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Heave and Pitch Motions of a Spar Platform with Damping Plate

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ABSTRACT

Deep-draft spar platforms have been regarded as a competitive alternative structure for deepwater oil field development. The natural periods of classical spar platforms for heave and pitch are relatively long due to small waterplane area compared to submerged volume and hence spar platforms are not usually excited vertically. However, the heave response increases drastically at resonance and also large coupled pitch motions are induced. In this paper, we consider heave and pitch motions of a spar platform with damping plate at its bottom in order to reduce the heave motion. Model tests are carried out in a wave tank with a scaled model with/without damping plate and experimental data are compared with numerical ones, which are obtained from a potential code. Compared to the classical spar platform, the spar platform with damping plate shows significantly reduced heave motions at resonance. In experiments in regular waves, it is observed that pitch motions are triggered when the magnitude of heave motion exceeds a certain threshold, when the pitch natural period is approximately double the heave natural period. The underlying mechanism may be understood in the manner that the large heave motion makes GM negative and consequently the platform becomes unstable even statically and finally kinetic energy transfers from heave mode to pitch mode due to a nonlinear mechanism.

INTRODUCTION

Spar technology has been utilized for offshore structures such as research vessels, communication relay stations, and storage and offloading platforms. Recently its application has extended to the deep-draft cylindrical spar for deepwater production. The shape of spar platforms is usually a long hollow cylinder with a large diameter. It is normally moored by means of conventional spread chains. Due to the deep draft, the spar hull generally has helical strakes to prevent VIV (vortex induced vibration) in current, and shows excellent motion characteristics even in extreme sea-states. Typical natural periods of the spars deployed in the Gulf of Mexico are 160s for surge, 60s for pitch and 28s for heave. Therefore the spar is an attractive design solution for regions where the environment is harsh. However, the spar platform undergoes large heave motions at resonance, up to 8~10 times of incident wave amplitude. Such large heave motions can affect the restoring moment of pitch, and it starts to vary with time in phase with the heave motion. In this situation, Mathieu-type stability must be examined.

In this work, model tests are carried out to investigate the heave and pitch motion characteristics of spar platforms. In order to reduce the large heave motion at resonance, a damping plate is attached to the bottom of the hull. Also the heave/pitch Mathieu-type instability that is caused by large resonated heave motions is studied mathematically and confirmed by model tests.

EXPERIMENTS

Experiments for a spar model with a scale of 1/400 are carried out in a wave tank. The heave and pitch motions of the model are measured in regular waves. The experimental setup is shown in Fig. 1.

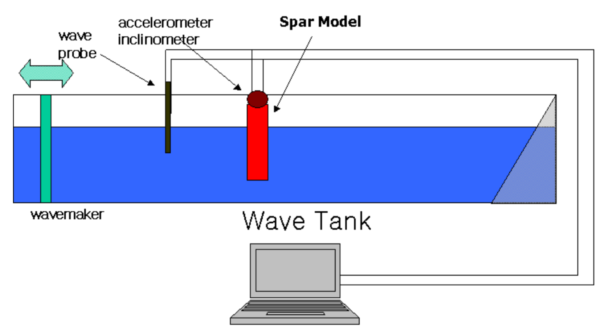

Fig. 1 Experimental setup in wave tank

A circular cylinder model with moonpool inside is made of acryl. The diameter of the model is 0.1m and the length is 0.65m. To investigate the effect of different hull forms, 4 cases are considered; hull with moonpool, hull with moonpool and strakes, hull with moonpool and damping plate, and hull with moonpool and strakes and damping plate. The width of strakes is 0.005m and the diameter of damping plate is 15% larger than the hull diameter. Their configurations are shown in Fig.2.

