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Hydrodynamic modeling of planing catamarans with symmetric hulls

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ABSTRACT

Despite rising popularity of planing catamarans, numerical methods for predicting their hydrodynamics are rather scarce and incomplete. The hydrodynamic interaction between hulls planing parallel to each other is known to become significant when spacing between hulls is sufficiently small. In the present study, a potential-flow method of hydrodynamic sources is applied for modeling steady hydrodynamic characteristics of twin-hull setups. Parametric calculations are carried out for symmetric hulls in variable speed regimes at different spacings, hull aspect ratio, and deadrise angles. Results are presented for the lift coefficient and center of pressure, and some illustrations are given for the water surface elevations. The lift coefficient is found to increase with smaller spacings and higher aspect ratios at moderate and high Froude numbers.

1. Introduction

Boats moving at high speeds operate in the planing mode when the hydrodynamic lift on their hulls overcomes the hydrostatic lift. To improve lateral stability of such boats and to increase available deck space, twin-hull arrangements are often implemented (Fig. 1). The hydrodynamic interaction between hulls operating in a proximity to each other can be significant and needs to be accounted for at the design stage. The hydrodynamic characteristics of catamaran hulls are often quite different from those of typical monohulls. As discussed by Faltinsen (2005), if the divergent waves generated by one hull impinge on and become reflected by the other hull, then the wave field generated by a multi-hull vessel cannot be a simple superposition of wave fields produced by each hull. This happens if the hulls are sufficiently close to each other; and as a consequence, the complex wave pattern in the central region will have strong influence on the hull hydrodynamics.

Over the last several decades planing catamarans have gained popularity for commercial, recreational and military purposes, yet there is a relatively limited body of literature on the subject of planing multi-hulls. Savitsky and Dingee (1954) tested flat plates planing in parallel at different spacings and very high Froude numbers and found that the lift increases as the hulls become closer to each other. Liu and Wang (1979) also conducted a test series with planing catamarans and suggested a modification to the empirical correlation for a single-hull lift (Savitsky, 1964) that accounts for the presence of another hull. Dubrovsky and Lyakhovitsky (2001) briefly described extensive studies conducted in Russia on high-speed multi-hulls and discussed performance-enhancing means, such as hydrofoils and interceptors. Morabito (2011) reviewed some of the archival and recent findings for planing catamarans, noting that the lift correction for a hull in the catamaran arrangement is usually below 5% (relative to the single hull lift) when the spacing between hulls exceeds two of the hull beams. Several CFD-type analyses of specific high-speed multi-hulls can be also found in the literature (e.g., Zhou, 2003; Kandasamy et al., 2011; Yousefi et al., 2014).

The main objectives (and novelties) of this paper are to apply a computationally efficient potential-flow method for evaluating hydrodynamics of planing catamarans and to present numerical results for the lift coefficient and the center of pressure of catamarans in a range of geometrical parameters and speed regimes. Only prismatic symmetric hulls with hard chines are considered here, as illustrated in Fig. 1. The current numerical model is based on the linearized three-dimensional method of hydrodynamic singularities of a source type that was previously developed and applied for hydrodynamic modeling of single planing hulls in early planing regimes (Matveev and Ockfen, 2009; Matveev, 2014a), when both hydrostatic and hydrodynamic lift components are important. It can be noted that the present method belongs to a family of boundary elements methods, and a number of publications exist on the subject of BEMs applied for single-hull hydrodynamics. For example, Doctors (1974) and Wang and Day (2007) utilized a distribution of pressure elements over planing surfaces, while Lai and Troesch (1996) and Benedict et al. (2001) applied vortex-lattice methods. A detailed review of modeling techniques for planing hulls has been recently given by Yousefi et al. (2013).

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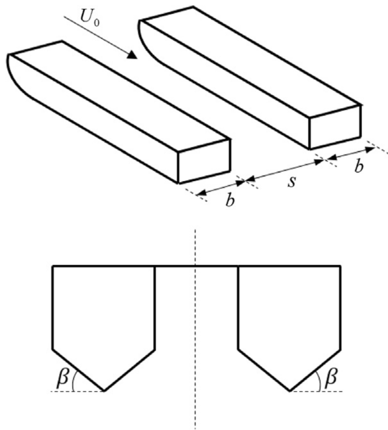

Fig. 1. Schematic of twin hull arrangement with flat or double-deadrise hull bottoms.

2. Mathematical model

To model hydrodynamics of hard-chine planing catamarans, a potential-flow method based on hydrodynamic sources is utilized in this study. In the flow with sufficiently high velocity (or Reynolds number), viscous forces can be usually neglected outside of thin boundary layers near solid surfaces and separation zones behind blunt bodies. The water flow in the present method is assumed to be inviscid, irrotational and steady. A general schematic for the numerical problem is given in Fig. 2. The water flow is assumed to be symmetric with respect to the catamaran centerline ($z=0$), which allows us to use mirror source images in the port side of the numerical domain and reduce the number of unknown variables.

