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Research on hydrodynamic pressure field causing by ship moving in mixed flow

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ABSTRACT

Based on the potential flow theory, shallow-water wave equation, slender-ship method, and continuous matched condition between inner and outer waters, the mathematical models of SHPF of sub-subcritical, sub-supercritical, and super-supercritical mixed flows in stepped canal are established, meanwhile, their characteristics are obtained and analyzed by numerical calculation. Simplifying the stepped canal to rectangular canal, the mathematical models and numerical calculation methods are verified by comparing the calculated results with the experimental ones. The influence among SHPF, sidewall, step and bottom are analyzed, the closer step, sidewall or bottom result in much wider waters and sidewalls will be under the influence of SHPF in super-supercritical mixed flow, and the SHPF of sub-supercritical mixed flow possesses the subcritical and supercritical mixed characteristics, which exists greater influence among SHPF, step, sidewall, and bottom.

1. Introduction

In recent years, with the development of rivers, lakes and high speed ships around the world, more and more ships move at high speed in restricted waterways such as rectangular, stepped canal, the variation in hydrodynamic pressure caused by ship and waters sidewall, bottom influence each other, which maybe lead coast and ocean destruction, accordingly, the wave-current interaction, sidewall and seabed may make ship sinkage and trim, and affect its safe navigation (Zhou et al., 2012, 2006; Zheng and Li, 2015). Meanwhile, the characteristics of ship hydrodynamic pressure field (SHPF) in restricted waterways are obvious, which can be used as key factor for discovering and identifying ship in military field. Since 1960, many experts and scholars pay more attention to ship safe navigation, ocean engineering and environment hydrodynamics pressure field (Tuck, 1966, 1978; Gourlay and Tuck, 2001; Zhou et al., 2013). A series of papers concerning the experiment of SHPF in tank and ocean were published, and the effects of ship type and flow on SHPF were analyzed (Sahin and Hyman, 2001). A series of analytic solutions of SHPF in open waters without concerning the nonlinear and dispersive effects had been obtained (Zhang et al., 2002; Zhang and Gu, 2006). The ship hydrodynamic force and ship squat were forecasted (Gourlay, 2000, 2008; Jiang, 2001). The characteristics of SHPF of subcritical and supercritical speed in rectangular canal were calculated (Deng et al., 2014a, 2015). However the studies about SHPF of restricted waterways are little, and rarely concern the waters with step, sidewall or bottom effects.

On the basis of our previous research (Deng et al., 2014a, 2014b, 2015), in this paper, we deduce the mathematical models and research on the numerical calculations of hydrodynamic pressure caused by ship moving in stepped canal, concerning three kinds of mixed flow, the accurate characteristics of SHPF in stepped canal have been obtained. And the mathematical models and numerical calculation methods which are used for stepped canal can be extended to solve other similar problems such as dredged channel, trapezoidal bottom and so on, which can also be used for the verification of analytical models in our future research.

2. Mathematical model

When ship moves along the centerline in a stepped canal, the fluid is assumed to be inviscid, incompressible and irrotational, as shown in Figs. 1 and 2, a Cartesian coordinate system $oxyz$ is employed and moves with ship, the origin o locates at the center of hull waterline, with z vertically upward, $z = 0$ is the plane of undisturbed free surface, and the x-axis coincident with the longitudinal axis of ship, the ship bow is oriented in the negative x-direction. The ship speed is V, its length is L, its width is $2b$, and its draft is d.

As shown in Figs. 1 and 2, in order to establish the mathematical model, we divide the stepped waters into two parts, one is the inner water, another is the outer water, supposing the depth of inner water is h, its depth Froude number is F_h, and its width is w_h, meanwhile, supposing the depth of outer water is H, its depth Froude number is F_H,

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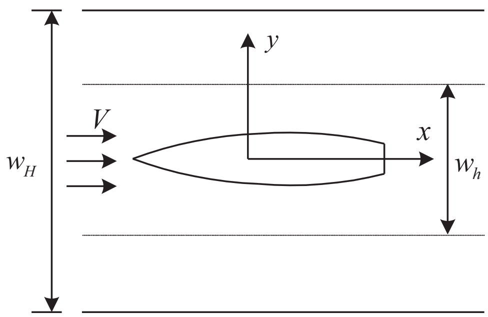

Fig. 1. Coordinate system.

