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Modeling wave and spectral characteristics of moored ship motion in Pohang New Harbor under the resonance conditions

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ABSTRACT

An integrated mathematical model is demonstrated to investigate the wave and spectral characteristics of the moored ship motion in an irregular geometrical domain due to diffraction, refraction, and partial reflection induced by incident ocean waves. The incidence angle of partial reflection boundary is assumed as zero. Fluid domain is divided into three regions entitled as bounded region (harbor), unbounded region (open sea), and ship region. A combined numerical approach including 3-D Boundary Element Method (BEM) in the ship region and a 2-D BEM in bounded region is performed to analyze the moored ship motion under the resonance conditions. Our proposed model is validated with existing well-known models, such as Sawaragi et al. (1989) and Takagi et al. (1993), revealing that it could efficiently capture the spectrum of waves. Then, the proposed numerical scheme is implemented in realistic Pohang New Harbor, which is situated in the southeast part of South Korea. The spectral characteristics of a moored ship motion are obtained under different directional incident waves with resonant frequencies. The reliable calculation results suggest that this method can be utilized for the safety and hazard mitigation of the moored ship in realistic harbor with complex geometry including sharp corners.

1. Introduction

PNH is an industrial harbor located in Pohang city South Korea, which was built to support Pohang Steel Corporation (POSCO), one of the biggest steel production companies in South Korea. During the seasonal weather conditions, loading and unloading is a difficult task due the high tides approximately 2–3 m in height. However, PNH is designed to obstruct incident waves from the open sea and to protect moored ships and offshore structures. The high amplitude incident waves generated by typhoon can be hazardous to harbor coastal structure and its interior boundaries, especially the moored ships as well. A small portion of incident waves is radiated out through the entrance into the open sea. But the major part, the remaining portion is diffracted, refracted, and partially reflected repeatedly by the moored ships and the interior boundary of harbor.

In fact, the magnitude of the incident wave impact in the harbor for long waves in the ports or harbor can be analyzed by various existing numerical models (Bellotti, 2007; Chou and Han, 1993; Dong et al., 2013; Guerrini et al., 2014; Hamanaka, 1997; Hwang and Tuck, 1970; Lee, 1971; Mei and Petroni, 1973). These models are based on Boundary Integral Equation Method (BIEM), Boundary Element Method (BEM), Finite Element Method (FEM), and etc. Several theoretical studies based on these numerical methods have been put forward to calculate the moored ship motion inside the harbor. For instance, Oortmerssen (1976) developed a numerical method to predict the wave field around the moored ship in shallow water with straight quays while Andersen (1978,1979) analyzed wave-induced ship motion in restricted water depth. BEM is implemented by using three-dimensional (3-D) Green's function, which was applied on a rectangular navigation channel (or floating body) in a harbor (Dusseljee et al., 2014; Lee et al., 2009; Ohyama and Tsuchida, 1994, 1997; Sawaragi and Kubo, 1982). Nowadays, high resolution numerical schemes of shallow water equations (SWEs), for examples, the finite difference, the finite volume and finite element, are well accepted to investigate the behaviors of harbor and ocean waves in spatial-temporal domains (Chen et al., 2003; Hanert et al., 2005; Madsen et al., 1991).

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Sawaragi et al. (1989) proposed a hybrid numerical approach, applicable to harbors of an arbitrary geometry with constant depth by using the three-dimensional (3-D) Green's function to represent the fluid flows near a floating body, and combined it with a 2-D BEM model applied in the bounded region (Lee et al., 2009). Takagi et al. (1993) independently developed a mild slope equation model applied to the 2-D geometry with the variation of bottom topography by employing finite element method (FEM) to evaluate the harbor response and 3-D BIEM to obtain the floating body response. Ohyama and Tsuchida (1994,'1997) developed a combined model of 3-D Boundary Element Method (BEM) with 2-D FEM model, and applied them to near the floating-ship-side region and in the remainder of harbor region, respectively. Subsequently, they used expanded mild slope equation to analyze the wave-induced moored ship motion in a harbor using 2-D FEM. The computational approach using a hybrid Boussinesq panel method is applied for predicting the wave-induced oscillation of a moored ship in restricted water (Bingham, 2000; Kubo et al., 2001). Schellin (2003) computationally analyzed moored ship motion by using a single point mooring (SPM) scheme and calculated the hydrodynamic response and exciting forces acting on the moored ship. van der Molen and Wenneker (2008) described a Boussinesq type wave model (Guerrini et al., 2014) combined with a time domain panel model, this approach was applied to determine the wave forces on moored ship motion including the harbor oscillation and drift forces acting on the moored ship. Sakakibara and Kubo (2008a, 2008b) observed the characteristic of low frequency motion of moored ship inside the harbor based on field observation induced by long period waves (Shi et al., 2014). Later on, Sakakibara et al. (2010) investigated a hybrid potential theory to predict the moored ship motion induced by large scale tsunami. Countermeasure parameters of long period wave oscillation inside the harbor for the moored ship motion are analyzed by Uzaki et al. (2010). Recently, a moored ship motion under the resonance condition in PNH is also analyzed by using CGWAVE model and 3-D green function (Kwak et al., 2012; Kwak and Pyun, 2013).

