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Hydrodynamic characteristics of a separated heave plate mounted at a vertical circular cylinder

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ABSTRACT

In this study, a wave flume experiment was performed with a scaled floating model to optimise the design of a floating body and control unwanted motions due to the offshore environment. A cylindrical test model was chosen as a standard and classical representative design of a floating structure in an ocean environment. The attachment of a heave plate at the bottom of the floating structure has been suggested as an effective tool to control its motion. However, the associated hydrodynamic effects, particularly the added mass variation, need to be investigated. Therefore, a scaled cylindrical model with a height of 300 mm, an outer diameter of 60 mm, and various heave plates was designed, manufactured, and tested. The motion responses of a scaled model in a water flume (i.e. forced oscillation, free decay, and regular wave response) were analysed. The results were compared for similar cylindrical models with various heave plates attached at different gaps from the cylinder bottom, different oscillating frequencies, and different Keulegan–Carpenter (*KC*) numbers. An empirical formula was formulated to calculate the added mass of the combined structure of the cylinder and heave plate. The results indicated that varying the heave plate diameter had the most significant effect on the added mass compared to the gap and *KC* (0.2–1.4). The added mass coefficient of the combined cylinder and heave plate was below 0.05, while *KC* varies from 0.2 to 1.4 and the gap ratio ($D_g/(0.5D_c + 0.5D_p)$) varied between 0.2 and 1.2. The peak heave response amplitude operator (RAO) for the combined cylinder and heave plate was 40% less than that of the cylinder without a heave plate.

1. Introduction

Because floating wind turbines continuously operate in a complicated environment subjected to various forces from winds, currents, and waves, a crucial challenge for designing an offshore platform is ensuring excellent stability. The motion of a floating body at sea has the six degrees of freedom of a rigid body: three translation motions (heaving, swaying, and surging) and three rotation motions (pitching, yawing, and rolling). These motions need to be controlled within certain ranges to maintain the sustainability and stability of the floating platform. In ocean engineering, additional mechanical damping devices or other active damping systems have been introduced to enhance the stability of the floating structure. One effective device is the heave plate, which can generate added mass and damping effects on the floating platform.

Phillip et al. (2012) examined the effects of a circular heave plate on a spar platform. Their results demonstrated that the added mass and viscous damping of the heave plate are key factors for reducing the motion response of a floating platform. However, increasing the added mass of the platform does not always improve the stability performance of the sub-platform. In the South Africa Sea, Teng and Li (2002) indicated that a heave plate increases the added mass of the platform and brings the resonance period of the platform close to the wave period, which causes an extremely dangerous situation. Therefore, the added mass and damping effects need to be studied.

Among the relevant parameters that can influence the added mass and damping, a commonly used non-dimensional parameter is the Keulegan–Carpenter (*KC*) number. Originally, Keulegan and Carpenter (1958) carried out experiments to examine the oscillatory flow around two-dimensional non-moving flat plates and horizontal circular cylinders separately. Their results showed that the added mass and damping coefficient depend on *KC* within the range of 2–100 and not on the Reynolds number (*Re*) over 4200.

$$KC = \frac{2\pi A}{D_p} \tag{1}$$

where A is the amplitude of oscillation, and D_P is the diameter of the heave plate.

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Later, Shih and Buchanan (1971) measured the forces on plates oscillating in still water. They carried out a laboratory experiment at a low Reynolds number and a low *KC* of 1.6–4.7. They clarified that the damping coefficient only depends on *Re* at values of less than 250. However, this is only applicable for two-dimensional waves.

Further experiments have also been conducted to understand the added mass and damping coefficient of a single plate on the basis of a variety of parameters such as *KC*, *Re*, the oscillation frequency, and the porosity. Prislin et al. (1998) considered a square solid plate and conducted free decay tests on an array of solid square plates to obtain the hydrodynamic coefficients of the plates at the resonance frequency. They observed that the added mass coefficient for the plate does not depend on the Reynolds number above 10^5. Li et al. (2013) conducted a series of forced oscillation experiments to investigate the hydrodynamic coefficients of a heave plate. Their results showed that the external forced frequency has little influence on the hydrodynamic coefficients when *KC* is 0.2–1.2. A heave plate with rectangular edges yields the largest added mass, and the drag coefficient is almost independent of the shape of the edge. Chua et al. (2005) conducted various forced oscillation experiments on solid and porous plates. Their results indicated that the damping coefficient increases with the perforation ratio, but the added mass coefficient decreases. On the basis of the ideal and irrotational flow assumption, Molin (2001) studied arrays of porous plates in an oscillatory flow and found that no extra damping can be gained by making a plate porous when *KC* is greater than 1.

