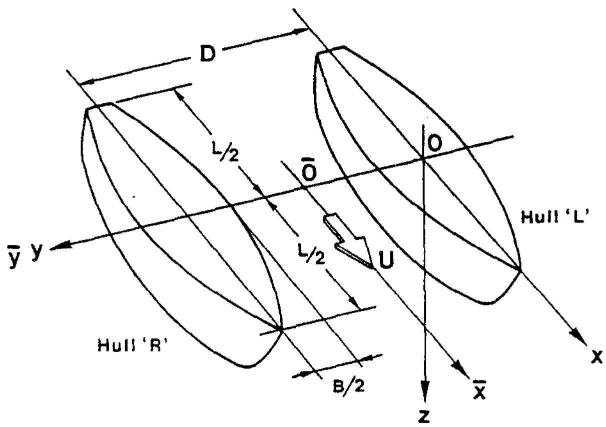

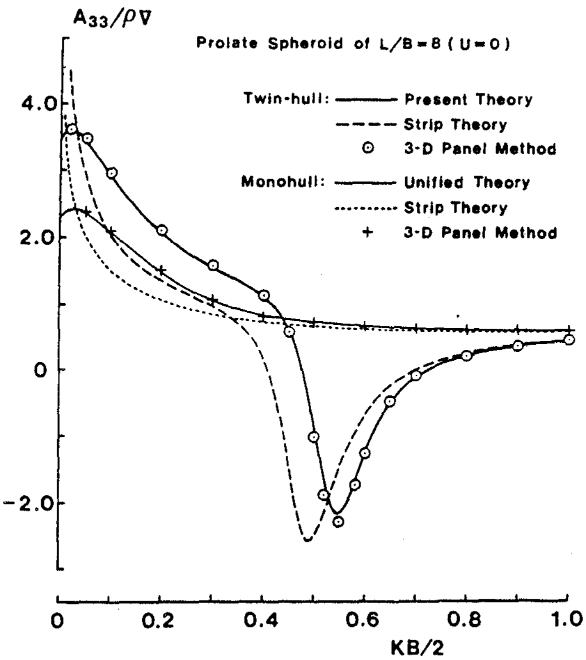

Fig.1 Coordinate system (above)
Fig.2 Heave added mass of twin half-immersed spheroids with $B/L = 1/8$, $D/B = 2$ at $U = 0$ (right)

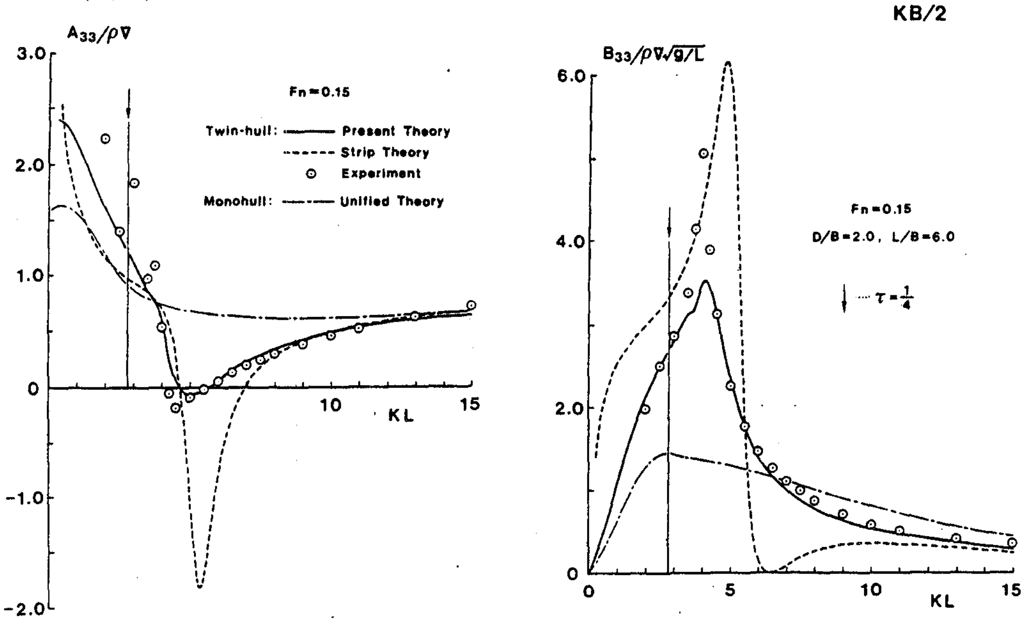

Fig.3 Heave added-mass and damping coefficients of twin Lewis-form ships with $D/B = 2$ at $Fn = 0.15$