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A potential flow model with viscous dissipation based on a modified boundary element method

X. Feng [a,b,*], X.B. Chen [a,c,*], F. Dias [d,e]

[a] Deepwater Technology Research Centre, Bureau Veritas, 20 Science Park Road, Science Park II, Singapore
[b] Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, UK
[c] Shipbuilding Engineering College, Harbin Engineering University, Harbin 15001, China
[d] School of Mathematics and Statistics, University College Dublin, Belfield Dublin 4, Ireland
[e] Centre de Mathmatiques et de Leurs Applications (CMLA), ENS Paris-Saclay, CNRS, Universite Paris-Saclay, Cachan 94235, France

A R T I C L E I N F O

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A B S T R A C T

Conventional potential flow models are known to exaggerate predictions in water wave resonance problems, attributed to the inviscid fluid assumption in the potential theory. In this paper, we present a modified potential flow model incorporating the viscous dissipation effect. We introduce some 'dissipative surfaces' inside the fluid domain which are defined such that the normal velocity through these surfaces remains continuous but a pressure drop occurs across them, representing physically the viscous dissipation. In formulating the boundary value problem using Green theorem by a boundary element method (BEM), modified boundary integral equations are deduced to include the integral over the dissipative surfaces. We apply this model to three cases where overestimation is reported using classical potential models: gap resonance, monocolumn moonpool resonance and tuned wave surge converter. Numerical results show that the dissipative surface is effective to dampen the responses at resonance. Validation is carried out by comparisons against either experimental data or analytical solutions. The spikes in the response amplitude operators (RAOs) produced from the non-dissipative model are removed with inclusion of dissipation. Importantly, the proposed model with dissipation effect favorably retains the same level of computational efficiency as with the classical potential flow model.

1. Introduction

For decades linear frequency-domain potential models have remained dominant in hydrodynamic analysis in the marine and offshore industry. Practical engineering applications have greatly benefited from the high efficiency of potential flow models and their well established theory. While most of the wave-body interaction problems can be solved in the framework of potential flow theory, viscous effects cannot be neglected in some circumstances when the problems become more complex. A potential flow model might produce unrealistic predictions in the case of wave resonance due to the lack of viscous damping. In contrast, a viscous flow solver based on the Navier-Stokes (N-S) equations would be capable of capturing the viscous effects which are expected to play a significant role. Though viscous CFD (Computational Fluid Dynamics) tools have been developed for years, till date the application of CFD in the marine offshore industry remains costly. Two major aspects have limited the wide application of CFD solvers: one is its high demand of computational resources; the other is the shortage of expertise in CFD in the industry. Both computational capacity and CFD competence can be expensive to establish. It is therefore becoming quite attractive and practical to develop potential-flow based models that can consider viscous effects, while retaining a same level of complexity as the linear potential model.

The idea of incorporating fluid viscous effects into potential flows is not new. The effect of fluid viscosity on free surface waves was discussed early by Lamb [1], who derived the decay rate of wave amplitude. Lamb showed the classical viscous decay law of wave amplitude, $A(t) \sim e^{-2\nu k^2 t}$, where A is the wave amplitude, k the wavenumber and ν the fluid kinematic viscosity. This decay law illustrates the dissipation effect on propagating waves in deep water due to viscosity. In case of violent wave-body interactions, one however must take into account the flow separation and vorticity. In the viscous-potential flow model proposed by Joseph and Wang [2], Wang and Joseph [3], vortical component of the velocity was included in the Bernoulli equation and a viscous pressure correction was incorporated. Later on Longuet-Higgins [4] modified the free surface kinematic condition to include the small vortical component of the velocity. Dias et al. [5] made use of the linear approximation of the N-S equations and derived a new set of equa-

* Corresponding author at: Deepwater Technology Research Centre, Bureau Veritas, 20 Science Park Road, Science Park II, Singapore.
E-mail addresses: fengxingya@u.nus.edu (X. Feng), xiao-bo.chen@bureauveritas.com (X.B. Chen).

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tions in the framework of potential flow. They assumed a small vortical component of the velocity and performed Helmholtz decomposition for the velocity. The viscous correction was then introduced into both the dynamic and kinematic boundary conditions. However, they remarked that the fluid kinematic viscosity is too small for the practical application for water wave problems and one ought to use the eddy viscosity.

Another idea of incorporating the viscous effects is to treat the dissipative effects as equivalent pressure losses, as that used in the modelling of flow through a porous screen. A few studies have been published to adopt the pressure loss law which assumes the pressure loss is a function of the local flow velocity, such as Evans [6], Yu [7] and Molin [8]. Among others, Chen and Duan [9] adopted the concept of 'fairly perfect' fluid to introduce a dissipative force to the fluid velocity field. Chen and Duan [9] obtained the modified linear boundary condition with a dissipative term. The resolved boundary value problem with the new boundary condition was shown to retain similar complexity as a traditional linear potential model for numerical simulation by a panel method. By introduction of some dissipative surfaces in the fluid domain and imposing the pressure loss on them, Chen et al. [10] effectively eliminated the unrealistic spikes in the resonant responses of a thin-wall bottomless cylinder. Recently a similar idea was also used in the analytical assessment of viscous dissipation effect on an oscillating wave surge converter by Cummins and Dias [11]. The inclusion of dissipative surfaces allows them to conduct parametric analysis of the hydrodynamic performance with viscous effect of the wave surge converter in a variety of environmental conditions and device dimensions. This may not be possible by CFD computations and laboratory tests. We have employed a similar concept in this study to introduce dissipation into potential flows and solve the wave-body interactions in a modified boundary element method.