The structural combination of a cylindrical body and heave plates has commonly been considered to examine the suppression of movement by a floating body. Tao and Cai (2004) investigated the hydrodynamic coefficient of a vertical circular cylinder with a circular plate mounted on its bottom. They investigated the geometry of the plate, such as the ratio of the diameter to the thickness, and found that it has a significant effect on the vortex shedding and viscous damping. Lake et al. (2000) observed the flow patterns around an oscillation plate and cylinder with a plate attached to the bottom. Their observations indicated that the presence of the cylinder has a substantial effect on vortex generation. In addition, the results of a forced oscillation experiment demonstrated the effect of the cylinder on the added mass coefficient of the cylinder–plate configuration. Tao et al. (2007) also considered the effect of spacing between heave plates on the added mass and damping to investigate the effects of the span-wise length and the gap between two plates on the hydrodynamic properties. In their numerical study, they developed simplified formulas under the assumptions of a homogeneous trapped fluid mass between the plates and negligible interference between the cylinder and the plate. The span-wise length was observed to have a significant influence on the vortex shedding patterns around the plates, and the spacing was observed to influence the heave added mass and damping. They also reported the influence of *KC* on the added mass due to the fluid viscosity. Unfortunately, their numerical study was performed at a very low *KC*, therefore, their cases were limited in terms of the effect of the heave added mass and damping. Phillip et al. (2012) also conducted forced oscillation experiments to study the effects of the spacing between heave plates on the added mass and damping, and they examined the suppression of movement by the entire body with the heave plate installed at the cylinder (spar) bottom. The heave excitation force on a spar buoy with a plate on the bottom was found to be 30% less than that of a classic spar buoy owing to the increased added mass of the heave plate. Their results also showed that having a heave plate substantially reduced the motion response, particularly at the resonant frequencies.

The previous studies showed that attaching a heave plate to the bottom of the main body produces two dominant effects on the heave added mass and damping. An increase in the heave added mass of the floating structure increases the heave natural period of the floating structure to close to the period range of the external wave. With regard to damping, the viscous damping of a vertical circular cylinder is negligible, and the majority of the energy dissipation is due to wave damping. A circular heave plate can generate vortex shedding when it moves along the vertical axis, which produces viscous damping due to the friction and pressure loss around the heave plate. Tao and Cai (2004) pointed out the possible effects of the interference between the cylinder and the plate on the heave added mass and damping. On the basis of these aspects, the heave added mass and damping have dominant effects on the hydrodynamic performance of a floating platform with a heave plate. Liu et al. (2015) explained the limitations of the numerical analysis by using a Green's function to solve for the heave added mass and damping coefficients of a thin circular dock (or disk). Therefore, these coefficients are crucial values for examination in a laboratory experiment. To the best of the authors' knowledge, the problems related to the gap between the heave plate and the cylinder have rarely been studied; the effects of the diameter and thickness of the heave plate must be addressed before performing a comparative assessment of various spars such as a truss spar or buoy.

In this study, a forced oscillation experiment was performed with the aim of effectively obtaining the added mass of a floating body while changing various related parameters (e.g. the gap length, the diameter, the thickness, and *KC*). This floating body consisted of a vertical circular cylinder and a circular plate mounted to the bottom of the main body. To evaluate the hydrodynamic performance of a cylindrical model with a plate placed in an ocean environment, the two-dimensional motion response of a vertical circular cylinder with a heave plate was considered with regular waves.

The detailed research objectives are summarised as follows: (1) to examine the effect of *KC* (range: 0.2–1.4) on the added mass coefficient, (2) to examine the effect of the gap ratio on the added mass coefficient, (3) to examine the effect of the diameter on the added mass coefficient, (4) to theoretically approach the added mass coefficient for a certain range, and (5) to evaluate the motion response of the model in regular waves.

2. Design of laboratory experiments

2.1. Governing equations of forced oscillation, free decay, and wave response

Three different categories of flume experiments were carried out: forced oscillation, free decay, and wave response. If the forced oscillation in the heave direction is considered to move with one degree of freedom, it can be described by a damped spring-mass system along the *z*-axis (vertical axis) under an imposed harmonic external force. The governing equation is described as follows:

$$(M_{33} + A_{33})\ddot{z} + b\dot{z} + \rho g A_{wp} z = F_z \qquad (2)$$

where M_{33}, A_{33}, b, and F_z are the mass, heave added mass, linearised damping coefficient, and external force in the *z*-direction, respectively. In addition, ρ, g, and A_{wp} are the density of water (the working fluid in which the model is submerged), the acceleration of gravity, and water plane area, respectively.

For the free decay experiment, there is no external force; therefore, F_z on the right side of Eq. (2) is equal to zero. The governing equation for the heave free decay experiment can be converted to

$$(M_{33} + A_{33})\ddot{z} + b\dot{z} + \rho g A_{wp} z = 0 \qquad (3)$$

Similar to the heave motion, the equation for the angular displacement in the pitch direction θ can be formulated as follows:

$$(I_{55} + A_{55})\ddot{\theta} + b^{eq}\dot{\theta} + \rho g V\cdot\overline{GM_L}\theta = 0 \qquad (4)$$

where I_{55} and A_{55} are the second moment of inertia of the *y*-axis and the added mass in the pitch direction, respectively. $\dot{\theta}$, $\ddot{\theta}$, b^{eq}, and V are the velocity and acceleration of the model in the pitch direction, the