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Hydrodynamic modeling of planing hulls with twist and negative deadrise

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ABSTRACT

Hulls of hard-chine planing boats often have complicated geometries. In this study, non-prismatic hulls with variable and negative deadrise angles are considered. The method of hydrodynamic sources is applied to model steady water flow around such hulls in the linearized approximation at finite Froude numbers. The solution includes pressure distribution on the hull surface which defines the lift force and center of pressure. For validation, modeling results are compared with an analytical solution for a flat plate and test data of a hull with a constant-deadrise section. Parametric calculations are carried out for a twisted hull at a fixed attitude and compared with an effectively similar prismatic planing surface in a range of Froude numbers. Non-prismatic hulls with variable aspect ratios are also investigated. In addition, results are presented for two hulls having positive and negative deadrise angles.

1. Introduction

Efficient boat motion at sufficiently high speeds often occurs in the planing mode. In this regime, the boat movement resembles skimming along the water surface rather than plowing through the water, and the hydrodynamic lift exerted on the hull becomes larger than the hydrostatic lift. The occurrence of the planing mode can be approximately characterized by achievement of high Froude numbers, e.g., when the length Froude number exceeds about one or the displacement Froude number is greater than about three.

For approximate estimations of planing hull hydrodynamics, simplified methods are commonly used, such as semi-empirical correlations for prismatic (constant-deadrise or monohedral) hulls given by Savitsky (1964). However, most real boats have more complicated geometry, including variable deadrise, steps, and so on. The motivation for using twisted hulls, for example, is to improve seaworthiness with larger deadrise near the bow, while keeping high lift-drag ratio with low-deadrise aft sections. To account for the hull twist, several simple methodologies were proposed in the past (Blount and Fox, 1976; Bertorello and Oliviero, 2006; Savitsky et al., 2007), which usually suggested using an equivalent prismatic hull with specially chosen geometrical parameters. Such recommendations, although useful as initial approximations, cannot fully account for intrinsically more complex hydrodynamics of hulls with more complicated geometries.

Although much less popular than traditional V-hulls, planing boats with negative deadrise angles have been also implemented. As noted by Egorov et al. (1978), such hulls are beneficial for higher loadings. For example, they indicated that at deadrise angles 5° and 15° the beam-based lift coefficient C_L (defined in Section 3 below) should exceed values of about 0.11 and 0.09, respectively, for the negative-deadrise hulls to perform better than positive-deadrise hulls at optimal trim conditions. At large magnitudes of negative-deadrise angles and especially at low trim angles, a foam-air zone can be formed along the boat centerline extending down to the transom, thus resembling a tunnel-hull configuration. However, the present analysis is limited to relatively low deadrise angles and sufficiently high trim angles without formation of multi-phase mixtures, modeling of which is very challenging.

A method of hydrodynamic sources is utilized in this study for modeling twisted and negative-deadrise planing hulls. This mathematical approach has been previously presented and applied for predicting hydrodynamics of monohedral hulls and near-hull/hydrofoil wave contours (Matveev and Ockfen, 2009). This method allows us to account for non-trivial hull geometry through appropriate boundary conditions on the hull, as well as for finite Froude numbers. This technique belongs to a wider class of boundary element methods that have been extensively used for computationally efficient modeling of planing hull hydrodynamics (e.g., Doctors, 1974; Wellicome and Jahangeer, 1978; Lai and Troesch, 1996; Xie et al., 2005; Ghassemi and Ghiasi, 2008).

A mathematical formulation of the current method is outlined in the next section. Results are presented for two validation cases involving three-dimensional problems and for some parametric variations of non-prismatic and negative-deadrise hulls.

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2. Mathematical model

To model hydrodynamics of three-dimensional planing hulls, a method of hydrodynamic singularities is utilized in this work. The water flow around the hull is assumed inviscid, irrotational and steady. A general schematic of the problem is shown in Fig. 1. The Bernoulli equation is applied on the water surface,

$$p_0+\frac{1}{2}\rho U_0^2=p+\frac{1}{2}\rho U^2+\rho gz, \tag{1}$$

where P_0 and U_0 are the pressure and velocity in the far upstream undisturbed water surface at $z=0$, ρ is the water density, and $p(x,y)$ and $U(x,y)$ are the pressure and velocity on the water surface with elevation $z_w(x,y)$. Assuming small trim angles of the hull and sufficiently high Froude numbers, one can expect relatively small flow disturbances caused by the hull presence. Therefore, the wave slopes and the x-axis velocity perturbation $u=U_x-U_0$ will be small as well. Then, the Bernoulli equation can be linearized and written as follows,

$$\frac{1}{2}C_p+\frac{u}{U_0}+2\pi\frac{z_w}{\lambda}=0, \tag{2}$$

where $C_p=(p-p_0)/(\rho\,U_0^2/2)$ is the pressure coefficient (zero on the free water surface) and $\lambda=2\pi\,U_0^2/g$ is the wavelength on the unconstrained free water surface.

