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A numerical modeling of hydrodynamic characteristics of various planing hull forms

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ABSTRACT

A numerical algorithm based on the boundary element method (BEM) is presented for predicting the hydrodynamic characteristics of the various planing hull forms. The boundary integral equation is derived using Green's theorem on the wetted body surface and the free surface. The ventilation function at the transom is estimated with Doctor's empirical formula. This function is defined as the transom zone free surface boundary condition. The combined boundary integral equation and modified free surface boundary condition are simultaneously solved to determine the dipole on the wetted hull surface and the source on the free surface. The method is applied to investigate three examples of planing hulls, which include flat-plates, as well as wedge-shaped and variable deadrise planing hulls. Their hydrodynamic characteristics are calculated for different speeds. Computational results are presented and compared with existing theories and experiments. On the whole, the agreement between the present method and the selected experimental and numerical data is satisfactory.

1. Introduction

Planing craft serve various purposes, including recreation, racing, trade and military operations. Depending on the intended use, such vessels vary in shape and size. It is, therefore, the task of the naval architect to design the planing hull for a particular purpose and produce an optimal form which maximizes the hydrodynamic efficiency. Planing may occur when the volumetric Froude number of the craft reaches $Fn_\nabla = U/\sqrt{g\nabla^{1/3}} \geq 2$, where U is the operating speed of the craft and ∇ is the volume displacement. The downward deflection of the water due to a trim angle produces a lifting force under the wetted surface of the hull. The pressure distribution acting on the planing hull determines the resulting hydrodynamic characteristics (lift and resistance force). The resulting trim is a critical parameter in defining a planing boat's performance.

Hull geometry is defined by the deadrise angle which is a measure of the angle of the bottom of the hull from the horizon (Flat-bottomed boats have a 0° deadrise angle). Generally speaking, in a properly configured planing hull form, the deadrise angle diminishes from bow towards stern. The planing hull is typically run with a small bow-up trim that is around 2–6°. However, it is necessary to design the hull form to reach the highest lift-to-drag ratio, good sea-keeping behavior, diminish slamming and avoid porpoising and dynamical heel.

Since the early 1950s, several planing hull forms have been systematically investigated.

Kapryan and Boyd (1955) reported various experimental measurements of pressure distribution on prismatic bodies. Clement and Blount (1963) performed extensive experiments on a systematic series and presented a simplified prediction method for the estimation of planing hull drag. Savitsky (1964) presented a performance prediction method using the empirical equations for lift, drag, wetted areas and the center of pressure, which is still used as a first estimate for planing hull drag. Experimental and numerical studies have been carried out by Katayama et al. (2002) to measure the drag, lift and moment coefficients as well as the pressure distribution on a prismatic planing hull at various speeds.

Numerical techniques for performance and comfort assessment are effective in the early stages of planing hull design, especially in selecting the hull form. Various theoretical and numerical approaches have been used to study planing. The planing of a flat plate has been studied by many researchers. Doctors (1975) presented a novel technique using a finite pressure element method to model planing hulls. Wang and Rispin (1971), Wellicome and Jahangeer (1978) studied the 3D linear planing problem based on the representation of the pressure distribution over the wetted area by assembling rectangular elements of constant pressure. Tong (1989) used a similar approach adopting swept-back constant pressure elements, which

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could match the leading edge profile of the wetted area quite well. Cheng and Wellicome (1994) used transverse pressure strips to represent the pressure distribution. The transverse pressure variation along each strip was expressed with a sine series which had the advantage of using clear mathematical formulation for each term of the series. Savander et al. (2002) used the boundary value method for steady planing hulls and obtained reliable relationships between the perturbation potential and the vortex distribution. Wang (2003), Xie et al. (2005) and Wang and Day (2007) used a finite pressure element method and developed procedures to remove fluctuations in pressure results. They have mostly presented predictions of pressure distribution on flat-plates. Doctors and Beck (2005) and Maki et al. (2005) developed an empirical formula to estimate the ventilation function of the transom. They employed this formula to provide an accurate calculation of the total drag of the craft.

Ghassemi and Ghiasi (2008), Ghassemi and Kohansal (2009a, b) used the boundary element method within a practical numerical approach to predict the hydrodynamic characteristics of three-dimensional planing and non-planing hulls. Recently, a very comprehensive textbook of the hydrodynamics of high-speed marine vehicles has been published by Faltinsen (2005), who has devoted one chapter of the book to planing hulls.