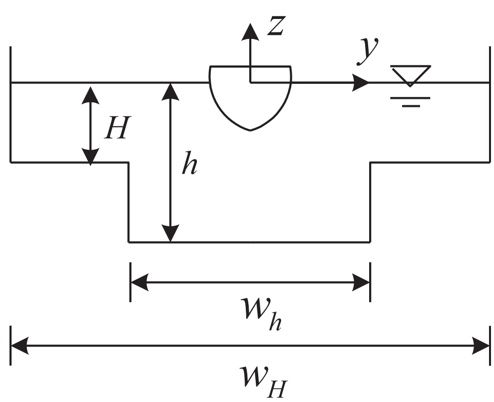

Fig. 2. Cross-section of stepped canal.

and the width of stepped canal is w_H. Then the disturbance velocity potential ϕ of inner water caused by the moving ship should meet the Laplace equation, the free-surface and seabed boundary condition, as follows:

$$\phi_{xx} + \phi_{yy} + \phi_{zz} = 0 \qquad \text{as } -h < z < \zeta \tag{1}$$

$$\zeta_t + (\phi_x - V)\zeta_x + \phi_y\zeta_y - \phi_z = 0 \qquad \text{on } z = \zeta \tag{2}$$

$$\phi_t - V\phi_x + \frac{1}{2}(\phi_x^2 + \phi_y^2 + \phi_z^2) + g\zeta = 0 \qquad \text{on } z = \zeta \tag{3}$$

$$\phi_z = 0 \qquad \text{on } z = -h \tag{4}$$

where ζ is the free-surface elevation. When $h \le 0.3L$, it can be considered as shallow-water, according to the shallow-water characteristics, two small parameters $\mu = h/L$ and $\varepsilon = A/h$ are defined, which are representative of dispersive character and nonlinear character, respectively. The Eqs. (1)–(4) can be transformed into nondimensional equations by multiple-scaling analysis and expressed as follows:

$$(x^*, y^*) = (x, y)/L,\ z^* = z/h,\ \zeta^* = \zeta/A,\ \phi^* = \phi/(\varepsilon\sqrt{gh}L),\ F_h = V/\sqrt{gh} \tag{5}$$

where "*" represents a nondimensional parameter, A the wave amplitude , and $F_h = V/\sqrt{gh}$ the depth Froude number. $F_h < 1$ and $F_h > 1$ are known as subcritical and supercritical speed respectively, $F_h \to 1$ is known as near-critical speed.

When the water depth is shallow, the Laplace Eq. (1) and the seabed boundary condition (4) are considered, ϕ can be expanded in the vertical direction.

$$\phi^* = \phi_o^* - \frac{1}{2}\mu^2(z^* + 1)^2\nabla^2\phi_o^* + \frac{1}{4!}\mu^4(z^* + 1)^4\nabla^4\phi_o^* + \cdots \tag{6}$$

where ϕ_o^* is a nondimensional velocity potential on the water bottom, $\nabla = (\partial/\partial x^*, \partial/\partial y^*)$ denotes the horizontal gradient.

We substitute ϕ^* into the nondimensional Eqs. of (2) and (3), and ζ goes away, meanwhile the order terms of $O(\varepsilon)$ and $O(\mu^2)$ are retained,ϕ_o^* can be expressed in the terms of the depth-averaged velocity potential $\overline{\phi}^* = \frac{1}{\varepsilon\zeta^* + 1}\int_{-1}^{\varepsilon\zeta^*}\phi^* dz^*$.

$$\phi_o^* = \overline{\phi}^* + \frac{1}{6}\mu^2\nabla^2\overline{\phi}^* + \cdots \tag{7}$$

