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Two-dimensional moonpool resonances for interface and surface-piercing twin bodies in a two-layer fluid

Xinshu Zhang [a,*], Piotr Bandyk [b]

[a] Department of Naval Architecture and Marine Engineering, University of Michigan, Ann Arbor, MI 48109, United States
[b] DRS Technologies, Inc., Advanced Marine Technology Center, Stevensville, MD 21666, United States

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ABSTRACT

We study the moonpool resonances of two interface and surface-piercing rectangular bodies in a two-layer fluid due to forced harmonic heave motion. The problem is solved by employing a domain decomposition scheme with an eigenfunction matching approach. Heave added mass and damping coefficients, as well as inner and outer region (far-field) radiated wave elevations, are computed to examine the hydrodynamic behavior of the twin floating bodies. The numerical solutions have been compared with those for the case investigated by Zhang and Bandyk [1], where the floating bodies remain in the upper layer fluid. The present analyses reveal that there exist both Helmholtz and higher-order, also called sloshing mode, resonances in the two-layer fluid. It is found that, for an interface and surface piercing twin bodies, the higher-order resonances are closely related with both the free surface and internal waves inside the moonpool gap. Moreover, it is also found that low frequency forced motion can excite higher-order resonances through forming standing internal waves inside the moonpool. Parametric studies have been performed to identify the dependence of hydrodynamic behavior and resonant characteristics on geometry and density stratification.

1. Introduction

This paper aims to study the moonpool wave resonance phenomenon in a two-layer fluid system due to the oscillating heave motion of two identical rectangular bodies (also called twin bodies). In contrast to a previous paper [1], which addresses the case where the floating twin bodies only remain in the upper layer fluid, the present study will focus on the moonpool resonance due to interface and surface piercing bodies. The moonpool studied in the present paper models the opening/gap between two floating bodies, such as a liquified natural gas (LNG) carrier and terminal in the case of side-by-side arrangements, or between the individual hulls of a multi-hull vessel. In offshore operation, the fluid motion inside the moonpool and the dynamic behavior of the hulls are critical to the design and analysis of ships, and also very important for the development of an efficient and reliable procedure for offshore operations such as drilling, pipeline laying, floatover installation, and cargo or crew transferring. In addition, the motion dynamics of the LNG ship during offloading is also crucial for tank sloshing analysis of the liquified gas.

Molin [2] and McIver [3] demonstrated a resonance inside the moonpool using linearized water wave theory. Yeung and Seah [4] studied moonpool resonance for two symmetric rectangular bodies in finite water depth using an eigenfunction matching method. Faltinsen [5] studied the two-dimensional piston-like wave sloshing inside a moonpool based on a domain decomposition scheme and the Galerkin method, comparing numerical results with experimental measurements. Later, Kristiansen and Faltinsen [6,7] investigated on the same problem using a vortex tracking method and CFD, and found the damping on the near resonant wave is mainly due to the vortex shedding from the sharp corner points. Molin [8,9] also extensively researched on the damping effects on gap resonances by experiments and numerical studies. Most of the previous moonpool hydrodynamic studies have been focused on a single-layer fluid; very few have been carried out for stratified flow, which occurs in the marine environment [10–12]. In stratified flow, the density changes with the variations in salinity or temperature in the vertical direction. For example, a pycnocline is defined as the layer where density change significantly. The fluid density above and below the pycnocline is almost constant. Therefore, we can model the stratified fluid system as a two layer fluid assuming the pycnocline is infinitely small.

When the wave-structure interaction is treated using potential theory, the boundary value problem may have an eigenvalue to satisfy the condition of no radiated waves at infinity. The corresponding eigenfunction is called a 'trapping structure'. At the

* Corresponding author. Tel.: +1 281 721 2369.
E-mail addresses: xinshuz@umich.edu (X. Zhang), pbandyk@drs.com (P. Bandyk).

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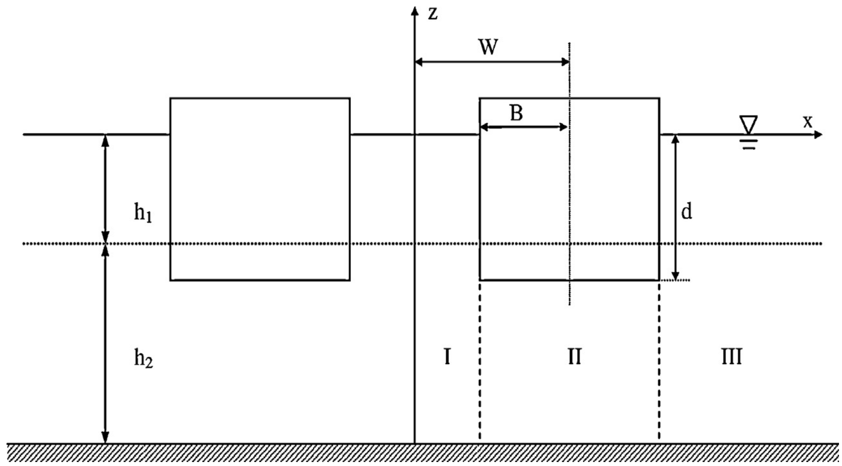

