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Control of wave-induced vibrations on floating production systems

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ABSTRACT

Ocean wave loading is in most cases the largest environmental force acting on offshore structures. For floating structures in particular, sea waves may induce considerable motions that the design practice must account for. This paper deals with the dynamics and vibration control of floating structures due to wave loading, with particular focus on heave motion of offshore production units. A semisubmersible model is considered. The design optimization of different structural arrangements is obtained first with the proposed simplified approaches considering the platform heave motion. Different model configurations are analysed with the purpose of mitigating the vessel vibrations, in particular the heave response. The fluid structure interaction is considered and FE-CFD techniques are employed for a comprehensive analysis of the performance of the models. The worked examples and the respective interpretation of the results shine lights on the scope and application of the structural arrangements and computation techniques presented here.

1. Introduction

During the design stage of any big engineering structures, their conception has to meet some desirable required performance criteria. Some structures may suffer from different types of dynamic loads more than others, and although a careful analysis at the design stage can minimise these, the vibration levels of many structures are excessive. The most established technology for vibration control of structures is the adoption of passive systems. The natural frequencies of interest in a system can be changed either by adjusting its mass or stiffness. Traditionally, additional masses about 1–2% of the modal mass are considered for vibration control absorbers. These should be sufficiently effective in avoiding resonance conditions. Tuned mass dampers (TMD) are usually divided into four types: conventional, pendulum, bi-directional and tuned liquid column dampers (TLCD). Lists of some structures in which different TMD systems are employed can be found in the literature (Holmes, 1995; Adeli and Soto, 2013). These can vary among structures such as bridges, towers or even chimneys. Studies involving structural control in other structures such as offshore wind turbines can also be found (Colwell and Basu, 2009).

With respect to active control systems, their popularity too has become increasingly important, especially owing to their smaller cost. For instance, the integral sliding mode control proposed by Zhang et al. (2012) to ensure the stability of offshore steel jacket platform systems under non-linear wave induced self-excited hydrodynamic forces is analysed numerically. In addition to the self-excited nonlinear wave forces, offshore structures may also subject to seismic and wind loads. The sliding mode H_∞ control scheme presented by Zhang et al. (2013) is aimed to reduce the horizontal oscillations. To face the control delays these systems might face, a discrete feedforward and feedback optimal tracking controller has been developed (Zhang et al., 2014a, 2014b). A similar study comparing the different control schemes of controlling steel jacket offshore structures subjected to hydrodynamic wave forces is presented by Nourisola et al. (2015). The performances are evaluated in terms of control force and amplitude reduction. In a more recent work, Zhang et al. (2016) investigated a network-based modelling and event triggered H_∞ reliable control for an offshore structure to deal with possible actuator failures, with the objective to guarantee the stability of the structure.

For floating bodies, like in other structures, one needs to decide on what load a particular structure will be able to bear. Here, the level of restraint is much lesser when compared to those where the TMD concept is applied. These facilities either are moored or may also act as a free rigid body interacting with the surrounding fluid. Lee et al. (2006) tested the application of tuned liquid column damper (TLCD) device on a TLP (tension leg platform) model. Through the water sloshing effects, a clear reduction of the dynamic response in terms of vibration amplitude and resonant frequency is observed from both analytical and experimental results for low frequency mode, i.e., surge motion. This efficiency is also tried in the same study considering other parameter variation such as mass, pontoon type or draft.

Dating from the 1950's, semi-submersible type offshore floating vessels are very representative of floating production units. These floating structures have ever since been found to be an economical

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solution for offshore drilling, production, transport, pipe laying and other shallow and deep-water applications. As the centre of the gravity of semi subs lies much above the centre of buoyancy of the lower hull (formed by columns and pontoons), the acting moments due to wind, wave and currents in the horizontal directions can be restored by the water plane areas of the columns and moment of inertia of the water plane areas. However, semi-submersibles are susceptible to large heave motions under wave loading and therefore some conceptual limitations such as having a dry-tree oil production system is not feasible. These platforms behave differently both hydrostatically and hydrodynamically with their smaller water plane areas and large submerged volume, responsible for their longer natural periods in heave, roll and pitch that lie above those of predominant wave action. Other types/variations of floating vessels used for similar purpose are SPAR (Single Point Anchor Reservoir), TLP and FPSO (floating production storage and offloading). SPAR units, in comparison, are large vertical column or caisson buoyant structures, where the stability of the vessel does not depend on the water plane area and the moment of inertia of the water plane area. Their stability is rather provided by lowering the centre of gravity of the vessel below its centre of buoyancy, making the vertical buoyancy to act upwards above the centre of gravity, and the total weight to act at the centre of gravity below the centre of buoyancy. Their main limitation is the small deck area and payload. SPAR units, in turn, have excellent heave performance.

