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On application of three-dimensional linearized potential-flow model for shallow-water planing

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Abstract

Hydrodynamics of planing hulls is affected by proximity to the seabed floor in shallow waters. In this study, a three-dimensional steady linearized model based on the potential theory is applied to model flat planing surfaces at finite water depth and finite Froude numbers. Modeling results for shallow waters agree with experimental data in the subcritical and supercritical regimes sufficiently far from the critical speed that corresponds to the depth Froude number of unity. At the critical speed, nonlinear and unsteady effects become important, and a different modeling approach is required.

Keywords: Shallow-water effects; Planing hulls; Potential flow modeling.

1. Introduction

At sufficiently high speeds, fast boats often rely on hydrodynamic lift to support a significant fraction or even most of their weights. This operational regime when a boat skims on the water surface is called planing. Hulls of planing craft usually employ hard chines for effective water separation on the sides and sometimes transverse steps to reduce the bottom wetted area. Hydrodynamics of planing boats has been extensively studied both experimentally and numerically (e.g., [10,12]).

In shallow-water operations of planing craft, a finite water depth affects the boat hydrodynamics. Near the critical speed, corresponding to the depth Froude number of one, a solitary wave is formed at the hull, accompanied by fluctuations in the lift force [9]. The depth Froude number is defined as $Fr_H = U/\sqrt{gH}$, where U is the boat speed, g is the gravity constant, and H is the water depth. In the supercritical regime ($Fr_H > 1$), the wave pattern shifts aftward [9], and the lift force exceeds that in deep water at the same speed.

Some experimental studies with prismatic planing hulls in shallow waters were carried out in the past [2,11]. Toro [13] tested a more complicated hull form. Morabito [9] has recently conducted towing experiments with flat-bottom planing hulls aiming at finer speed resolution over a broad speed range, from the subcritical ($Fr_H < 1$) through supercritical speeds.

Theoretical analyses of two-dimensional planing at finite water depth were done by Haskind [3] and Fridman and Tuck [4]. Mousaviraad et al. [10] employed more sophisticated (and computationally demanding) CFD tools to study a variety of planing hull phenomena including shallow water effects.

The purpose of this note is to apply a computationally inexpensive potential-flow model for shallow-water planing. This model is based on a steady three-dimensional linearized approach previously validated for hydrodynamics of planing hulls in deep water [6], flows with developed air cavities [8] and air-supported marine craft [7]. Due to steady and linearized treatments, the present model is unlikely to perform well near the critical speed, so the main objective here is to

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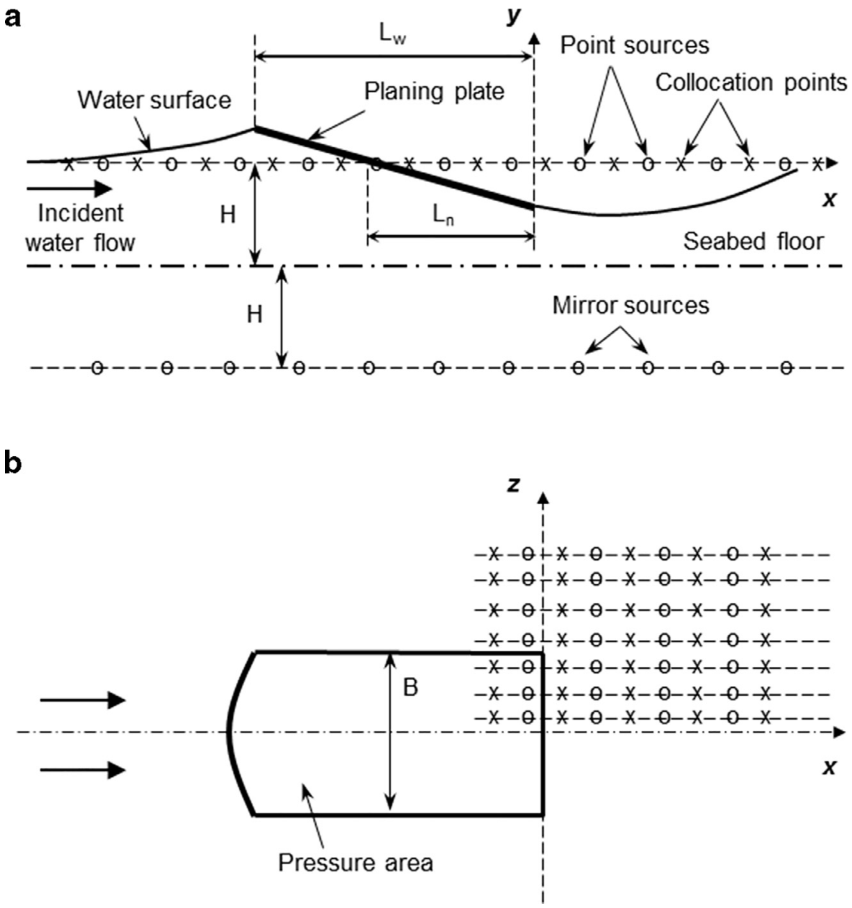

Fig. 1. Geometrical schematic for the numerical model. (a) Side view of a longitudinal section. (b) Top view of a planing surface. Sources and collocation points are shown by circles and crosses, respectively. Only a small part of the numerical domain is depicted. Distances between sources are exaggerated.

determine whether the model is adequate for the subcritical and supercritical regimes of planing hulls in shallow water.

2. Mathematical model

The problem schematic for the mathematical model is shown in Fig. 1. A flat plate with beam B and trim angle τ is steadily planing with velocity U on the surface of water with depth H. The water flow is considered to be inviscid and irrotational and symmetric with respect to the plate centerline. The seabed floor is assumed to be rigid. The numerical domain has upstream, downstream and side boundaries, which dimensions are determined from mesh-convergence studies. In this note, a description of the model is focused on dealing with a finite water depth, whereas more detailed mathematical background can be found in previous publications (e.g., [6–8]).

The hull trim angle and the water surface slopes are assumed to be small, so the velocity perturbations in the water flow are much smaller than the incident flow velocity U. Hence, a linearized form of the Bernoulli equation can be used as a dynamic boundary condition on the water free surface,

$$\frac{1}{2}C_p + \frac{u}{U} + 2\pi\frac{y_w}{\lambda} = 0, \qquad (1)$$

where $C_p = (p - p_0)/(\rho U^2/2)$ is the pressure coefficient (non-zero only under the plate), p and p_0 are the pressure values on the water surface and above the free surface, respectively, ρ is the water density, u is the x-component of the velocity disturbance, y_w is the water surface elevation, $\lambda = 2\pi U^2/g$ is the length of propagating waves on the unbounded free water surface, and g is the gravitational constant.

In the linearized formulation, the flow perturbations can be modeled with a distribution of point hydrodynamic sources over a horizontal plane at $y = 0$, coinciding with the undisturbed water surface, and a set of mirror sources on a plane shifted down by $2H$, as shown in Fig. 1. This arrangement eliminates vertical velocities at the seabed floor at $y = -H$. A velocity potential of each source satisfies the governing Laplace equation in the water domain. The collocation points, where Eq. (1) is fulfilled, are located on a plane $y = 0$ and are shifted upstream from the sources. Such a staggered arrangement suppresses the wave reflection from the downstream border of the numerical domain [1]. Due to the problem symmetry with respect to x-y plane, only the starboard portion of the setup ($z > 0$) can be considered with the mirror sources placed on the port side ($z < 0$).

The x-component of the velocity perturbation in the starboard domain is computed by summing contributions from