In this paper, we present a potential flow model with incorporation of viscous dissipation effect and demonstrate its effective application in some critical offshore problems. The viscous dissipation is introduced into the potential flow by adding some dissipative surfaces near the bodies where violent viscous effects are expected. With this introduction, the boundary integral equations are modified to include the conditions on the dissipative surfaces. To represent the viscous dissipation, a pressure discharge is imposed across the dissipative surfaces, which is assumed to be a function of the local normal velocity. Additional boundary integral equations for normal flow velocity on the dissipative surfaces are formulated, where second derivatives of Green function need to be computed. A dimensionless dissipation coefficient, quantifying the viscous effects, can be determined by comparison with model tests or systematic analysis by CFD. The dissipation coefficient shall be treated as empirical values.

We apply the numerical model to investigate three practical problems in the marine offshore industry, gap resonance, moonpool resonance and flap-type wave surge converters. For the three cases, viscous effects (flow separation and vortex shedding) are found to be significant in the experiments as well as CFD simulations; while linear potential flow models tend to dramatically overestimate the resonant responses. It is demonstrated that the exaggerated predictions in the three examples can be effectively reduced to reasonable ranges with introduction of viscous dissipation. The importance of viscous effect is evaluated for varying structure parameters. Among other advantages, the efficiency of the present model remains almost the same as a traditional potential code.

This paper is organized as follows. Section 2 presents the governing equations of the boundary value problem, the boundary conditions and detailed description of the dissipative surfaces. Formulation with dissipation in the modified boundary element method is demonstrated. Technique of eliminating irregular frequencies is also briefly described. Section 3 simulates gap resonance between two side-by-side rectangular barges in beam sea. The dissipation effect on the resonant modes of free surface elevation in the gap is illustrated. Section 4 investigates the hydrodynamic performance of a monocolumn platform with a moonpool. Comparisons are made between the numerical analysis and tests, and excellent agreement is achieved for the water column elevation in the moonpool with dissipation effect. Section 5 studies an oscillating wave surge converter with the dissipation effect imposed at the edges of its flap. The relative importance of dissipation to its hydrodynamic performance is evaluated through different widths of the flap. Concluding remarks are drawn in Section 6.

2. Mathematical model

2.1. Governing equations

The mathematical model is formulated in the Cartesian coordinate system $P=(x,y,z)$ with $z=0$ on the still water surface and $z-$axis pointing positively upwards. The fluid is assumed incompressible, inviscid and the flow irrotational. The fluid velocity can be expressed by the gradient of a scalar velocity potential $\Phi(P,\,t)$ as $\mathbf{u}=\nabla\Phi$. Assuming a small steepness of the incident wave and small unsteady body motions, the free surface boundary conditions are linearized about $z=0$ and the body boundary condition about its mean position. Thus all oscillatory quantities can be expressed in a time-harmonic dependent complex notation. The velocity potential is written as

$$\Phi(P,t)=\Re_e\{\phi(P)e^{-i\omega t}\} \tag{1}$$

where ω is the circular frequency of the regular incident wave and $\Re_e\{\cdot\}$ stands for taking the real part.

The Laplace equation is satisfied in the fluid domain

$$\nabla^2\phi(P)=0. \tag{2}$$

The linearized kinematic-dynamic boundary condition on the mean free surface $z=0$ is

$$\phi_z-k'\phi=0, \tag{3}$$

where $k'=\frac{\omega^2}{g}$ and g is the acceleration due to gravity. Subscripts denote partial differentiation with respect to the coordinates, normal vector n or time t in the formula. The boundary condition on the body hull surface H is

$$\phi_n=v_n, \tag{4}$$

where v_n is the body surface normal velocity pointing into the fluid. On the sea bed B the condition becomes

$$\phi_z=0. \tag{5}$$

In addition, the far field at infinity ($r\to\infty$) satisfies the Sommerfeld radiation condition

$$\lim_{r\to\infty}\sqrt{r}\left(\frac{\partial\phi}{\partial r}-ik'\phi\right)=0. \tag{6}$$

The free surface elevation η is given by

$$\eta=-\frac{1}{g}\phi_t, \tag{7}$$

and the pressure on the body surface is

$$p=-\rho gz-\phi_t. \tag{8}$$

In solving the wave diffraction and radiation problems, the velocity potential can be decomposed as the sum of several components

$$\phi=-i\omega\sum_{j=1}^{6}A_j\phi_j+A_0(\phi_0+\phi_7) \tag{9}$$

where $\phi_{1,\,2,\,\cdots,\,6}$ are radiation potentials corresponding to 6 degrees of freedom oscillations of the body and $A_{1,2,\ldots,6}$ are amplitudes of the corresponding motions. A_0 and A_7 are the wave amplitudes of the incident and diffracted waves. Here ϕ_0 is the potential of the incident wave and given by