Engineering Structures 81 (2014) 162–174

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Reducing response of offshore platforms to wave loads using hydrodynamic buoyant mass dampers

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ARTICLE INFO

Article history:
Received 16 February 2014
Revised 22 July 2014
Accepted 22 September 2014
Available online 10 October 2014

Keywords:
Fixed offshore platform
Nonlinear wave-induced motion
Platform response mitigation
Hydrodynamic damping
Buoyant mass damper
Dual performance

ABSTRACT

In this paper, an innovative concept is introduced for reducing the displacement response of tower type fixed offshore platforms to wave loads. The idea is based on utilizing a Hydrodynamic Buoyant Mass Damper (HBMD), which employs damper's buoyancy and inertia forces, along with hydrodynamic damping effects, to reduce the displacement response of the platform. A four-legged platform is investigated in which the HBMD is added at the appropriate elevation. Because of the high volume of the damper, the associated added mass and consequently the generated inertia force is significant. On the other hand, as a result of the damper's eccentricity with respect to the platform's position in its deformed configuration, the upward buoyancy force causes reversal moment that can potentially counteract those generated by wave loads. Our results indicate that, if positioned and attached appropriately, the damper interacts with the platform in a way that could result in reducing the response of the platform to wave loads. Response reduction factors are proposed to evaluate the performance of the hydrodynamic buoyant mass damper and seek the optimal stiffness in damper's attachment to the platform.

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1. Introduction

Increasing the safety, serviceability and fatigue life of offshore as well as land structures is of great interest to structural engineers. For offshore structures such as fixed multi-functional offshore platforms, in addition to usual design requirements, complex failure modes, such as soil liquefaction around the supporting piles due to extreme cyclic loading, often times call for special design considerations that are costly and time consuming to implement. An appealing alternative (or rather complementary solution) is reducing the displacement response using an active or passive control methodology. Such methodologies can help achieve the required design goals while keeping the construction and maintenance costs at minimum.

The literature on the modeling of structural response to wave loading is quite rich. Many researchers have focused on modeling wave-structure interactions considering nonlinear effects of waves and one or two-way coupling between the wave motion and the structural response. This line of research laid the foundation for predicting the response of floating offshore platforms to waves more accurately and resulted in proposing new types of platforms. Although seemingly different, these platforms have a few things in common. One of these commonalities is the use of buoyancy force to maintain the upright position of the structure supporting the deck payload and/or to increase the stability of the deck when subjected to wave loads. Tension Buoyant Tower (TBT) introduced by Halkyard et al. [1], for example, consists of a buoyancy module in the form of a cylindrical spar which is moored to the sea bottom using a group of tendons located at the centerline of the buoyancy module. Buoyant Leg Structure (BLS) [2] is another example. BLS is a floating deep draft structure intended for use in deep and very deep water. It is secured to the seafloor with a restraining system and in its simplest form consists of a large diameter cylindrical buoyant leg attached to the seafloor using a single small diameter cylindrical tether. One can also mention innovative semi-submersible platforms such as those with articulated buoyancy [3] or the column-stabilized floating structure with telescopic keel tank [4]. Another commonality is the use of hydrodynamic damping in reducing the vibration response. Kibbee [5] for example modified a previously proposed SeaStar [6] with a vertical cylindrical hull connected to three radially tapered rectangular pontoons. The horizontal pontoons increase the damping associated with heave motion of the cylindrical hull column, which is problematic for classical spars (uniform cylinders) as discussed by Fischer and Gopalakrishnan [7]. Along the same lines, Chandrasekaran and Jain [8] compared the dynamic response of three- and four-legged Tension Leg Platforms (TLPs) and concluded that the triangular

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http://dx.doi.org/10.1016/j.engstruct.2014.09.037
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TLP exhibits a lower response in surge and heave directions while the square TLP has a lower response when it comes to pitch motion. The idea of adding "heave plates" is also based on exploiting hydrodynamic damping and added mass in controlling the motion of floating platforms. As examples of exploring this idea one can mention the work of Srinivasan et al. [9] where semi-submersible platforms having horizontal heave plates are analyzed to show their effectiveness in the design of large vessel platforms or Chakrabarti et al. [10] where the concept of Truss Pontoons Semi-submersible (TPS) platforms is introduced.

