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Mitigation of structural responses of a very large floating structure in the presence of vertical porous barrier

Sofia Singla[a], S.C. Martha[a,*], T. Sahoo[b]

[a] Department of Mathematics, Indian Institute of Technology Ropar, Rupnagar, 140001, Punjab, India
[b] Department of Ocean Engineering and Naval Architecture, Indian Institute of Technology, Kharagpur, 721302, India

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ABSTRACT

The effectiveness of partial vertical permeable barriers of three different configurations located at a finite distance from a very large floating structure is analyzed for mitigating the wave-induced response of the structure. The eigenfunction expansion method is employed to obtain solution in case of normal incidence and the study is extended to the case of oblique incident waves. In case of normalized incident waves, a detailed analysis of the results on various physical quantities such as the reflection and transmission coefficients, wave force on the barrier, free surface elevation, plate deflection, shear force and surface strain on the floating structure are presented. For the case of oblique incidence, results on reflection coefficient for various structural parameters are presented. Using Green's identity, energy balance relations are derived in both the cases of normally and obliquely incident surface waves and certain results for normally incident waves are compared for accuracy. The study reveals that wave reflection follows an oscillatory pattern and the minima in the oscillatory pattern increase with an increase in structural porosity. Wave reflection and dissipation attain their optima for the same wave number irrespective of barrier configurations. Occurrences of wave diffraction are observed in case of long waves for barriers of varied configurations with a narrow gap which decreases with the introduction of barrier permeability. Moreover, when the distance between the barrier and the very large floating structure is close to an integer multiple of half of the wavelength, both the wave reflected by the barrier as well as wave forces acting on the barrier attains their optima.

1. Introduction

In recent decades, there is a significant interest to analyse interaction of surface gravity waves with very large floating structure (VLFS) for the utilization of ocean space. This interest is due to urban development which is expanding continuously due to increasing population in the countries where land scarcity exists and in the countries which have long coastlines. Such nations resort to land reclamation from the sea in order to avoid congestion in the used land space. So, engineers and researchers have proposed the use of VLFS for habitation, industrial space, airports and storage facilities in response to the above problems. VLFS has the advantage that it is an artificially created land which floats on water body and at the same time has a minimal effect on aquatic habitats, tidal current flows. The VLFS is assumed to behave elastically as the localized deflection/vibration of the long structure becomes significant due to the continuous excitation of small amplitude waves, although the motion of the whole body is small as compared to its length (see Sahoo et al. (2001)). Thus, a floating elastic plate renders a simple model for practical structures such as VLFS. Recent developments on VLFS can be found in Wang and Tay (2011), Lamas-Pardo et al. (2015) and the literature cited therein. A parallel branch of study is the wave-ice interaction problems in which the floating ice sheet is modeled as an elastic plate and Squire (2011) reviewed the state of the art research and future challenges of the hydroelastic problems on wave-ice interaction in the polar and subpolar seas. Mandal et al. (2017) discussed the characteristics of the eigensystems associated with the gravity wave interaction with very large floating structures and studied the flexural gravity wave scattering due to multiple articulations in the presence of compression in both the cases of homogeneous and two-layer fluid systems.

It is observed that due to high wave impact on the floating structure, the amplitude of wave-induced structural responses becomes very high which may damage the floating structure. Hence, it is important to mitigate the structural responses of VLFS that demands convincing and tough serviceability requirements. During the last two decades, several techniques have been introduced to minimize the wave-induced

* Corresponding author.
E-mail addresses: sofia.singla@iitrpr.ac.in (S. Singla), scmartha@iitrpr.ac.in (S.C. Martha), tsahoo1967@gmail.com (T. Sahoo).

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structural responses on VLFS. An extensive review of the methods can be found in Wang et al. (2010) and Tavana and Khanjani (2013). For instance, conventional methods such as the bottom-founded type or floating-type breakwaters are used to attenuate the wave forces impacting on the VLFS. Ohmatsu (2000) presented an effective scheme for calculating the wave-induced hydroelastic response of a pontoon-type very large floating structure (VLFS) when it is near a breakwater. Often floating box like breakwaters can be used for reducing structural responses of VLFS. In this context, Headland (1995) revealed that floating box like breakwater is effective in reducing the wave forces for waves with periods ranging from 4 to 6 s. Hong et al. (2002) employed boundary element method in performing hydroelastic analysis on VLFS in the presence of floating breakwater. Yang (2017) recently developed a hybrid active and passive control method to reduce structural vibration such that the resulting controlled VLFS will enhance serviceability. Besides the above method, an innovative method namely pressurized air cushions are used to reduce the drift forces of the VLFS. In this technique, the bottom hulls of VLFS are raised above the water surface in order to reduce the surface interference, water drag, and wave making, thereby, reducing the hull resistance against waves and current flow. At the same time, the entrapped air is compressed and this creates an air-cushion to eliminate the friction between the bottom hull and the water surface (see Lee and Newman (2000); Thiagarajan and Morris-Thomas (2006)). Ikoma et al. (2009) performed extensive studies on the effect of a different number of air cushion units for attenuating motions of VLFS. Recently, Hong and Lee (2016) analyzed the hydroelastic responses of pneumatically supported VLFS (VLFS supported by air cushion below structural bottom) using coupled boundary element method and finite element method.

