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Nonlinear effects on hydrodynamic pressure field caused by ship moving at supercritical speed in shallow water

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ABSTRACT

Based on the shallow-water wave potential flow theory and the assumption of a slender ship, a mathematical model has been established for the pressure field caused by ship moving at supercritical speed in shallow water, with nonlinear and dispersive effects taken into account. The finite difference method is used for the numerical calculation of the ship hydrodynamic pressure field (SHPF), with the central and upwind difference schemes as a combination for the second derivative of the nonlinear term. And the artificial viscous terms are added in the hull and upstream boundary conditions to ensure the stability of solving the nonlinear equation. The comparison between the calculated results and the experimental results shows that both the mathematical model and the calculation method are effective and feasible. The analysis of the nonlinear effects of different-depth water, different depth Froude number and different-width channel on SHPF indicates that the closer to the critical speed the ship in sailing, the narrower the channel becomes, the greater the nonlinear effects on SHPF are.

1. Introduction

With the development of shipping, there are more and more ships moving at high speed in shallow water, such as coastal waters. The wave generation and some changes in hydrodynamic pressure caused by ships have a great washing effect on the shore, seabed and offshore architectures. It is the washing effect that has led to the instability and destruction of the seabed now and then in recent years in terms of ocean engineering, and also that bring about sharp changes in ship posture which are likely to affect the safe navigation of ships. Therefore, the research on the ship dynamics of shallow-water is of great importance to shipbuilding, coastal engineering and ocean engineering, which has been paid attention to by scholars at home and abroad. When a ship moves, there will be variation in pressure creating the ship hydrodynamics pressure field (SHPF), which represents the physical field characteristics difficult to remove by itself. However, its signal characteristics can be used as key factors in discovering and identifying ships. Also, the dynamics of shallow-water ships can be applied to the study of SHPF. Based on the method of matched asymptotic expansions, Tuck (1966) got an approximate solution of the SHPF concerning a shallow-water slender vessel in 1966. In 1985, Müller (1985) presented a formula of SHPF under the condition of linear free surface, according to the wave source potential method of finite-depth water. In 1993, Sahin and Hyman (1993, 2001), Sahin et al., (1994, 1997), made research on the theoretical modeling and numerical computation of the SHPF caused by submarines, surface ships and hovercraft by using Green function method of finite-depth water. An analytic solution of SHPF in an open-sea area was performed by Zhi-hong (2002a, 2002b) (Zhi-hong and Jian-nong, 2006), who used the Fourier integral-transform method and carried out relevant experiments. In 2007, Lazauskas (2007) calculated the variation in pressure caused by a 5900-ton destroyer, using the Kelvin source Green function method. Gourlay (2006, 2008) (Gourlay and Tuck, 2001) calculated the up-and-down movement and the squatting of ship which traveled at subcritical speed respectively between 2001 and 2008 by use of the shallow-water governing equation without the nonlinear and dispersive effects taken into account. Using the panel method, Tao Miao (2011, 2012) calculated the distribution of pressure created by ship moving in the finite-depth water in 2011. The SHPF caused by ship moving at subcritical speed was calculated by Hui et al. (2013) with the source distribution, Fourier integral-transform and finite difference methods. However, most of the above papers did not refer to the nonlinear and sidewall effects. For this reason, this paper is directed towards the numerical calculation of the pressure variation caused by ship moving at supercritical speed in shallow water with the finite difference method, and based on the theoretical model of SHPF concerning the nonlinear and sidewall effects. And then makes a comparison between the calculated results and the experimental results.

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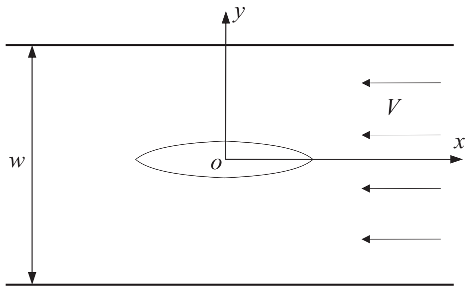

Fig. 1. Coordinate system of mathematical model.

