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Spacing effects on hydrodynamics of heave plates on offshore structures

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Abstract

The nonlinear viscous flow problem associated with a heaving vertical cylinder with two heave plates in the form of two circular disks attached is solved using a finite difference method. Numerical experiments are carried out to investigate the spanwise length effects on the hydrodynamic properties, such as added mass and damping coefficients. Over a Keulegan–Carpenter (KC) number range from 0.1 to 0.6 at frequency parameter ($\beta = 7.869 \times 10^7$), calculations indicate that a KC-dependent critical value of spanwise length L/D_d (L—the distance between the disks, and D_d—the diameter of the disks) exists. A significant influence of L/D_d on the vortex shedding patterns around the disks and the hydrodynamic coefficients is revealed when L/D_d is smaller than the critical value due to strong interaction between vortices of different disks. Beyond that limit, however, both added mass and damping coefficients are shown to be rather stable, indicating the independence of the vortex shedding processes of different disks.

Keywords: Heave plate; Spar; Viscous damping; Added mass; Vortex shedding

1. Introduction

The spar platform has attracted much attention of researchers and design engineers in offshore engineering. It is one of the most reliable and cost effective structure for offshore oil and gas exploration in deep water. Due to reduced amplitudes of oscillations in the vertical plane (i.e. heave, pitch and roll), one of the principal advantages of the spar concept compared to other conventional floating systems is the use of dry well-heads and rigid risers. Typically a spar has a natural heave period above 25 s, which in most circumstances is sufficiently outside the prevailing wave frequency range. However, a spar may still suffer from resonant heave motions, which are excessive for riser integrity, in sea states with long peak periods due to its low damping. A typical example is in the swell waves offshore West Africa, with peak period lying in the 23–25 s range. Such a wave spectrum will have appreciable energy even at up to 30 s.

The heave response of a spar platform depends on the linear and nonlinear wave exciting forces, natural period of the system and hydrodynamic damping forces. The earliest spar concept, called the classic spar, with cylindrical shape and constant cross section obtained its low heave characteristics due to its deep draft resulting in low wave excitation force.

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The heave natural period (T) of a classic spar structure is primarily dependent on its draft and inertia coefficient,

$$T = 2\pi\sqrt{\frac{T_d C_m}{g}}, \tag{1}$$

where T_d and C_m represent the draft of the spar and the inertia coefficient which equals to $1 + C_a$ with C_a being the added mass coefficient, g is the acceleration due to gravity, respectively. Eq. (1) indicates that the long heave natural period can be achieved by extending the draft of the spar column. However, increasing the draft, and consequently increasing the system mass, is normally subject to many other considerations in the design, such as the cost of construction, transport and installation of the structure.

In addition to increasing the heave natural period of a spar platform beyond the dominant wave energy range, increasing heave damping is another efficient means of reducing the heave response. Apart from the damping forces from the mooring system, a classic spar hull is considered a lightly damped system. Ways of increasing heave damping may thus offer significant advantages in terms of heave stabilisation of the spar.

Recent developments of the spar concept led to the second generation of truss spars. Based on the consideration of both added mass and damping characteristics, heave plates oriented normal to the spar axis are introduced in the truss structure. The plates increase added mass and damping when the spar moves in heave, which results in longer heave natural period (see Eq. (1)), as well as reduced motion due to higher damping.

Appendages have long been used to control amplitudes of undesirable motions of structures in fluids. Typical examples are bilge keels on ships and helical strakes which are widely applied to spar hulls. Srinivasan et al. (2005) presented a new concept of truss pontoons with heave plates on a semi-submersible which had reduced vertical plane motions. A similar idea without the truss structure was used by Cermelli and Roddier (2005) on a minimal platform. Further, the use of plates was generalised to other cylindrical structures. In particular several offshore buoys were found to have favourable motion characteristics with a base plate (also called skirt) structure [see e.g. Cozijn et al. (2005), for application to a CALM buoy].

Thiagarajan and Troesch (1998) measured the heave damping of a vertical cylinder with a disk attached to the base. Their experiments were conducted in the range of $\mathrm{KC} = 0.1\sim1.0$ ($= 2\pi a/D_d$, a is the amplitude of heave oscillation; D_d is the diameter of the disk) and frequency parameter $\beta = 89\,236$ (β is defined as $D_d^2 f/\nu$, where f is frequency and ν is kinematic viscosity). The results showed that the heave damping induced by the disk is linear with the amplitude of oscillation. The disk was found to increase the form drag coefficient (C_d) two-fold. However, previous investigations were primarily focused on the oscillation suppression due to the damping increased by the external devices.

Tao and Thiagarajan (2003a, b) investigated the hydrodynamics of a heaving vertical cylinder with a single disk attached at the keel. The effects of the geometry of the disk, such as aspect ratio t_d/D_d (t_d is the thickness of the disk) and diameter ratio D_d/D_c (D_c is the diameter of the cylinder or spar) on heave damping and added mass were examined. The aspect ratio of disk t_d/D_d was found to have the most striking effect on the vortex shedding and the viscous damping, especially when the aspect ratio is small. However, the effect of changing aspect ratio on damping was also found to be dependent strongly on KC number, while D_d/D_c was found to have a significant impact on the hydrodynamics, especially on added mass. The recommendation of a spar hull and disk geometry was made to achieve optimum heave response.

In order to obtain better heave characteristics of a spar, several heave plates attached to a spar hull or truss spar were proposed. Recent studies by Downie et al. (2000) and Magee et al. (2000) revealed that the increased added mass is the dominant contribution to the reduction of the heave amplitude of a classic spar with heave plates attached or a truss spar compared to the increase in damping resulting from the heave plates. However, damping is also important for relatively shallow draft spar or truss spar designs. A typical example is the truss spar proposed for West Africa, where very long swells, with periods approaching the heave natural period, occasionally occur. Preliminary study of Thiagarajan et al. (2002) has shown a classic spar will suffer heave resonance.

In their experimental study, Prislin et al. (1998) carried out model tests on an array of solid square plates, oscillating perpendicular to their plane in an otherwise quiescent fluid. Based on the measurements, Prislin et al. (1998) concluded that the added mass coefficient for the single plate does not depend on the Reynolds number higher than 10^5. However, this conclusion could not be extended to the case of multiple plates due to insufficient data on the variability in Reynolds number. It was further pointed out by the authors that special precautions should be taken when analysing model test results for a spar with heave plates. Because of a relatively low Reynolds number for the model in comparison to the full scale (the ratio is about two orders of magnitude), drag coefficient for the model plate can be two to three times larger than that for full scale spar. However, Thiagarajan and Troesch (1998) as well as Lake et al. (2000) have argued that the predominant damping contribution from plate edges arises from convective motion of vorticity and hence should be scalable to full scale.