Another technique for reduction of hydroelastic response on VLFS involves the use of anti-motion devices that are connected to VLFS. Lee et al. (2003) used composite grid method to analyse hydrodynamic interactions of anti-motion device and VLFS and concluded that the submerged plate generates vortex which reduces the structural response by increasing the added mass and damping force of VLFS. Ohta et al. (1999) investigated the effect of submerged vertical as well as a horizontal plate attached at the fore end of the VLFS. Watanabe et al. (2003) examined the effect of attached horizontal plates to VLFS. Cheng et al. (2014) experimentally analyzed VLFS edged with submerged horizontal plates. Recently Cheng et al. (2016) studied the fluid-structure interaction of irregular waves with VLFS edged with dual inclined perforated plates in context of time domain theory by employing hybrid finite element-boundary element method and eigenfunction matching method. Mohapatra and Sahoo (2014) studied the effect of submerged flexible structure in reducing the structural responses of a flexible floating structure. Mondal and Banerjea (2016) presented results of dissipation of wave energy by inclined porous plate submerged beneath the ice cover.

Oscillating water column (OWC) devices because of their effectiveness in absorbing the wave energy finds an application in mitigating structural responses of VLFS. OWC floating breakwater was considered for reducing the structural response of VLFS by Ikoma et al. (2002). It can be used as an anti-motion device as suggested in Maeda et al. (2001). The effectiveness of various hybrid techniques known as hybrid anti-motion devices is discussed in Shigemitsu et al. (2001). Wang et al. (2012) developed a novel hybrid system for reducing the hydroelastic response of very large floating structures. Moreover, Gao et al. (2013) employed boundary element method and finite element method to study the effect of flexible connector and gill cells in reducing the hydroelastic response of pontoon-type very large floating structures. Recently, Yoon et al. (2014) performed hydroelastic analysis of floating plates with multiple hinge connections in regular waves.

On the other hand, in the last three decades, there is a significant progress on wave interaction with porous structures which helps in dissipating a major part of wave energy. Sahoo et al. (2000) investigated the trapping of surface gravity waves by vertical partial barriers located near a rigid wall in a two-dimensional channel of uniform depth and reveals that in the presence of partial porous barriers of three different configurations, all the incident waves are reflected back when the distance between the end-wall and the barrier is an integer multiple of half of the wavelength. Moreover, it was demonstrated that for moderate values of structural permeability, wave reflection attends certain minimum when the distance between the end-wall and the barrier is equal to a quarter-wavelength plus an integer multiple of the half wavelength of the incident wave, all the waves are absorbed within the confined zone. Behera et al. (2015) analyzed the trapping of obliquely incident gravity waves by porous barrier located near a rigid wall in the presence of a step type bottom bed using mild-slope approximation method. Koley and Sahoo (2017) studied oblique wave trapping by permeable vertical flexible membrane barriers located near a rigid wall in water of uniform depth under the assumption of linear water wave theory and small amplitude membrane response. In the aforementioned studies, the emphasis was given on the creation of tranquility zone with the help of a vertical porous structure located near a wall. Moreover, all these studies reveal that the maxima in wave reflection by the porous structure was associated with the minimum wave force on the vertical wall. Moreover, the aforementioned studies on wave trapping reveals that because of their ability to absorb and dissipate wave energy, porous barriers can be used as breakwaters for mitigating the structural responses.

In the present study, effects of three different configurations of permeable barrier namely, surface-piercing barrier, bottom-standing barrier and a barrier with a gap are analyzed for mitigating hydroelastic response of a very large floating structure. Here, the emphasis is on the use of partial porous barriers for reducing wave-induced structural responses on a very large floating structures when kept at a finite distance from the structure. The problem is studied for normally incident waves in the two-dimensional Cartesian coordinate system under the assumption of linearized water wave theory and small amplitude structure response and the results are generalized to deal with obliquely incident waves in three dimensions. Wave past the porous barrier is modeled based on Darcy's law for wave past thin porous plate. The mathematical problem is handled for a solution using suitable application of eigenfunctions expansion method for both normal incidence and oblique incidence. The study aims at finding the optimum distance between the porous plate and the floating structure for obtaining maximum wave reflection by the porous barrier which in turn will reduce the wave loads on the very large floating structure. Various hydrodynamic characteristics are analyzed from the computed results of the reflection and transmission coefficients, plate deflection and forces acting on the barriers and the floating plate for different wave and structural parameters. The energy balance relation is derived and used to check the accuracy of the computational results and to obtain quantitative information about wave energy dissipation.

2. Mathematical formulation

Under the assumption of the linearized theory of water waves, the wave-structure interaction problem is formulated in a two-dimensional channel of finite water depth. The physical problem is studied in the Cartesian co-ordinate system with x-axis being in the horizontal direction and y-axis being positive in the vertically downward direction. The fluid occupies the region ($-\infty < x < \infty$, $0 < y < h$) except the barrier and the floating structure in the fluid region. The notations L_b and L_g represent the regions of the barrier and gap respectively. The very large floating structure of length $2l$ is floating on the mean free surface and occupies the region $-l < x < l$ and the barrier occupies the region $x = -a_1,\ y \in L_b$ as shown in Fig. 1. The length of the barrier is a for surface-piercing barrier, b for bottom-standing barrier and $c + d$ for barrier with a gap where, c and d are the lengths of the upper part and the submerged part of the barrier. The fluid domain under consideration is divided into four regions: region 1 ($-\infty < x < -a_1,\ 0 < y < h$),