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Analytical models of ship hydrodynamic pressure field with dispersive effect in super-supercritical mixed flow

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ABSTRACT

According to potential flow theory and considering the dispersive effect, a shallow-water wave equation that satisfies the Laplace equation and free surface and seabed boundary conditions is established in this study. On the basis of the slender ship assumption and continuous matched conditions on the interface of a dredged channel, the mathematical problems of super-supercritical mixed flow are solved by adopting the Fourier integral transform method and the finite difference method, respectively. Meanwhile, the analytical models of super-supercritical ship hydrodynamic pressure field (SHPF) are derived, and those of the open water or rectangular canal can also be deduced by further simplification. The characteristics of super-supercritical SHPF with the dispersive effect are analyzed, and the influences of transverse distance, inner or outer depth, width, and depth Froude number on SHPF are studied. Comparisons between the calculated and experimental results show that the proposed analytical models of SHPF in this research are reasonable, effective, and accurate.

1. Introduction

The characteristic of ship wave in shallow water is closely related to the depth Froude number $F_h = V/\sqrt{gh}$, where V is the ship speed; h is the water depth; g is the gravitational acceleration; and $F_h < 1$ and $F_h > 1$ denote the subcritical and supercritical speeds, respectively. If a ship sails in shallow water of constant depth, the flow may only exist as one depth Froude number. However, if a ship sails in shallow water with different depths, the flow may exist as several depth Froude numbers. For a dredged channel (Fig. 1), its flow exists as two depth Froude numbers. If the low depth Froude number is subcritical and the high one is supercritical, the flow can be called as the sub-supercritical mixed flow. If the low depth Froude number is supercritical and the high one is also supercritical, the flow can be called as the super-supercritical mixed flow.

The wake-waves of a high-speed ship may influence the safety of other ships or architectures and cause the washing effect on the sidewall or seabed (Zhou et al., 2012; Zheng and Li, 2015). Meanwhile, the variation of hydrodynamic pressure caused by a sailing ship is generally called the ship hydrodynamic pressure field (SHPF), which not only exists in the same effect as the wake-waves but also can be used as the signature of discovering and identifying a ship target for underwater ordnance (Zhang et al., 2002, 2006). Therefore, studies on shallow-water ship hydrodynamics have practical significance in shipbuilding, coastal research, ocean engineering, and environmental protection.

By ignoring the dispersive and nonlinear effects and considering Michell's shallow-water wave equation, Tuck (1966) examined the hydrodynamic forces of a slender ship moving at subcritical or supercritical speed in open water. Beck et al. (1975) used the continuous matched condition between the shallow and deep regions and solved the ship hydrodynamic forces of sub-subcritical or sub-supercritical mixed flow of a dredged channel with different depths. By using the Fourier transform method, Gourlay (2000, 2008) further extended the method of Beck et al. (1975) to calculate the sub-subcritical ship hydrodynamic forces in rectangular canal, stepped canal, and dredged channel and then presented an approximate solution for canals of arbitrary cross-section. However, because the dispersive and nonlinear effects were not included in the above studies, their calculated results were generally reasonable only for the speed far from the critical depth Froude number. Considering the dispersive effect, Gourlay and Tuck (2001) solved the hydrodynamic problems caused by a slender ship moving at a constant speed in open shallow water. Gourlay also applied slender ship method to predict the ship squat and developed a program to model ship hydrodynamics in shallow water (Gourlay, 2008, 2014). In the military field, Lazauskas (2007) performed numerical calculation to predict the bottom pressure signatures of a 5900 ton displacement air warfare destroyer and found that the pressure variation had some effect on the seabed disruption. In addition, by considering the dispersive,

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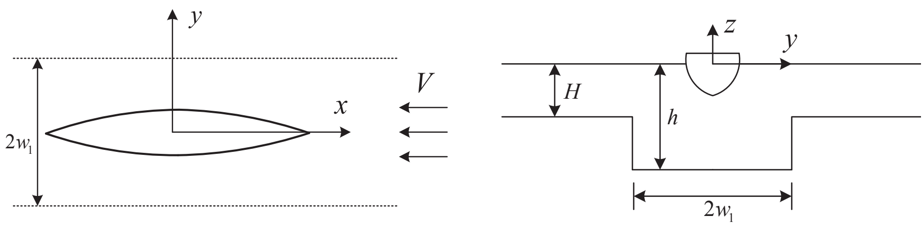

Fig. 1. Coordinate system of a dredged channel.

nonlinear, and unsteady effects, the complicated KP and Boussinesq equations were used to calculate the solitary wave and hydrodynamic forces of the ship in a rectangular canal at transcritical speed (Chen and Sharma, 1995, 1997; Jiang, 2001). On the basis of the simplified KP equation, Deng et al. (2014, 2016) obtained the hydrodynamic pressure characteristics of a ship moving at subcritical and supercritical speed in a rectangular canal.

