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Short communication

On hydrodynamics of a planing plate in a laterally restricted channel

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ABSTRACT

A problem of a planing surface moving steadily at finite Froude numbers in a laterally restricted seaway is considered in this note. A linearized potential flow method based on point sources is applied to model hydrodynamics of a planing plate. Numerical results are obtained and presented for the lift coefficient and the center of pressure. The variable parameters include the ratio of the channel width to the plate beam, beam-based Froude number, and nominal aspect ratio of the plate. A comparison is shown with empirical correlations for unrestricted seaway and with theoretical results for the limiting two-dimensional case.

1. Introduction

It is well known that restricted seaways can significantly affect hydrodynamics of traditional ship hulls (e.g., Tuck, 1978; Zhou et al., 2012). The confined flow phenomena are also important for air-supported marine vehicles (e.g., Doctors, 1993; Rozhdestvensky, 2000). Finite-depth effects on planing craft hydrodynamics were discovered and studied in the past as well as recently (e.g., Green, 1935; Morabito, 2013). Hence, it can be also presumed that laterally restricted seaways may have a significant impact on the planing boat performance. Determining the influence of the channel width on the lift coefficient and the center of pressure of the simplest planing configuration, a flat plate, is a subject of this communication. Somewhat related to the present problem are studies of planing catamarans, where hydrodynamic interactions between demi-hulls are found to modify hydrodynamic properties of each demi-hull (e.g., Savitsky and Dingee, 1954; Bari and Matveev, 2016).

A linearized potential-flow method is applied in this work to model steady hydrodynamics of a planing plate in a channel. Three-dimensional planing surfaces in unrestricted seaway were previously analyzed with related linearized potential-flow approaches. Wang and Rispin (1971) derived an analytical solution for a plate planing at high but finite Froude numbers. Doctors (1974, 1975) and Wellicome and Jahangeer (1979) employed a distribution of pressure elements on planing surfaces. Cheng and Wellicome (1994) developed a pressure strip method for planing hulls to achieve better numerical convergence. Xie at al. (2005) and Wang and Day (2007) gave further recommendations on how to avoid numerical instabilities in the pressure element methods.

In the present study, a distribution of point hydrodynamic sources placed on the boundaries of the water domain is utilized. The numerical model is built upon our previous modeling efforts that addressed various configurations of planing hulls (e.g., Matveev and Ockfen, 2009; Bari and Matveev, 2016), developed cavitating flows (Matveev and Miller, 2011), and air-supported marine craft (Matveev, 2014).

2. Mathematical model

A general schematic for the numerical model is given in Fig. 1. A flat plate with trim angle α is steadily planing on a water surface in a deep, infinitely long channel parallel to the channel walls. The water flow is considered to be inviscid and irrotational. At the channel boundaries ($z = \pm W/2$) the flow velocity normal to the walls must be zero. To satisfy this condition, an equivalent problem of an infinite series of identical plates planing parallel to each other can be analyzed instead of a single channel with rigid walls; a fragment of such a setup is shown in Fig. 1c. The numerical domain also has upstream and downstream boundaries, whose dimensions are discussed below.

In this communication, only a brief outline of the mathematical model is given, focusing on specifics of treating an infinite series of flow strips. For other modeling details, one can refer to our previous publications (e.g., Matveev and Ockfen, 2009; Matveev, 2014; Bari and Matveev, 2016).

The trim angle of the hull and the water surface slopes are assumed to be small, so velocities of the disturbed flow (caused by the presence of the plate) are much smaller than the incident flow velocity, U, with respect to the plate. Then, the problem can be linearized, so that Bernoulli equation on the water surface can be presented in a linear non-dimensional form as follows,

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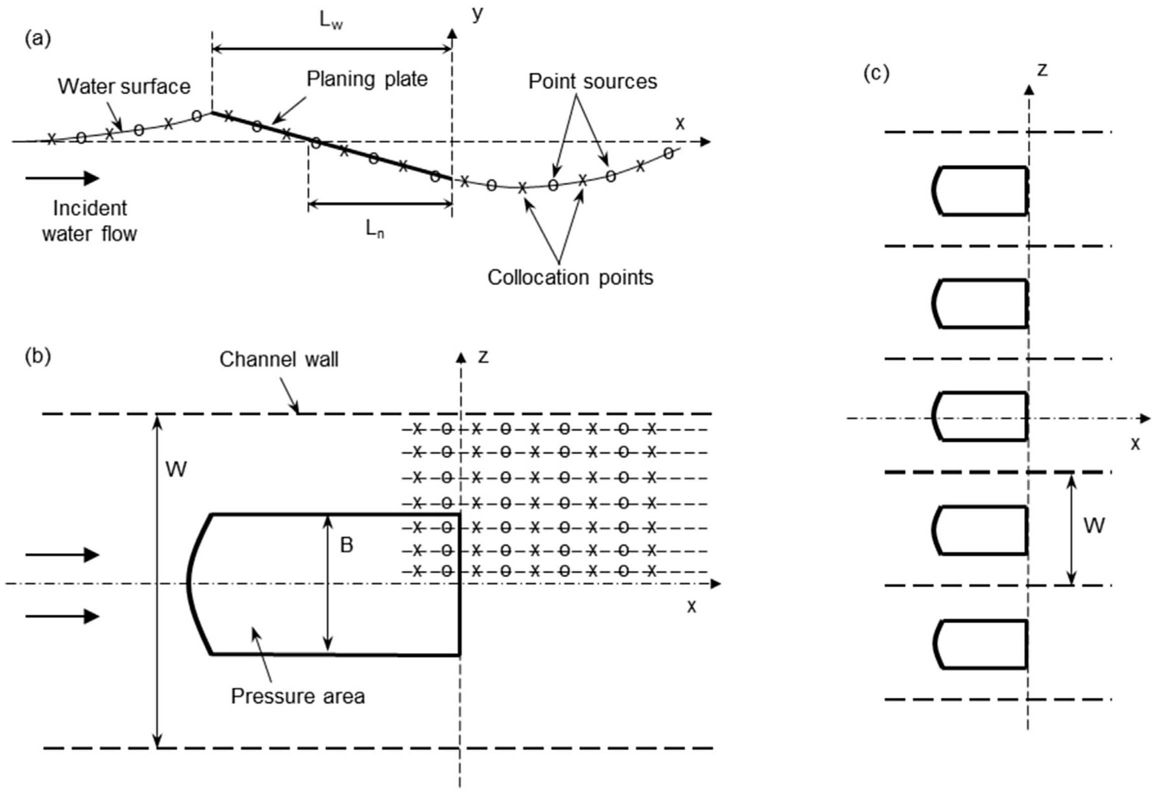