Reducing the vertical motion is of importance when accounting for marine operations like drilling and oil production, making it desirable to minimize the heave motion to reduce its down time to weather. The increase of the hydrodynamic mass and damping, for instance, can be achieved by increasing the draft of these platforms. A good example of this is the turning point of the classical spar to the truss spar. Heave plates are used for the purpose of generating huge added mass and reduce the steel weight and consequently the cost of the hull (truss spar). The resemblance with the TMD concept is discussed for a semi-submersible platform with heave plates by Hang et al. (2012) and Liu et al. (2016) and alternative designs for offshore platforms have also been proposed (Chakrabarti and Chakrabarti et al., 2005, 2007) as well as a diversity of design solutions have been patented.

In practical design of semi-submersibles it is usually desired that the heave period lies above 20 s so that wave energy will be extremely unlikely to excite resonant wave oscillations. The generalized design values for these and other floating structures are illustrated in Fig. 1 for reference.

To sum up, the displacement and/or vibration control of floating structures can be tackled following both structural dynamics and hydrodynamics principles. The present work addresses this problem considering a semi-submersible model type, with particular emphasis on controlling the vertical oscillations (heave motion). Along with this, the implication of producing accurate and detailed numerical analyses for verification (in the absence of testing facilities) that include both structural response to dynamic loading and fluid-structure interaction constitutes itself a contribution to the current state of the art of simulation methods using coupled FEA-Computational Fluid Dynamics (CFD) codes. It is naturally known that offshore structures vary a lot in topology and hence layout depending on their purpose, location or exposure. Fig. 1, for instance, where a wide range of heave periods are visible, is well exemplificative. Nonetheless, the modelling approach used in the current study can easily be adapted and followed in other applications. This issue and the respective methodology used here are addressed more in detail in Section 3 of this paper. Before then, the design optimization of the adopted numerical model(s) is first carried out in the following section.

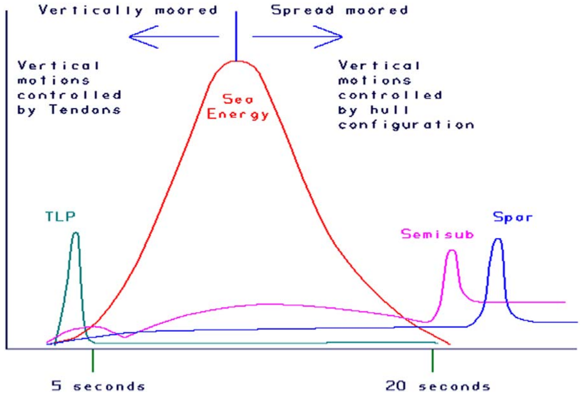

Fig. 1. Natural periods of heave for different vessels.

2. Heave response of floating structures

The dynamic response of a floating body to wave loading, in particular the vertical oscillations, is described in this section through some simplified numerical models. Such simplified analogies are of interest for the evaluation of an optimal solution to be considered in the later detailed numerical analyses carried out in this study. Without loss of generality, a generic semi-submersible model with two columns on each pontoon as shown in Fig. 2 is considered first.

2.1. Single Degree of Freedom (SDOF) system analogy

For the estimation of the heave motion (Fig. 3) of a vessel, the fluid-structure interactions of a floating platform can be simplified into the classical second-order linear differential equations of motion for a single degree-of-freedom system with inertial (mass m), damping (c) and stiffness (k) components (Eq. (1)) subjected to an excitation force (wave, F).

$$m\ddot{z} + c\dot{z} + kz = F(t) \tag{1}$$

Comparatively to the single degree of freedom system considered in Eq. (1), for a semi-submersible structure the total force acting on the structure includes added mass, damping and the hydrostatic stiffness induced forces resulting from the differential motion between the structure and the surrounding fluid. The net force caused by these effects accelerates the floating body. The equation of motion then becomes:

$$m\ddot{z} = \alpha(\ddot{z}_0 - \ddot{z}) + \beta(\dot{z}_0 - \dot{z}) + \kappa(z_0 - z) \tag{2}$$

where z and z_0 are the resultant body vertical motion and the vertical motion of the water surface respectively, m is the mass of the floating structure and α, β, κ the coefficients relative to the added mass,

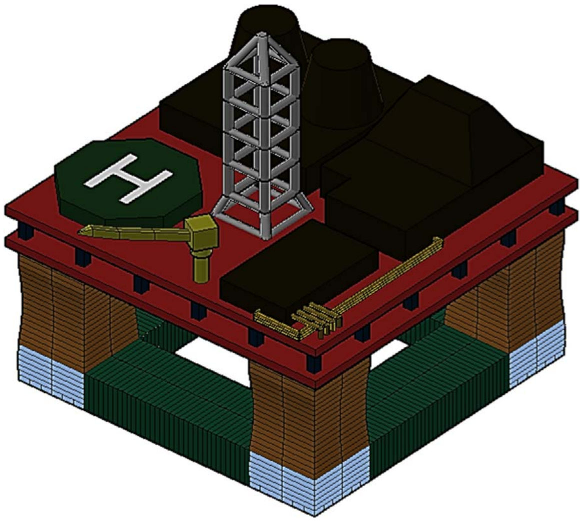

Fig. 2. Semi-submersible model.