Fig. 2 Model configurations : model with moonpool, strakes, and damping plates

Wave probe, 1-axis accelerometer and inclinometer are used to measure incident wave height, heave and pitch, in this order. The vertical acceleration($\ddot{h}_3$) is recorded and the heave displacement(h_3) is evaluated with heave frequency(w_3) from the harmonic relations as shown below

$$h_3 = -w_3{}^2 \ddot{h}_3 \quad (1)$$

RESULTS

Fig.3 and Fig.4 show the heave motion obtained experimentally in regular waves. The numerical results are also plotted in the figures. The numerical result of heave responses at resonance is highly exaggerated because potential code ignores dampings. Except near the heave natural period, however, experimental and numerical results are in good agreement over all periods.

From the figures, it can be concluded that the moonpool does not affect the heave motion and the strakes reduce heave motions by about 25% at resonance. In Fig.5 it is also observed that the damping plate reduces the resonant heave motion significantly, up to 50%. Furthermore, Fig.6 shows that the hull with damping plate and strakes shows outstanding heave characteristics to reduce by 70%. Meanwhile pitch motions are only slightly affected by the strakes and the damping plate as shown in Fig.7. In other words, the heave motion can be controlled to be small by introducing strakes and damping plate, which give almost no effects on pitch motions.

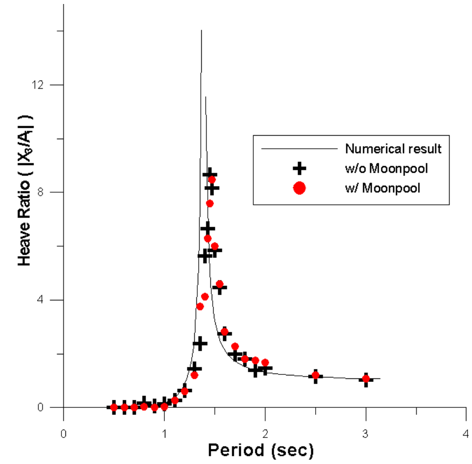

Fig.3 Heave amplitude ratio for a Spar model with moonpool

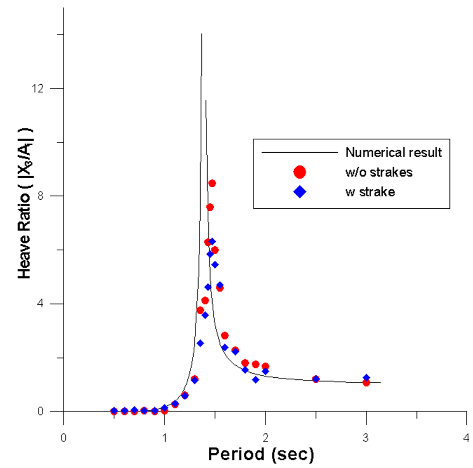

Fig.4 Heave amplitude ratio for a Spar model with strakes

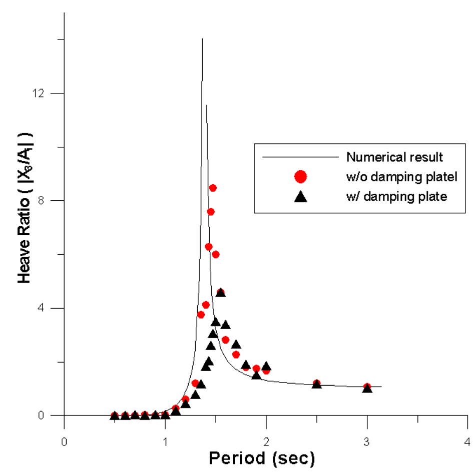

Fig.5 Heave amplitude ratio for a Spar model with damping plate

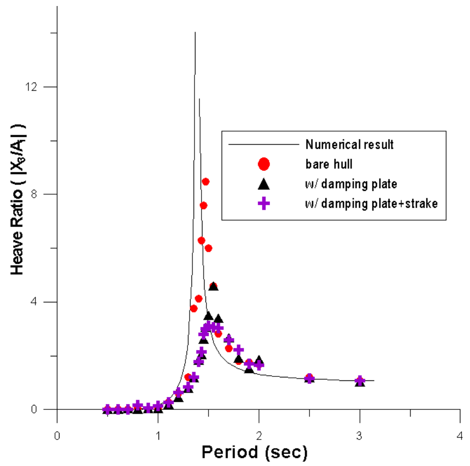

Fig.6 Heave amplitude ratio for a Spar model with strakes and damping plate

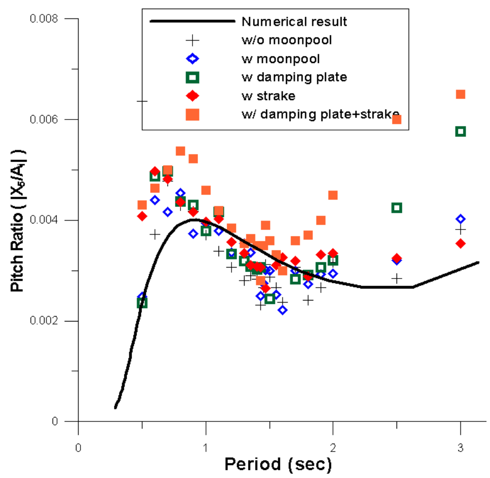

Fig.7 Pitch amplitude ratio for a Spar model with strakes and damping plate

MATHIEU-TYPE INSTABILITY

At resonance, the heave response becomes very large as discussed previously. In this case, the non-linearity plays a non-negligible role and it affects the restoring moment of the pitch. Hence Mathieu effects must be considered.