Following the influential works of Frahm [11], researchers started looking into the possibility of reducing the vibration response through energy dissipation resulting from counteracting inertia forces (see [12–16]). It was not until about two decades ago, however, that researchers started exploring the applicability of the tools and ideas developed for controlling land structures (see, e.g. [17,18]) to offshore structures. Of these, we mention here only a few that belong mainly to the class of passive control methodologies. One of the early studies on the application of the structural control to offshore platforms appears in the work of Glacel [19] where the effectiveness of the Tuned Mass Damper (TMD) with varying parameters in reducing the response of the platform to frequency dependent sea states was examined. Kawano and Venkataramana [20] studied the behavior of platforms equipped with TMD under seismic loading in both frequency and time domains and Taflanidis et al. used a simulation-based framework to arrive at robust TMD designs for response mitigation of TLPs [21]. Lee et al. [22] investigated the applicability of Tuned Liquid Column Damper (TLCD) in mitigating wave-induced vibration of floating platforms. Both experimental and analytical results indicated that accurately tuned TLCDs could effectively reduce the dynamic response of offshore platforms. TLCD was also used to control wind and wave induced vibration of offshore wind turbines [23]. Patil and Jangid [24] compared the efficiency of viscoelastic, viscous and friction dampers as energy dissipating devices to moderate the dynamic response of steel jacket platforms to sea wave excitations. Ou et al. [25] proposed a damping isolation system for reducing the response of steel jacket offshore platforms subjected to ice and seismic-induced forces and examined it both experimentally and numerically. Lee [26] proposed using viscoelastic dampers within the jacket bracings to improve the dynamic performance of offshore platforms. Jin et al. [27] studied fixed offshore platforms controlled by TLDs and subjected to near fault earthquake excitations. Model tests and numerical simulations were carried out to verify the feasibility of using TLDs in jacket type platforms. Golafshani and Gholizad [28] used stochastic linearization technique and investigated the performance of nonlinear friction dampers to reduce the wave-induced random vibrations in jacket-type offshore platforms.

In this paper, we draw upon the ideas discussed above and introduce an innovative concept that has the potential to reduce the displacement response of fixed offshore platforms to wave loads. We call it Hydrodynamic Buoyant Mass Damper (HBMD) since it employs both buoyancy and added mass of an oscillating cylinder, in conjunction with the inertia force of its vibrating mass, to counteract the wave-induced deformations and dampen the displacement response. The proposed HBMD is added to a four-legged fixed offshore platform at a given elevation. Dynamic analyses are performed for three different incident waves. A complete structural analysis code, Offshore Jacket Structural Analysis Program (OJSAP), is developed in MATLAB, which takes different effects such as large structural deformations and hydrodynamic damping into account. The extracted time history responses illustrate resemblance between HBMD and traditional mass dampers. The combination of buoyancy and inertia action (dual performance), however, is shown to have the potential to be beneficial to the effectiveness of HBMD as a passive control device. The results indicate that, if positioned and attached appropriately, the damper would interact with the platform in such a way that could result in reducing the response of the platform to wave loads. It is nevertheless noted that the size and shape of the HBMD affects its performance by, for example, changing the fluid velocity field at the position of the jacket legs or its added mass dramatically. The location at which the HBMD is attached to the offshore platform is another important factor affecting its performance. A precise examination of these factors may require solving (in 3D) the coupled equations of structural motion and the Navier–Stokes equations. Such analysis is outside the scope of present work. To form a simple design perspective, however, appropriate response reduction factors are proposed to evaluate the performance of the hydrodynamic buoyant mass damper and seek the optimal stiffness in damper's attachment to the platform. It is also noted that a comparison between HBMD and other passive control devices used in offshore platforms (see, e.g. [19–23,27]) is not intended here. Such a comparison needs to incorporate design considerations that aim at arriving at optimally performing control devices (e.g. optimal tuning for TMDs, etc.). Therefore, the present work is aimed at examining the potential of HBMD in offshore platform response mitigation and these design considerations as well as others such as those that pertain to detailing of the connections to ensure the integrity of the structure will be the subject of our future work. It is finally noted that a detailed cost analysis is absolutely necessary if HBMD is to be installed on an existing offshore tower. The cost associated with maintenance or the installation cost when HBMD is added to the tower as it is being built, however, should not be significant.

2. Working mechanism of HBMD

A schematic view of HBMD is presented in Fig. 1. It consists of a fully submerged vertical short closed cylinder placed at a depth far enough from the water surface to reduce the direct impact of incident waves. It can move freely in a predefined direction letting the platform experience a dynamic center of buoyancy. The cylinder's upward buoyancy force reduces the vertical loads transmitted to the lower part of the structure due to deck payload. Eccentric with respect to the platform's deformed position, this buoyancy force also causes reversal moments that counteract those generated by wave loads. The HBMD's motion is restricted by a set of springs that attach it to the platform. Because of the high volume of the cylinder, its induced added mass, as it moves through the surrounding fluid, is significant. Properly selected springs can therefore be used to have HBMD act as a mass damper.

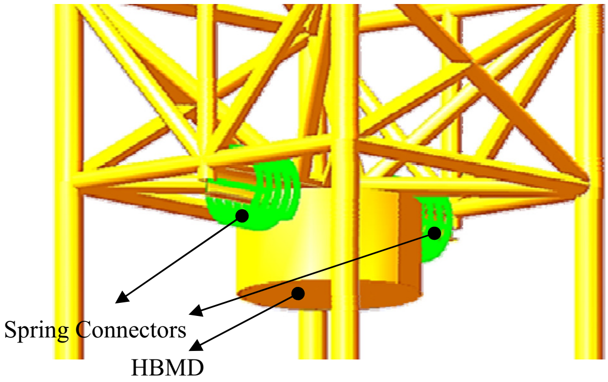

Fig. 1. Schematic view of Hydrodynamic Buoyant Mass Damper (HBMD) and its attachment to the platform.

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