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Numerical analysis of the forces exerted on offshore structures by ship waves

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ABSTRACT

Ship-generated waves can contribute to the fatigue of offshore structures. This paper presents a numerical model for evaluating the forces exerted on a nearby fixed structure by ship-generated waves. The ship waves were modeled using Michell's thin-ship theory (Wigley waves), and the forces were computed using a boundary element method in the time domain. The simulation was validated by comparing its results with those of frequency-domain methods reported in the literature. It was then applied to calculate the forces exerted on a hemisphere by ship waves varying with the ship's speed, dimensions and distance from the hemisphere to the ship's path. Our results indicate that the ship waves have enormous effects on offshore structures and are not neglectable.

1. Introduction

As a ship moves in calm water, it generates waves on the free surface. These waves have been generically named *ship waves*. Part of the ship's power is diverted to generating these waves, which carry away energy as they propagate outwards. The loss of energy can be expressed as a resistance variously called *ship wave resistance* or *wave-making resistance*. Ship waves are complicated in nature, so the study of ship waves and wave-making resistance remains a relevant research topic.

As modern ships become larger, the dangers of ship waves are receiving more attention. Some enormous effects will be induced by the ship waves. The waves generated by a ship may produce violent motions of nearby smaller ships, affect the comfort of their passengers or delay the normal loading and unloading operations of the smaller vessels. A much smaller ship may even lose stability and be capsized by the waves. Several cases testify to the importance of these two effects. Within Victoria Harbor of Hong Kong, for instance, multiple ship waves have been reported as high as 1.5 m above the mean water level. In October 2005, a tour yacht (Ethan Allen) on Lake George was capsized by a passing larger ship. Twenty passengers lost their lives in this tragedy. Herein, the detrimental effects of ship waves, which have been ignored in the past, should be seriously considered in Ocean Engineering.

No numerical studies have mentioned the action of ship waves on marine structures; only river banks and breakwaters have been considered (Weggel and Sarensen, 1986; Chen and Sharma, 1997, 2003). Therefore, a numerical method, which can be used to simulate the action of ship waves on arbitrary fixed structures, is given in present paper.

This work employs a time-domain Green's function (the Kelvin source boundary element method) to compute the wave forces exerted on fixed structures. This method has been widely used in solving diffraction and radiation problems and wave-action problems (Lin and Yue, 1990; Sen, 2002; Singh and Sen, 2007). The Kelvin source method avoids setting panels on the free surface, greatly reducing CPU time. However, it is difficult to rapidly evaluate a time-domain Green's function (Stoker, 1957; Wehausen and Laitone, 1960) with satisfying precision. Many efforts have been done to develop accurate and efficient numerical methods for this purpose (e.g. Newman, 1985, 1990; Beck and Liapis, 1987; Magee and Beck, 1989; Huang, 1992). This paper accelerates the calculation by tabulating the Green's function and its derivatives, interpolating their values on the grid during run time.

The validity of our simulation is demonstrated on simple geometries embedded in a regular wave field, where the output can be compared with present frequency domain results. Later on, the regular wave field is replaced with the waves from a Wigley ship. The numerical model is used to determine how the action of ship waves was influenced by a vessel's speed, dimensions, and distance from the structure.

The paper is organized as follows: Section 2 presents the theoretical principles behind our numerical time-domain method. Section 3 describes our method for accelerating the calculation of the time-domain Green's function. In Section 4, two simple geometries are computed to validate the method. Section 5 reports our numerical results for ship waves in more realistic

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cases and describes how the force of ship waves on a hemisphere evolves under various factors. Our conclusions are given in Section 6.

2. Numerical method

The fluid is assumed to be inviscid and incompressible, and its motion is irrotational. The fluid domain is bounded by the free surface and the body surface, but is unbounded in the horizontal directions. The fluid depth is taken to be infinite. As shown in Fig. 1, the coordinate system x, y, z is fixed; the x- and y-axes lie in the plane of the undisturbed free surface, the x-axis is parallel to the ship's path, and z-axis points upwards.

2.1. Initial boundary value problem

The problem is defined by the following control equations, boundary conditions, and initial conditions:

$$\begin{cases} [L]: \nabla^2 \Phi^S(x,y,z,t) = 0, \\ [F]: \left(\dfrac{\partial^2 \Phi^S}{\partial t}\right) + g\left(\dfrac{\partial \Phi^S}{\partial z}\right) = 0,\ z=0, \\ [B]: \dfrac{\partial \Phi}{\partial n} = 0, \\ [R]: \nabla\Phi(x,y,z,t) \to 0, x^2+y^2 \to \infty \text{ or } z \to -\infty, \\ [I]: \Phi^S, \Phi^S_t = 0,\ t=0. \end{cases} \tag{1}$$

The total velocity potential is $\Phi = \Phi^I + \Phi^S$, where Φ^I and Φ^S are the incident potential and scattering potential, respectively. The n is the unit normal vector of the body surface.