Then the shallow-water governing equation can be shown in the terms of $\overline{\phi}^*$.

$$\begin{aligned}\nabla^2\overline{\phi}^* - F_h^2\overline{\phi}^*_{x^*x^*} + 2F_h\overline{\phi}^*_{x^*t^*} - \overline{\phi}^*_{t^*t^*} - \varepsilon[\frac{1}{2}(\nabla\overline{\phi}^*\bullet\nabla\overline{\phi}^*)_{t^*} \\ - \frac{F_h}{2}(\nabla\overline{\phi}^*\bullet\nabla\overline{\phi}^*)_{x^*} - F_h\nabla(\overline{\phi}^*_{x^*}\nabla\overline{\phi}^*) + \nabla(\overline{\phi}^*_{t^*}\nabla\overline{\phi}^*)] \\ - \frac{1}{3}\mu^2\nabla^2(2F_h\overline{\phi}^*_{x^*t^*} - \overline{\phi}^*_{t^*t^*} - F_h^2\overline{\phi}^*_{x^*x^*}) = 0\end{aligned} \tag{8}$$

Because the unsteady effect caused by solitary wave exists only at a near-critical speed, in other speeds, the unsteady effect can be unconsidered, and ignoring the nonlinear effects (Zhang and Gu, 2006; Deng et al., 2014a, 2014b), the inner governing equation can be derived to the dimensional equation, as follow:

$$(1 - F_h^2)\phi_{xx} + \phi_{yy} + \frac{F_h^2h^2}{3}\phi_{xxxx} = 0 \quad \text{as } y \le w_h/2 \tag{9}$$

where ϕ is the depth-averaged velocity potential of inner water.

In the similar way, the outer governing equations can be derived to the dimensional equation, as follows:

$$(1 - F_H^2)\Phi_{xx} + \Phi_{yy} + \frac{F_H^2H^2}{3}\Phi_{xxxx} = 0 \quad \text{as } w_h/2 \le y \le w_H/2 \tag{10}$$

where Φ is the depth-averaged velocity potential of outer water.

When ship moves in a stepped canal, as shown in Fig. 2, because of $h \ge H$, then $F_h \le F_H$,therefore, there are three kinds of mixed flow named as sub-subcritical, sub-supercritical, and super-supercritical mixed flow in inner and outer waters. Though no matter what kind of mixed flow, the upstream, hull, sidewall and stepped interface boundary conditions are same respectively, some differences on their numerical calculations still exist, because of the different characteristics between subcritical and supercritical flows.

The upstream boundary condition at infinity is

$$\nabla\Phi(x, y),\ \nabla\phi(x, y) \to 0 \quad \text{as } x \to +\infty \tag{11}$$

The sidewall boundary condition should satisfy the impenetrable condition along the sidewall normal direction,

$$\Phi_y(x, y) = 0 \quad \text{as } y = w_H/2 \tag{12}$$

We use the wigley mathematical model for calculation, and slender-ship method is used

for the hull boundary condition,

$$\phi_y = \mp\frac{VS_x(x)}{2h} \quad \text{as } |x| \le L/2 \text{ and } y = 0 \tag{13}$$

where $S(x)$ is the cross-sectional area under the waterline at position x, namely $S(x) = \frac{4bd}{3}[1 - (\frac{x}{L/2})^2]$.

The flow on the stepped interface between inner and outer waters should match the disturbance velocity potential and transverse volume flux on interface continuity respectively (Gourlay, 2008),

$$\phi(x, y) = \Phi(x, y) \quad \text{as } y = w_h/2 \tag{14}$$

$$H\Phi_y(x, y) = h\phi_y(x, y) \quad \text{as } y = w_h/2 \tag{15}$$

3. Numerical calculation of stepped canal

We use the finite difference method to calculate the SHPF caused by ship moving in stepped canal, and discrete the calculation region with upstream $3L$, downstream $9L$ in x-direction and $3L$–$12L$ in y-direction to uniform rectangular grids. The flow is symmetric about $y = 0$. The x-direction along the ship length is marked with i, the