The linear uncoupled equation of pitch by ignoring damping and wave excitation is given by

$$(I_{55} + A_{55})\ddot{h}_5 + rg\nabla GM h_5 = 0$$

(2)

It is to note in this equation that the pitch restoring moment depends on two parameters; the submerged volume (∇) and the meta-centric height (GM). The dominant factor affecting the GM is the vertical position of the center of buoyancy(B) above the center of gravity (G). The BM is small due to the relative small moment of inertia of the waterplane area compared to its displacement.

If the restoring term is evaluated at the instantaneous position instead of the mean position as used in the linear theory, both the GM and the ∇ are not constant, but vary with the heave motion h_3. Ignoring the fluctuation of the submerged volume with time and the effect of wave elevation, the equation of pitch motion is approximated by

$$\ddot{h}_5 + w_{n5}^2\left(1 - \frac{h_3}{2GM_0}\right)h_5 = 0$$

(3)

By substituting $h_3 = h_3 \cos(w_3 t)$, $t = w_3 t$, $\overline{w} = w_{n5}/w_3$, $e = h_3/2GM_0$, Mathieu's equation (3) takes the form

$$\ddot{h}_5 + \overline{w}^2(1 - e\cos t)h_5 = 0$$

(4)

For certain values of the parameter $(e, \overline{w})$, the solution of the Eq. 4 becomes unstable. The pair of $(e, \overline{w})$ in which the solution becomes unstable is indicated as unstable region in the $e\overline{w} - plane$ (see Fig.8). Physically, e represents the change in the stiffness of restoring term and $\overline{w}$ represents the ratio between the heave natural frequency and the pitch natural frequency. From the stability diagram, it is seen that for certain critical frequencies, unstable solutions exist even in the case of $e \to 0$

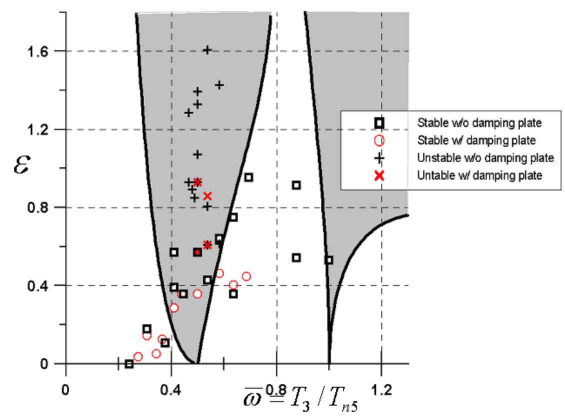

Fig.8 Stability diagram of Mathieu equation with experimental results

In this investigation, the heave natural period is set to be half the natural period of pitch, which can easily be realized by adjusting the weight distribution. The heave motion is usually very small in incident waves of shorter periods than the heave natural period, and the relative heave responses to waves are almost zero in waves of longer periods.