2.2. Incident potential

The velocity potential of waves generated by a Wigley ship will be adopted as the incident potential in the present numerical model. Thus, the thin-ship method is employed to predict the ship waves. The hull shape of the Wigley ship can be described by

$$f(\xi,\zeta) = \frac{B}{2}\left(1 - \frac{4\xi^2}{L^2}\right)\left(1 - \frac{\zeta^2}{H^2}\right), \tag{2}$$

where L is the length, B is the beam and H is the draft. Obviously, $-L/2 \leqslant \xi \leqslant L/2$ and $-H \leqslant \zeta \leqslant 0$. Using the thin-ship theory, the velocity potential of the Wigley ship can, therefore, be written as

$$\Phi^I(x,y,z) = -\frac{U}{2\pi}\iint_{s_0} \frac{\partial f(\xi,\zeta)}{\partial \xi} W(x,y,z;\xi,0,\zeta)\,\mathrm{d}\xi\,\mathrm{d}\zeta, \tag{3}$$

where s_0 is the wet surface of the Wigley hull. Following Noblesse (1977, 1978), the W denotes the *fundamental wave potential* of the Kelvin Green's function. More generally, the Green's function has two parts: the *fundamental near-field potential* and the *fundamental wave potential*. It is assumed that the source and field point has a sufficient distance, so that the influence of the fundamental near-field potential vanishes. After integrating over the Wigley hull for the wave height of ship waves in the free surface, the well-known Kelvin wave system for Wigely hull is obtained and shown in Fig. 1.

2.3. Scattering potential evaluation

Using Green's third identity and the time-domain Green's function, the following integral equation determines the velocity potential on the body surface:

$$\begin{aligned} &\frac{\Omega(Q)}{4\pi}\Phi^S(Q,t) + \iint_{S_b(t)} \Phi^S(P,t)\frac{\partial}{\partial n_P}G_0(P,Q)\,\mathrm{d}S_P \\ &= \iint_{S_b(t)} G_0(P,Q)\frac{\partial}{\partial n_P}\Phi^S(P)\,\mathrm{d}S_P \\ &+ \int_0^t \mathrm{d}\tau \iint_{S_b(\tau)} \left[\Phi^S(P,\tau)\frac{\partial}{\partial n_P}G^f_t(P(\tau),Q(t),t-\tau)\right. \\ &\left.- G^f_t(P,Q,t-\tau)\frac{\partial}{\partial n_P}\Phi^S(P,\tau)\right]\mathrm{d}S_P \\ &+ \frac{1}{g}\int_0^t \mathrm{d}\tau \int_{\Gamma(\tau)} \left[\Phi^S(P,\tau)G^f_{tt}(P(\tau),Q(t),t-\tau)\right. \\ &\left.- G^f_t(P,Q,t-\tau)\frac{\partial}{\partial \tau}\Phi^S(P,\tau)\right] V_N(P,\tau)\,\mathrm{d}l, \end{aligned} \tag{4}$$

where $\Omega(Q)$ is the solid angle containing the fluid domain and $\Gamma(\tau)$ is the intersection of the instantaneous body surface $S_b(\tau)$ and the free surface $S_f(\tau)$ (a closed curve). The V_N is the velocity of a point on $\Gamma(\tau)$ and governs the occurrence of the line integral term. For example, the value of V_N is zero for a linearized problem without forward speed, in which case $\Gamma(\tau)$ is invariant. For a submerged body, the line integral will vanish. The G^0 and G^f are the instantaneous and memory terms of the time-domain Green's function, respectively (see Appendix A). The instantaneous term G^0 is evaluated using the method of Hess and Smith (1964). The memory term G^f and its derivatives, which should be evaluated many times for calculating the convolution integrals, are evaluated using the method shown in Appendix A.

To solve the integral equation, the body surface is discretized into plane polygons (panels) over which the singularity distributions are assumed to be constant. The time domain is divided into uniform steps, and the convolutions are evaluated using a trapezoidal rule. The discretized form of Eq. (4) is given by

$$\begin{aligned} &\left[\frac{\Omega(Q_i)}{4\pi} + \sum_{j=1,j\neq i}^{N_B}\int_{-1}^{1}\int_{-1}^{1}\mathrm{d}\xi\,\mathrm{d}\eta\left(\frac{\partial G^0(P_i,Q_j)}{\partial n_P}|J|\right)\right]\Phi^S(P_i,t)\sqrt{2} \\ &= \sum_{j=1}^{N_B}\int_{-1}^{1}\int_{-1}^{1}\mathrm{d}\xi\,\mathrm{d}\eta\left(\frac{\partial \Phi^S(P_i,t)}{\partial n_P}G^0(P_i,Q_j)|J|\right) \\ &+ \Delta t\sum_{k=0}^{N_T-1}\left[\sum_{j=1}^{N_B}\int_{-1}^{1}\int_{-1}^{1}\mathrm{d}\xi\,\mathrm{d}\eta\left(\frac{\partial G^f_\tau(P_i,Q_j,t)}{\partial n_P}\Phi^S(P_i,t-\tau)\right.\right. \\ &\left. - \frac{\partial \Phi^S(P_i,t-\tau)}{\partial n_P}G^f_\tau(P_i,Q_j,t)\right)|J| \\ &+ \frac{1}{g}\sum_{j=1}^{N_L}\int_{-1}^{1}\left(\Phi^S(P_i,t-\tau)G^f_{\tau\tau}(P_i,Q_j,t)\right. \\ &\left.\left. - G^f_\tau(P_i,Q_j,t)\Phi^S_\tau(P_i,t-\tau)\right)V_N(P_i,\tau)|J_L|\,\mathrm{d}\xi\right]. \end{aligned} \tag{5}$$

In the above equation, $i, j = 1, \ldots, N_B$ where N_B is the number of panels in the body surface. The time index k runs from 0 to N_T-1 and the index m runs from 0 to N_T-k-1 ($t = k\Delta t$, $\tau = m\Delta t$, where Δt is the time step). And the N_L is the number of line elements at the waterline. An adequate time step can substantially reduce the number of Green's function evaluations without compromising the precision of the numerical results (Ferrant, 1991). Then Eq. (5) can be written as a linear system of equations of the form $[A]\{\Phi\}^S = \{B\}$. Through solving for the unknown scattering potential Φ^S by Gaussian elimination, the total velocity potential can be obtained.