The Bernoulli equation can be applied on the water surface as the dynamic boundary condition,

$$p_0+\frac{1}{2}\rho\, U_0^2=p_w+\frac{1}{2}\rho\, U_w^2+\rho\, g\, y_w, \quad (1)$$

where p_0 and U_0 are the pressure and velocity in the water flow far upstream of the hull at $y=0$, ρ is the water density, and $p_w(x,z)$ and $U_w(x,z)$ are the pressure and velocity on the water surface with elevation $y_w(x,z)$. With consideration of small trim angles of the hull and sufficiently high speeds, flow disturbances induced by the hulls can be assumed relatively small. Therefore, the wave slopes and the x-axis velocity perturbation $u'=U_x-U_0$ will be also small. Then, the linearized form of Bernoulli equation on the water surface can be presented as follows,

$$\frac{1}{2}C_p+\frac{u'}{U_0}+2\pi\frac{y_w}{\lambda}=0, \quad (2)$$

where $C_p=(p_w-p_0)/(\rho\, U_0^2/2)$ is the pressure coefficient (zero on the free water surface and non-zero on the wetted hull surface) and $\lambda=2\pi\, U_0^2/g$ is the length of a wave on the unconstrained free water surface.

The water flow perturbations produced by the hull are modeled here with distribution of hydrodynamic sources over a horizontal plane at $y=0$ (Fig. 2). A velocity potential of each source satisfies the Laplace equation in the water domain. The collocation points, where Eq. (2) is satisfied, are shifted upstream from the sources. This staggered arrangement eliminates the wave reflection from the downstream boundary of a numerical domain (Bertram, 2000). Then, the x-component of the velocity disturbance can be calculated from the source intensities as follows,

$$u'(x_i^c,z_i^c)=\frac{1}{4\pi}\sum_j q_j(x_i^c-x_j^s)\left(\frac{1}{r_{i,j}^3}+\frac{1}{R_{i,j}^3}\right), \quad (3)$$

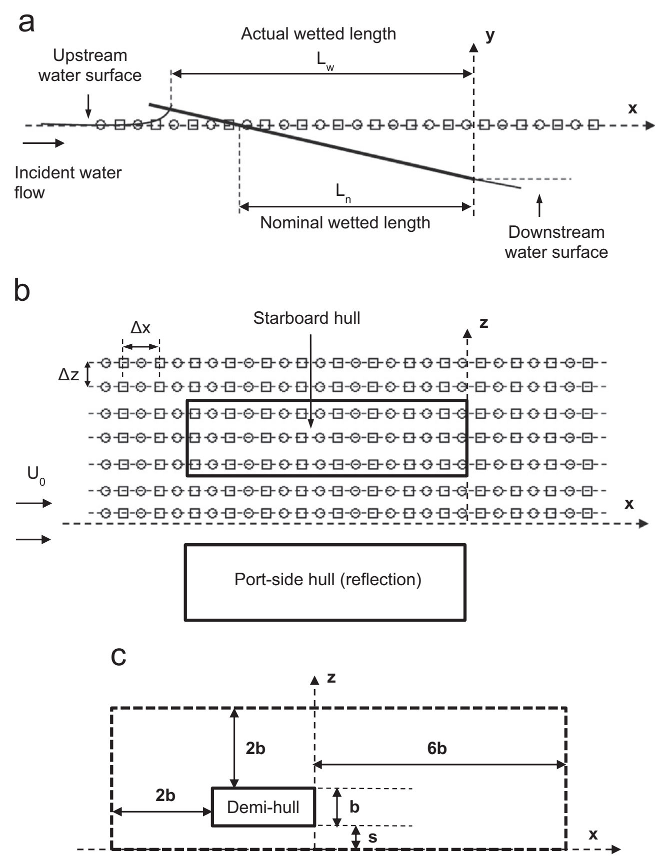

Fig. 2. Geometrical schematic for the computational model. (a) Side view, (b) top view. Sources and collocation points are shown by circles and squares, respectively. Distances between sources are exaggerated. (c) Numerical domain with main dimensions. The x-axis is the symmetry line.

where (x_i^c,z_i^c) and (x_j^s,z_j^s) are the coordinates of the collocation point i and the source j with intensity q_j in the starboard part of the numerical domain, $r_{i,j}=\sqrt{(x_i^c-x_j^s)^2+(z_i^c-z_j^s)^2}$ is the horizontal distance between these points, and $R_{i,j}=\sqrt{(x_i^c-x_j^s)^2+(z_i^c+z_j^s)^2}$ is the distance between the considered collocation point and the mirror reflection of source j (with respect to $z=0$ plane).

The linearized kinematic boundary condition on the water surface gives an additional relation between the source strengths and the local water surface slope (e.g., Matveev, 2014b),

$$\frac{1}{2}\left(\frac{q_{i-1}}{\Delta x_{i-1}\Delta z_{i-1}}+\frac{q_i}{\Delta x_i\Delta z_i}\right)=-2U_0\frac{y_i^s-y_{i-1}^s}{x_i^s-x_{i-1}^s}, \quad (4)$$

where q_{i-1} and q_i are the source strengths of the upstream and downstream neighbors of the collocation point i, and Δx and Δz are the intervals between the source locations in x and z directions. On the wetted hull surface, the slope is assigned, so the source strengths can be directly related to the hull trim angle. Thus, the linear system of equations (Eqs. 2–4) is solved for the water surface elevations beyond the hull, pressure coefficient on the hull wetted surface, source intensities, and velocity perturbations. The lift force on the hull and the center of pressure are found by integrating the pressure distribution on the hull wetted surface.

One complication in the considered problem is the initially unknown wetted areas of the hull, since the water rises in front of the planing surfaces (Fig. 2). The water jet that appears above the water impingement point on the plate is ignored similar to Riabouchinsky model applied for flows with developed cavitation (e.g., Matveev, 2003). An iterative solution procedure is implemented to find the final wetted length of the plate, L_w, as it is not precisely known in the beginning. The front point can be initially