Of course, for a ship that moves near the critical speed in restricted waterways, solitons may occur. The theory, computation, and experiments of shallow-water soliton generation by a ship model with different blockage coefficients in various depths were produced by Ertekin (1984, 1988). He also discussed some related shallow-water equations and calculated the solitons and waves by using the Green–Naghdi equation and Wu's equation (Wu and Wu, 1982). The results calculated with different shallow-water equations were compared with one another, and the author proposed better calculation methods and numerical solutions of solitons and waves, demonstrated that soliton generation was directly controlled by the blockage coefficient (Ertekin, 1984), and predicted that the periodic creation of solitons was accompanied by a correspondingly periodic oscillation of the wave drag, as well as a dramatic increase in the mean wave drag (Ertekin et al., 1986). Meanwhile, the Kdv equation was used by Mei (1986) and Choi et al. (1990) to calculate ship solitons. Ertekin et al. also calculated the upstream solitons and wave resistance caused by the vertical strut by using the Boussinesq equation, and the calculated results of different blockage coefficients for the strut and ship were both compared with the experimental dates (Ertekin et al., 1990, 1997). They found that the blockage coefficient played a significant role in determining soliton properties and wave resistance. Thus, we based our work on the findings of the above studies.

Previous studies mainly paid attention to the numerical calculation and the experiments on the soliton or ship wave, but rarely on the mixed flow in non-uniform depth waters. Conversely, our research focuses on the theoretical solutions of SHPF and on the establishment of the mathematical models of super-supercritical SHPF in mixed flow, presenting their analytical and numerical calculation methods simultaneously and obtaining the characteristics and influence factors of super-supercritical SHPF.

This study extends the subcritical or supercritical flow in open water to the super-supercritical mixed flow in a dredged channel and applies the pressure calculation on ship hull surface to one of the whole fluid field. Similarly, the analytical models of sub-supercritical SHPF with the dispersive effect are also proposed.

2. Governing equations

For a ship moving along the centerline of a dredged channel, we suppose that the ship length is L (or 2l) and its constant speed is V. As shown in Fig. 1, the dredged channel can be divided into the inner and outer regions. The depth of the inner region is h, its width is $2w_1$, and $F_h = V/\sqrt{gh}$. Meanwhile, the depth of the outer region is H, and its $F_H = V/\sqrt{gH}$. For a high-speed ship moving in shallow water, $F_h > 1$ and $F_H > 1$. We establish a Cartesian coordinate system moving with ship and whose origin o *is* located at the center of the hull waterline. The x-axis points to the direction of ship motion, the y-axis points to the wall, and the z-axis is vertically upward.

Supposing the fluid is inviscid, incompressible, and irrotational, the elevation of the free surface is ζ and its wave amplitude is A. Then, the perturbation velocity potential ϕ caused by a moving ship should satisfy the Laplace equation, and the free surface and seabed boundary conditions (Zhang and Gu, 2006), i.e.,

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

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

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

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

Two defined small parameters $\mu = h/L$ and $\varepsilon = A/h$ represent the dispersive and nonlinear effects, respectively. Equations (1)–(4) can be transformed into non-dimensional equations by taking $(x^*, y^*) = (x, y)/L$, $z^* = z/h$, $\zeta^* = \zeta/A$, and $\phi^* = \phi/(\varepsilon\sqrt{gh}L)$ (here "*" indicates non-dimensional parameters). For shallow water, ϕ^* can be expanded along the vertical direction by combining Equation (1) with Equation (4) and substituted into $\varphi^* = \frac{1}{\varepsilon\zeta^*+1}\int_{-1}^{\varepsilon\zeta^*}\phi^* dz^*$. Meanwhile, the order terms of $O(\varepsilon)$ and $O(\mu^2)$ are reserved, and ζ can be eliminated by combining Equation (2) with Equation (3). By transforming back into the dimensional form, the steady KP equation with the nonlinear and dispersive effects can be deduced.

$$(F_h^2 - 1)\varphi_{xx} - \varphi_{yy} - \frac{3V}{gh}\varphi_x\varphi_{xx} - \frac{F_h^2h^2}{3}\varphi_{xxxx} = 0 \tag{5}$$

where φ is the depth-averaged perturbation velocity potential; the third term shows the nonlinear effect, and the fourth term shows the dispersive effect.

Equation (5) is suitable for subcritical or supercritical flow. For a slender ship, the nonlinear effect of Equation (5) can be ignored. For a wider speed range, the dispersive term should be reserved. Given that the flow symmetry is about $y = 0$, only the region $y \geq 0$ is considered. Supposing the depth-averaged perturbation velocity potentials in the inner and outer regions are φ and Φ, respectively, the governing equations with dispersive effect can be expressed as

$$\beta_1^2\varphi_{xx} - \varphi_{yy} - \gamma_1^2\varphi_{xxxx} = 0 \qquad \text{as} \quad F_h > 1 \tag{6}$$

$$\beta_2^2\Phi_{xx} - \Phi_{yy} - \gamma_2^2\Phi_{xxxx} = 0 \qquad \text{as} \quad F_H > 1 \tag{7}$$

where $\beta_1 = \sqrt{|F_h^2 - 1|}$, $\gamma_1 = F_h h/\sqrt{3}$, $\beta_2 = \sqrt{|F_H^2 - 1|}$, and $\gamma_2 = F_H H/\sqrt{3}$.

The hull boundary condition for a slender ship can be written as

$$\varphi_y(x, 0) = -Vf_x(x) \qquad \text{as} \quad |x| \leq l \tag{8}$$

where $f(x)$ is the equation of the ship hull.

The flow on the stepped interface of the inner and outer regions should satisfy the continuous matched conditions wherein the longitudinal perturbation velocity and transverse volume flux are equal (Beck et al., 1975; Gourlay, 2008), i.e.,

$$\varphi_x(x, w_1 - 0) = \Phi_x(x, w_1 + 0) \quad \text{and} \quad h\varphi_y(x, w_1 - 0) = H\Phi_y(x, w_1 + 0) \tag{9}$$

Moreover, the upstream and downstream boundaries at infinity