The water flow disturbance induced by the hull is modeled here by hydrodynamic sources distributed over a horizontal plane at $z=0$ (Fig. 1b and c). A velocity potential of each source satisfies the Laplace equation in the fluid domain. The collocation points, where Eq. (2) is fulfilled, are shifted upstream from the sources. This staggered arrangement minimizes the influence of the downstream boundary of the numerical domain (Bertram, 2000). Then, the x-component of the velocity perturbation can be determined from the source intensities,

$$u\,(x_i,y_i)=\frac{1}{4\pi}\sum_j\frac{q_j}{r_{i,j}^2}\frac{x_i-x_j^s}{r_{i,j}}, \tag{3}$$

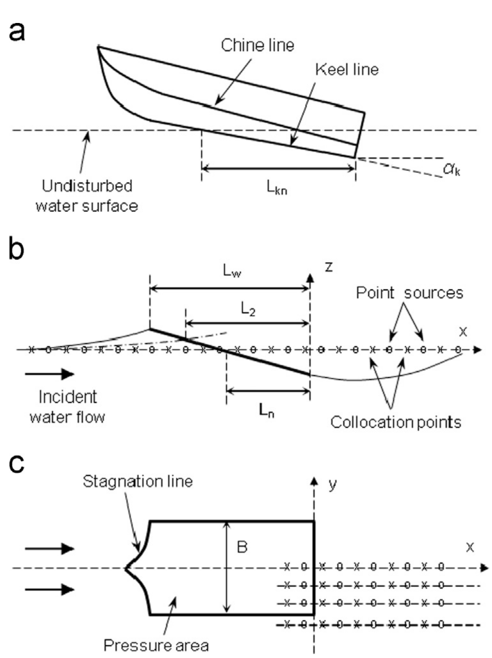

Fig. 1. (a) Planing hull with variable deadrise. (b) Longitudinal cross-section. (c) Top view of a planing hull. Only a small part of the numerical domain is shown. Distances between sources are exaggerated.

where (x_i,y_i) and (x_j^s,y_j^s) are the coordinates of the collocation point i and the source j with intensity q_j, and $r_{i,j}=\sqrt{(x_i-x_j^s)^2+(y_i-y_j^s)^2}$ is the horizontal distance between these points. In the analytical integral-differential approach, there would be an integral in the Cauchy principal value sense instead of a finite sum in Eq. (3). The linearization of the kinematic boundary condition on the water surface results in the additional equation relating source intensities and the local water surface slope (Matveev, 2007),

$$\frac{1}{2\Delta y}\left(\frac{q_{i-1}}{\Delta x_{i-1}}+\frac{q_i}{\Delta x_i}\right)=-2U_0\frac{\partial z_w}{\partial x}(x_i,y_i), \tag{4}$$

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 Δy are the intervals between the source locations in x and y directions. On the hull surface, the slope is known; therefore, the source intensities can be related to the local trim angle of the hull. The linear system of equations involving Eqs. (2)–(4) is solved directly for the water surface elevations outside the hull, pressure coefficient on the hull, source intensities, and velocity perturbations. The lift force on the hull and the center of pressure are then determined from pressure distribution on the hull surface.

One complication in the problem under consideration is the initially unknown wetted lengths of the hull $L_w(y)$, since the water tends to rise in front of the planing surface (Fig. 1). In order to determine the water rise, an iterative solution procedure is applied. In the beginning, the water rise is neglected, and the wetted lengths are assumed to be equal to the nominal lengths ($L_n(y)$ in Fig. 1). Then, a solution is found for the water surface elevations. A representative water surface contour obtained after the first iteration is shown by a dash-dotted line in Fig. 1b. Since it crosses the hull surface, the wetted lengths must be corrected. So in the second iteration, the wetted lengths $L_2(y)$ are selected as indicated in Fig. 1b; their left boundaries correspond to the intersections between the hull surface and the water surface calculated in the first iteration. A new solution obtained in the second iteration produces another shift of the water surface, and the wetted lengths have to be corrected again. Such iterative calculations are repeated until the intersections between the water and hull surfaces, as well as wave contours, stop changing. Additionally, the water spray that can appear above the water rise line is neglected in this model.

The conducted mesh-independence studies suggested the following recommendations for selecting dimensions of numerical cells and a size of the entire domain. The distances between sources on the hull in both x- and y-directions should be chosen as $\min(B/12,\ L_w/12,\ \lambda/30)$, where B and L_w are the beam and the mean nominal wetted length of the hull, respectively, and λ is the wavelength on the unconstrained free water surface. Outside of the hull, Δx can gradually increase towards the front and back boundaries of the numerical domain (to make computations more efficient), but it is capped by the value $\lambda/30$. The distances in front and on the sides of the hull up to the domain boundaries are chosen as $2B$; and the distance from the hull transom to the downstream domain boundary is taken as $\max(12B,\ 0.1\lambda)$. Selecting finer cells or larger domain does not lead to significant changes in calculated hydrodynamic properties of the hull.

3. Results

3.1. Validation cases

The first validation is carried out for a flat planing surface with a finite aspect ratio. Wang and Rispin (1971) obtained an analytical