In the experiments, the model without any appendages is taken to observe coupled heave and pitch motions. When the period of incident waves is equal to the heave natural period and half of the pitch natural period, the Mathieu type instability occurs clearly, as shown in Fig.9.

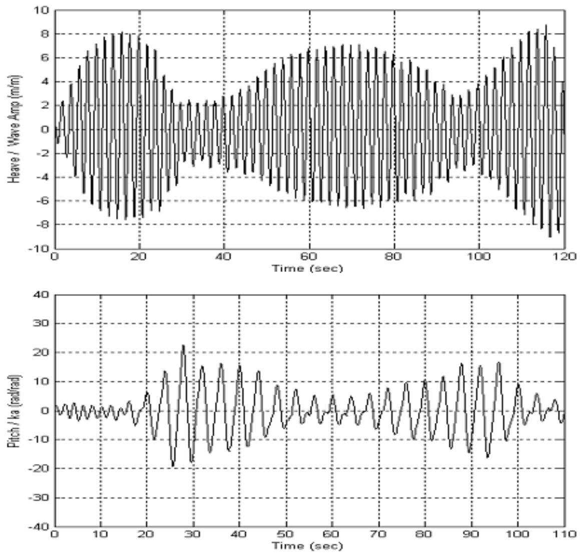

Fig.9 Time history of coulpled pitch motion caused by large heave motion

However, Mathieu-type instability does not always occur in incident waves of the heave resonance period. When the wave height is small, the heave motion also becomes small and the Mathieu-type instability does not appear as confirmed in Fig.10, which shows the experimental data in the case of small incident waves. It is thought that the damping in heave and pitch motions resists the occurrence of Mathieu-type instability.

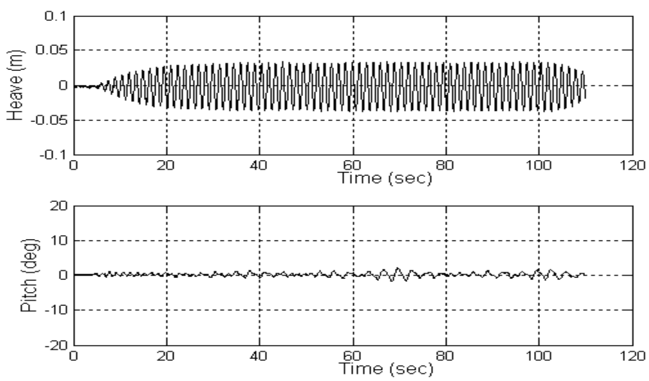

Fig.10 Time history of coulpled pitch motion caused by small heave motion

The experimental results for stability are plotted in Fig.8. In this diagram, it is to observe that unstable pitch motions occur densely in the region of the heave resonance ($\overline{w} = 0.5$). Stable motions were observed experimentally in the theoretical unstable region. This is believed due to damping effect as mentioned previously. Therefore in order to avoid Mathieu-type instability, the doubling relation between heave and pitch natural periods should not exist or some appendages such as damping plate and strakes are to be installed so that the heave motion is constrained within a certain limit.

CONCLUSION

Experimental results obtained from wave tank tests for various spar configurations are presented. The measured data are analyzed to clarify the heave and pitch motion characteristics of the spar platform. It is shown that the spiral strake and the damping plate are effective in reducing heave motions. And Mathieu-type instability is investigated. It is experimentally confirmed that coupled non-linear motions occur when the pitch natural period is twice the heave natural period.

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