2. Mathematical mode

The flow is assumed to be inviscid, incompressible and irrotational. As shown in Fig. 1, a Cartesian coordinate system moving at the same speed as the ship is used, with the origin O located at the center of hull waterline, the axis x pointing to the direction of ship motion, the axis y pointing to the coastal sidewall and the axis z being vertical up. Suppose the ship length is L, its constant speed V, the depth of water h, and the elevation of the free surface ζ then the disturbance velocity potential ϕ caused by the moving ship should meet the following equations:

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

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

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

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

When the depth of water is less than $0.3L$, it can be considered as a shallow-water area. 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 governing 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 the depth Froude number. As for the ship dynamics of shallow-water, the depth Froude number F_h is an important characteristic parameter. $F_h<1$ and $F_h>1$ are known as subcritical speed and supercritical speed, respectively. $F_h=1$ denotes critical speed. As the ship moves at a near-critical speed, it tends to make particularly solitary waves appear; then $0.8<F_h<1.2$ is also referred to as transcritical speed.

When the water depth is shallow, the Laplace equation (1) and the boundary condition on the water bottom (4) are considered, ϕ can be expanded in the vertical direction in the following form:

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

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

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

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

Then the shallow-water governing equation can be showed in the terms of Φ^*.

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

For a steady condition, the above Eq. (8) can be deduced to a steady shallow-water wave equation which exactly satisfies the Laplace equation, the free-surface conditions and the seabed boundary conditions,

$$(1-F_h^2)\Phi^*_{x^*x^*}+\Phi^*_{y^*y^*}+3\varepsilon F_h\Phi^*_{x^*}\Phi^*_{x^*x^*}+\mu^2\frac{F_h^2}{3}\Phi^*_{x^*x^*x^*x^*}=0 \tag{9}$$

where the third term expresses the nonlinear effects and the fourth the dispersive effect.

Formula (9) can be transformed into the dimensional form by Formula (5). When $F_h>1$, the shallow-water wave equation of the supercritical-speed with nonlinear and dispersive effects considered can be deduced,

$$(F_h^2-1)\Phi_{xx}-\Phi_{yy}-\frac{3V}{gh}\Phi_x\Phi_{xx}-\frac{F_h^2h^2}{3}\Phi_{xxxx}=0 \tag{10}$$

Without the nonlinear effects taken into account, Formula (10) can be simplified as follows:

$$(F_h^2-1)\Phi_{xx}-\Phi_{yy}-\frac{F_h^2h^2}{3}\Phi_{xxxx}=0 \tag{11}$$

Most high-speed ships are slender, so the slender-body theory can be used for setting the hull boundary condition (Tao, 2001),

$$\Phi_y=\mp\frac{VS_x(x)}{2h} \qquad \text{as } |x|\le L/2 \tag{12}$$

where $S(x)$ is the cross-sectional area under the waterline at position x. The Wigley mathematical model with the same main dimensions as the experimental ship model is selected for the calculation, namely $S(x)=4bd/3[1-(x/L/2)^2]$, where b is half width of the ship and d is the draft.

For ship moving in the open-sea area, the sidewall condition is

$$\Phi=0 \qquad \text{as } y\to\infty. \tag{13}$$

For ship moving along the center line of the channel, the sidewall condition is

$$\Phi_y=0 \qquad \text{on } y=\pm w/2 \tag{14}$$

where w is the width of channel.

For ship moving at supercritical speed, the governing equation is a hyperbolic equation. The upstream radiation condition is no wave before the ship, the downstream condition does not need to be given. But because of the limited calculation region, it is necessary to set the condition for the downstream waves still moving backward so as to avoid the wave reflection on the downstream truncation boundary (Xue-nong and Deo Sharma, 1995).

3. Numerical calculation method

The finite difference method is used to calculate SHPF by discretizing the calculation region to a uniform rectangular grid. The x-direction along the ship length is marked with i, the grid spacing is Δx, the upstream truncation boundary is at $i=1$, and i increases downstream in turn. The y-direction along the ship width is marked with j, the grid spacing is Δy, the longitudinal ship-centerplane is at $j=1$, and j extends to the sidewall in turn.