As mentioned above, existing studies are mostly model based, which are valuable to predict the wave field of the moored ship in the harbor of arbitrary geometry. In this paper, we first solve the Helmholtz equation by using 2-D BEM model in the interior domain (harbor), and then coupled with 3-D BEM model in ship region with consideration of fluid mass and momentum continuity at the common boundary of moored ship S_M. The major contents of this article consist of following sections. Firstly, the solution of the Helmholtz equation is solved by applying the Green's identity under the linearized kinematic and dynamic boundary conditions with partially reflecting harbor walls. In partial reflection boundary condition, the angle of incidence and reflection phase angle at each boundary points on the harbor is considered as zero. Secondly, the governing equations and boundary conditions are given to analyze the six different modes of moored ship motion. Thirdly, for the validation of moored ship motion, the simulation results are compared with the previous studies accomplished by Sawaragi et al. (1989), Takagi et al. (1993) and Yoo (1998). Fourthly, the current numerical approach is implemented on PNH domain to analyze the six different components, i.e., surge, sway, heave, roll, pitch, and yaw of the moored ship motion for various directional incident waves under the resonant frequencies (modes). The wave field in the ship region has been demonstrated to predict the response of different directional incident waves and resonance modes. Our primary results approve that the resonance near the moored ship is dependent on the multiple factors, such as the direction of incident waves, geometry of the harbor, resonant frequency, and location of the moored ship. Our investigation of the moored ship motion may provide guidance to detect the safe location for moored ship during the harbor resonance generated by typhoon, other type of hazardous long waves.

2. Geometry and formulation of the harbor region

In this section, geometrical interpretation of the mathematical model for moored ship motion and the theoretical analysis of wave induced oscillation in complex geometry domain are given. In later section, the governing equation in ship region is brought forward to analyze the various modes of moored ship motion subjected to incident waves from different directions.

2.1. Geometry of the harbor region

As mentioned above, fluid domain is divided into three regions, i.e., a bounded region Ω_b (harbor), an unbounded region Ω_u (open sea), and the ship region Ω_s. The bounded region Ω_b with uniform depth ih s surrounded by the harbor wall S_W including the harbor entrance E_1E_2 (see Fig. 1). The entrance E_1E_2 is common in both bounded and unbounded region. The ship region Ω_s includes the moored ship S_M enclosed by semicircular boundary S_0. The origin in the Cartesian coordinates is placed at the harbor entrance, x-axis along the shoreline, whereas, y-axis is placed towards the open sea and z-axis is placed vertically upwards from the sea surface. The exterior boundaries at the entrance are denoted by X_1E_1 and E_2X_2. The wave fields for bounded and unbounded region are expressed by f_b and f_u, respectively.

Therefore, the wave fields can be obtained by solving the Helmholtz equation with different boundary conditions in each region. The bounded region is surrounded by partially reflecting harbor walls S_W with sharp corner with an angle θ. The moored ship S_M is located on the boundary of harbor (PNH) with ship size approximately 56,000 DWT. The motion of the moored ship is explained by six different modes, of which translation motion is described as surge (front/back), sway (side/side) and heave (up/down), and rotational motion is described due to rotation as roll (front/back), pitch(side/side), and yaw (up/down), respectively.

In order to understand the wave induced oscillation in a harbor with irregular geometry, the governing equation is given by Laplace equation, which is derived from continuity equation in terms of the potential function. The fluid motion is assumed to be irrotational with small amplitude, and the fluid is incompressible and

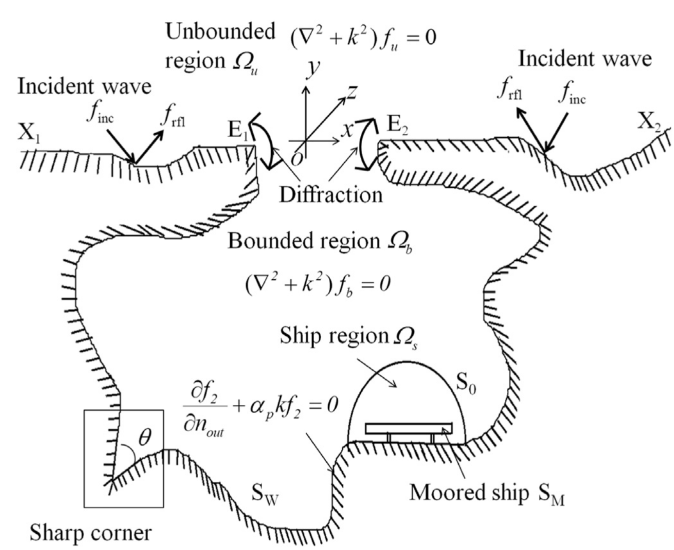

Fig. 1. Definition sketch of a moored ship motion model including the bounded region Ω_b, the unbounded region Ω_u, and the ship region Ω_s with sharp corner with angle θ.