Fig. 1. Definition of the problem and coordinate systems.

trapped mode frequency, the added mass coefficients can be infinite. Extensive research has been conducted to investigate on the possibility of 'wave trapping', a phenomena for both fixed and floating bodies. The so-called 'trapped mode' has been researched by McIver [13–15] and Kuznetsov [16] for two-dimensional and three-dimensional cases, respectively. Newman [17] also studied the trapped wave resonance in a floating torus using WAMIT. Kuznetsov et al. [18] investigated the wave trapping modes for two-dimensional bodies in a two-layer fluid. However, the existence of wave trapping may be a rare exception for actual moonpools, including the presently studied dual heaving rectangular bodies. Nevertheless, identifying the trapped resonant characteristics for a given moonpool structure is critical; and a motivation for the present study.

Linton and McIver [19] studied the wave radiation and scattering of a horizontal cylinder in a two-layer fluid. Yeung and Nguyen [20,21] derived a Green function for a steadily translating source and a two-dimensional transient Green function for an oscillating source. The latter can be used for the computation of wave-structure interaction in the time domain. Alam et al. [22] investigated the three-dimensional Green function for an oscillating source translating with steady speed and compared the far-field radiated waves with the results using direct numerical simulation. The method developed in this paper is applicable to twin rectangular bodies. In order to study the case for a generalized geometries, a free surface Green's function or Rankine panel method may be employed. Ten and Kashiwagi [23] and Kashiwagi et al. [24] studied the wave radiation and diffraction problems for a two-dimensional body of arbitrary shape using Green function, and compared their numerical results with experiments.

An eigenfunction matching method is developed in the present study to solve the boundary value problem for a two-layer fluid system. The eigenfunction matching method has been widely used to study wave-body interaction problems (Yeung [25], Shipway and Evans [26]) for either two-dimensional or three-dimensional cases. Mavrakos [27] also applied the method to compute the hydrodynamic coefficients for two concentric surface-piercing truncated circular cylinders. More recently, Mavrakos and Chatjigeorgiou [28] used the method to study the second-order wave diffraction problem for two concentric circular cylinders.

The principal focus of the present paper is the wave radiation due to heave excitation of the twin bodies in both upper and lower fluid layers. We first give the mathematical formulation, followed by a numerical scheme to solve the discretized linear system. The hydrodynamic behavior of the floating twin bodies near Helmholtz (also called piston mode) and higher-order (also called sloshing modes) resonant modes is examined. The outer region (far field) radiated free surface and internal waves are computed and discussed. Parametric studies are performed to examine the effects of moonpool geometry and density stratification on the resonant fluid motion and hydrodynamic coefficients. It should be noted that the assumption of potential flow during resonant behavior generally over-predicts wave amplitudes, and viscous effects (such as vortex shedding from the corners) must be considered. However, the method proposed here is effective in quickly predicting resonant characteristics given a moonpool configuration, which may be used in design and optimization.

2. Mathematical formulation

The surface and internal waves caused by forced small amplitude vertical (heave) motion of two rectangular hulls with identical geometry in a two-layer fluid are studied. The problem sketch is shown in Fig. 1. The width of each rectangular body is $2B$. The distance between the two centers of the bodies is $2W$. The draft of each floating cylinder is d. The depth of upper and lower fluid is h_1 and h_2, respectively, with a total water depth $h = h_1 + h_2$. The fluid is assumed to be ideal and the flow irrotational. The fluid density for the upper and lower fluid are ρ_1 and ρ_2, respectively. Since only heave motion is studied here, the hydrodynamic problem is symmetric about $x = 0$; therefore only the domain $x \geq 0$ is considered. The present study considers the case of $d > h_1$, which assumes the twin bodies penetrate the interfacial surface at $z = -h_1$.

Let the heave motion of the two identical bodies be $\zeta \cos(\omega t)$, where ω is the angular frequency and ζ is the motion amplitude. We assume $\zeta \ll O(1)$. The velocity potential within the two-layer fluid can be written as

$$\Phi^{(m)}(x, z, t) = \Re[-\mathrm{i}\omega\zeta\phi^{(m)}(x, z)e^{-\mathrm{i}\omega t}] \quad (1)$$

where $\phi^{(m)}(x, z)$ is the spatial velocity potential. $m = 1$ represents the solution in the upper fluid and $m = 2$ represents the solution in the lower fluid. The governing equation for $\phi^{(m)}$ is the Laplace equation

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2}\right)\phi^{(m)} = 0 \quad (2)$$

The linearized free surface boundary condition is written as

$$\phi_z^{(1)} - K\phi^{(1)} = 0 \quad \text{at} \quad z = 0 \quad (3)$$

where $K = \omega^2/g$, and g is the gravitational acceleration and $\phi_z = \partial\phi/\partial z$.