Fig. 1. Geometrical arrangement of the numerical model: (a) side view of a longitudinal section including planing plate with a schematic view of the disturbed water surface, (b) top view of one flow strip restricted by channel walls, (c) top view of five parallel flow strips. Sources and collocation points are schematically indicated by circles and squares, respectively; only a small number of them are shown. The x-axis is the symmetry line.

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

where $C_p = (p - p_0)/(\rho\, U^2/2)$ is the pressure coefficient (zero on the free water surface), p and p_0 are the pressure on the water surface and above the free surface, respectively, ρ is the water density, u is the x-component of the velocity perturbation, y_w is the water surface elevation, $\lambda = 2\pi\, U^2/g$ is the wavelength on the unconstrained free water surface, and g is the gravity constant.

The flow disturbance under consideration can be modeled by a distribution of standard hydrodynamic sources placed on the water surface (Fig. 1a and b). A velocity potential of each source satisfies the Laplace equation in the water domain. The collocation points, where Eq. (1) is fulfilled, are shifted upstream from the sources. This staggered arrangement removes the wave reflection from the downstream boundary of a numerical domain and ensures the radiation condition (Bertram, 2000). Due to symmetry in this problem with respect to x-y plane and an infinite number of identical parallel flow strips (associated with each planing plate), the x-component of the velocity perturbation in the starboard part of the central strip ($0 < z < W/2$) can be computed as follows,

$$u\left(x_i^c, z_i^c\right) = \frac{1}{4\pi}\sum_j q_j\left(x_i^c - x_j^s\right)\sum_{k=-\infty}^{+\infty}\left(\frac{1}{r_{i,j,k}^3} + \frac{1}{R_{i,j,k}^3}\right), \tag{2}$$

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 located in the starboard part of the central strip, and $r_{i,j,k} = \sqrt{(x_i^c - x_j^s)^2 + (z_i^c - [z_j^s + kW])^2}$ and $R_{i,j,k} = \sqrt{(x_i^c - x_j^s)^2 + (z_i^c + [z_j^s + kW])^2}$ are the distances between the considered collocation point and all the sources (in all strips). Due to linearization, the vertical distances of the sources and collocation points from the undisturbed water level are ignored in the expressions for distances. The infinite summation in Eq. (2) accounts for the identical strips shifted along z-axis by the integer number of the channel widths kW. In the numerical implementation, however, one has to use a finite number of strips, N, so $k = -N, ..., N$. Determining the adequate quantity of strips that must be included to achieve results almost the same as those with the infinite number of strips is demonstrated in the next (Results) section.

Equation (1) represents the dynamic boundary condition for the present problem. The linearized kinematic boundary condition on the water surface follows from a relation between the source strengths and the local water surface slope (e.g., Matveev, 2014),

$$\frac{1}{2}\left(\frac{q_{i-1}}{\Delta x_{i-1}\Delta z_{i-1}} + \frac{q_i}{\Delta x_i \Delta z_i}\right) = -2U\frac{y_i^s - y_{i-1}^s}{x_i^s - x_{i-1}^s}, \tag{3}$$

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 source intensities can be immediately found from the given trim angle of the planing plate. Thus, the linear system of equations (Eqs. (1)–(3)) can be formed. The unknowns include water surface elevations outside the plate, pressure coefficients on the plate, source intensities, and velocity perturbations. The lift force on the hull and the center of pressure are found by simply integrating the obtained pressure distribution on the plate wetted surface. The position of the center of pressure, L_P, is measured from the transom and the lift coefficient, C_L, is based on the plate beam,

$$C_L = \frac{\sum C_p \Delta x \Delta z}{B^2}, \tag{4}$$

where the summation is carried out over the wetted plate area. The current method allows us to evaluate the lift-induced drag; for a flat plate it is equal to the lift multiplied by the trim angle. Other drag components