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An Extended Boundary Integral Equation for Structures with Oscillatory Free-Surface Pressure

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The conventional boundary integral equation for the solutions of linear wave–body interactions is extended to include the radiation solutions because of oscillatory pressures applied on the free surface. Coupled with the constraints that determine the pressure, the extended integral equation is applicable to various problems where a part of the bodies contains the free surface with oscillatory pressures. As illustrative examples, the analyses of wave interactions with an air-cushion vehicle and an oscillating water column device are made. As an additional application, we consider moon pool and gap resonances where the use of oscillatory pressures is an efficient way to introduce artificial damping to suppress excessive free-surface elevation of the potential flow.

INTRODUCTION

Structures such as oscillating water columns (OWCs) and air-cushion vehicles (ACVs) have air chambers with internal free surfaces (air/water interfaces). To analyze the behavior of these types of structures, the hydrodynamic and aerodynamic solutions in the respective regions are matched at the interface. In the context of the linearized potential theory, two alternative approaches are available. In one, the vertical displacement (or vertical velocity) of the free surface is represented by a set of prescribed modes, and the continuity of pressure is applied to determine the coefficients of these modes. In the second approach, the coefficients of the prescribed oscillatory pressure modes can be determined from the continuity of the vertical velocity. In the earlier applications of the panel methods, the former was preferred primarily because the relevant modes are defined by Neumann boundary conditions in the same manner as the conventional rigid body modes. The application of this approach to the analysis of OWCs is described in Lee et al. (1996) and of ACVs in Pinkster (1997), Pinkster et al. (1998), and Lee and Newman (2000).

The second approach, which was briefly described in Lee et al. (1996), is expanded in this paper. The characteristic acoustic wavelength is of O (1000 m) at the frequency of O (1/s). Since the air pressure varies slowly compared to the free-surface elevation, fewer modes are required in the second approach relative to the first, where a relatively large number of modes may be required to describe the vertical displacement of the interface. The advantages of the second approach include (i) little effort to find and describe an appropriate set of modes, (ii) direct interpretation of the computational results, and (iii) improved computational efficiency due to the reduced number of modes.

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In the following section, the theory of the present approach is described. First, the pressure radiation potentials that satisfy the boundary condition of oscillatory pressure on the interface and homogeneous Neumann conditions on the body surface are defined. To be general, the air pressure is assumed to be spatially variable. Then the extended integral equation is derived to evaluate the pressure radiation potentials. Finally, a set of equations governing the motion of the body and the pressure on the interface is derived.

As a first computational example, a rectangular ACV model is analyzed, and the computational results obtained by two approaches are compared along with the experimental results from Pinkster et al. (1998). The OWC is analyzed next. The parameters, such as the optimum pressure and the capture width, are evaluated in a simpler manner, using the integrated forces corresponding to the pressure mode.

As a last example, we consider resonance of the free-surface elevation observed in the moon pool or in the gap between narrowly spaced vessels where the computations based on the linear potential flow often overpredict the wave height. Feng and Bai (2015), in their fully nonlinear simulations, found that the free-surface nonlinearity plays a minor role in suppressing the overpredicted resonance in the linear solutions. This confirms the experimental findings by Molin et al. (2009) that the viscous effects, primarily flow separation, account for the discrepancy between the linear solutions and measurements.

A few techniques have been proposed to introduce drag forces, simulating the viscous effects, to damp the resonant modes. For example, in Newman (2004), a flexible lid is placed on a part of the free surface, and the vertical displacement of the lid is subject to an appropriate damping force. Chen (2004) proposed a method that, in effect, applies a continuous pressure distribution on the free surface to extract energy out of the fluid. The effect of this pressure distribution can be taken into account efficiently by using a set of prescribed pressure modes. Using a couple of computational examples, we show that the use of pressure modes is a simple and effective alternative to the flexible lid to damp the resonant behavior.