The aim of the present paper is to determine the hydrodynamic characteristics of various three-dimensional planing hull forms using the boundary element method. The numerical results of three types of planing bodies are presented here. The results include pressure, lift, drag and wave pattern at various Froude numbers. Comparisons reveal that the method is efficient and the results are in good agreement with experimental measurements.

2. Mathematical modeling of the problem

Consider a three-dimensional planing hull moving at the constant speed $\vec{U}$ in a calm and unrestricted flow. The global coordinate system is fixed on the body and is presented in Fig. 1. The x-axis is positive in the direction of forward motion, the z-axis is positive upwards and the y-axis completes the right-handed system. The origin of the coordinate system is located at the point of intersection of the keel, transom and center plane. It is assumed that the fluid is incompressible, inviscid and without surface tension and that the flow is irrotational. Therefore, a boundary value problem is established in which Laplace's equation is taken as the governing equation of the flow field around the planing hull. Moreover, the fluid disturbance generated by the planing hull is very small if the trim angle and deadrise angle of the planing hull are small. In this way, the linearized boundary conditions are adopted in which the first order terms are retained and the boundary value problem is assumed to be satisfied on the horizontal plane (z=0) instead of the exact free surface. The potential function is introduced by $\Phi(x,y,z)$, so its velocity is given by Φ_x and Φ_y in the x and y directions, respectively. In the fluid domain, the total potential function $\Phi(x,y,z)$ satisfies Laplace's equation:

$$\nabla^2 \Phi = 0, \quad x, y \in R, \quad z < \zeta(x,y), \tag{1}$$

where $\zeta(x,y)$ is the free surface elevation.

The total velocity potential, Φ, is harmonic in the fluid domain and consists of the perturbation potential, ϕ, and free stream velocity potential, ϕ_{in}, and can be expressed as follows:

$$\begin{cases} \Phi = \phi + \phi_{in}, \\ \phi_{in} = -\vec{U}\vec{X}, \end{cases} \tag{2}$$

where $\vec{U}$ is the planing forward speed and $\vec{X}$ is the position vector. The perturbation potential ϕ is computed by the boundary element method, which is based on Green's identity. The perturbation potential is governed by Laplace's equation:

$$\nabla^2 \phi = 0. \tag{3}$$

The boundary value problem can be constructed by specifying the boundary conditions. The domain boundary is composed of the free surface, body (ship hull) boundary, bottom boundary, far field (downstream or upstream) boundaries, and vertical side boundaries. The following boundary conditions should be satisfied by the perturbation potential on these boundaries in order to solve Eq. (3).

2.1. Hull-boundary condition

The hull-boundary condition simply expresses the fact that the normal component of the velocity must be zero. This boundary condition requires that the flow should be tangent to the body wetted surface. Therefore, the flow velocity normal to the solid boundary is zero:

$$\frac{\partial \phi}{\partial n} = -\vec{U}\hat{n} \quad \text{on body hull} \tag{4}$$

in which $\hat{n} = n_x\hat{i} + n_y\hat{j} + n_z\hat{k}$ is the unit normal vector on the surface and is positive into the fluid.

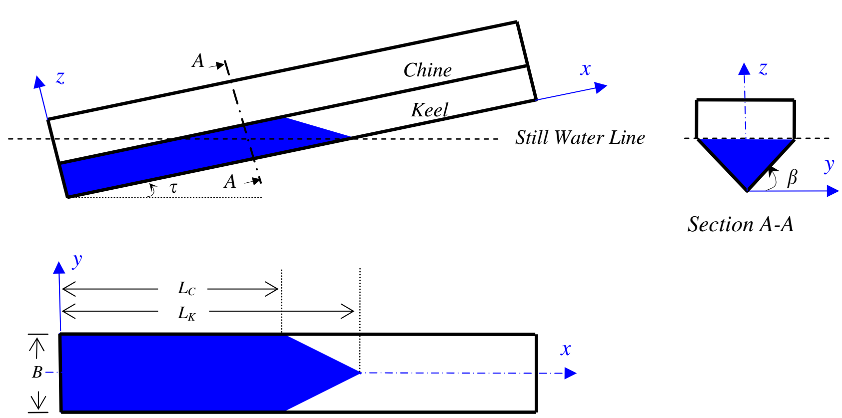

Fig. 1. Coordinate system and definition sketch in planing problem.