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Control of surge and pitch motions of a rectangular floating body using internal sloshing phenomena

Minho Ha and *Cheolung Cheong[1)]

School of Mechanical Engineering, PNU, Busan 609-735, Korea
[1)] *ccheong@pusan.ac.kr*

ABSTRACT

In this paper, possibility of controlling floating wind turbines using a tuned liquid damper (TLD) is investigated numerically. The TLD is a tank partially filled with liquid. For simplicity, a two-dimensional rectangular tank partially filled with water is considered. First, a grid refinement study is carried out to ensure that surface wave is generated with amplitude specified at the target location where the floating body is placed. Then, the surge and pitch motions of a floating body with and without water are investigated by varying excitation frequency of a wave maker. Normalized amplitudes of surge and pitch motions are compared for the cases with and without water inside the floating body. Finally, the coupled surge and pitch motions of the floating body with and without water are investigated by varying the excitation frequency. On a basis of these results, it is shown that the surge and pitch motions of a floating body can be reduced by matching the natural frequency of the liquid sloshing to the external excitation frequency.

1. INTRODUCTION

Interests in renewable energy due to the exhaustion of fossil fuel have encouraged a lot of researches on wind turbines in various aspects. A wind turbine is a facility to generate electricity from wind power and has generally been installed in a land. Offshore wind turbines have, however, increased due to better wind speeds available offshore compared to on land as well as environmental problems caused by wind turbines such as noise and damaged landscape. In developed countries, many offshore wind farms are already in operation. Recently, floating wind turbines that can generate electricity in water depths where bottom-fixed towers are not feasible get more and more interests due to more consistent and stronger wind sources over wider deep sea region than on land and near coastal area. Despite this merit of a floating wind turbine, there are also many technical issues to solve for commercializing it. One of most important problems is that a floating wind turbine is exposed to more external exciters

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such as wave and current as well as wind. Stability of the floating substructure is a critical factor for the efficiency of floating wind turbines. In this paper, a tuned liquid damper (TLD) is proposed as one of potential methods to control the motion of a floating wind turbine.

A TLD is a tank partially filled with water and has been used in a high-rise building to reduce a vibration by seismic force (Kareem, 1999). If a building with a TLD is shook by external force, sloshing phenomena that is a motion of fluid in the TLD generate a reaction force against the external force. Due to the reaction force, response of the structure to the external force is reduced. Sloshing phenomena in a TLD have natural frequencies depending mainly on liquid height inside a tank. A TLD exerts the maximum reaction force at the natural frequencies. Therefore, if the sloshing natural frequency is the same as a frequency of external force, a motion of the structure can be reduced by maximum.

It is impossible to test the effects of TLD using a full scale prototype due to an enormous cost. A scaled model test has a difficulty in adapting its result to a full scale case due to multi-physical properties inherent in the phenomena itself. In this paper, the effects of a TLD on the motion of the floating substructure subject to external water surface waves are numerically investigated.

Surface wave have been theoretically and numerically investigated by a lot of studies. Dean & Dalrymple (2000) summarizes linear potential theories for surface wave and a wave maker. Maguire (2011) numerically generated surface waves using the virtual wave maker and compared the numerical results with the theoretical ones. Silva et al. (2010) investigated the effects of mesh sizes, time steps and turbulence models on the surface wave. Internal sloshing phenomena also have been numerically and experimental investigated. Ha et al. (2012a; 2012b) investigated liquid sloshing phenomena inside a rectangular tank in a sway motion. The results are compared with experimental data. The coupled motion of a floating body with internal sloshing was studied experimentally and theoretically by Rognebakke & Faltisen (2003). They study the surge motion of a floating body with and without water by varying frequency and amplitude of surface wave. The results were compared with theoretical model based on the multimodal method. In a present study, the numerical methods validated for the internal sloshing problem in the preceding studies (Ha et al. 2012a; 2012b) are extended for coupled external and internal sloshing problems. Using this numerical technique, the effects of internal sloshing phenomena on the surge and pitch motions of a rectangular-shaped floating body are investigated.

2. THEORY

Theoretical models about surface wave and a wave maker can be found in Dean & Dalrymple (2000). In this section, the related theories are briefly reviewed.

2.1 Surface wave theory

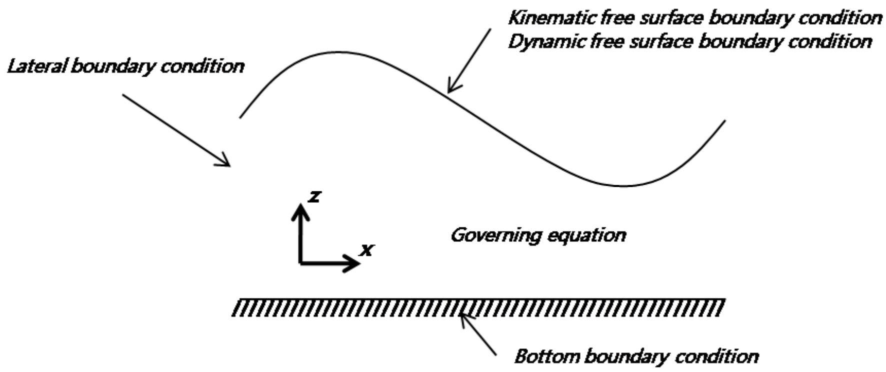


Fig. 1 Boundary conditions for deriving potential theory of surface wave

Fig. 1 shows one wavelength of a surface wave and the related boundary conditions that allow the problem to be a boundary value problem. Under the assumptions of invicid, irrotational and incompressible flow, the governing equation can be derived to be the Laplace equation for the velocity potential in the form.

$$\nabla^2 \phi = 0 \tag{1}$$

The wall boundary condition is applied on bottom. This means that the normal velocity on bottom is zero.

$$w = 0 \tag{2}$$

Kinematic and dynamic free surface boundary conditions are written in the forms.

$$-\frac{\partial \phi}{\partial t} = \frac{\partial \eta}{\partial t} - \frac{\partial \phi}{\partial x}\frac{\partial \eta}{\partial x} \tag{3}$$

$$-\frac{\partial \phi}{\partial t} + \frac{1}{2}\left[\left(\frac{\partial \phi}{\partial x}\right)^2 + \left(\frac{\partial \phi}{\partial z}\right)^2\right] + g\eta = C(t) \tag{4}$$

Lateral boundaries are set to be periodic in space and time as follows

$$\begin{aligned} \phi(x,t) &= \phi(x+L,t) \\ \phi(x,t) &= \phi(x,t+T) \end{aligned} \tag{5}$$

Then, solving Eq. (1) with the BCs of Eqs. (2) to (5) leads the potential function in the form:

$$\phi = \frac{H}{2}\frac{g}{\sigma}\frac{\cosh k(h+z)}{\cosh kh}\sin(kx - \sigma t) \tag{6}$$

where, $\sigma^2 = gk \tanh kh$ (7)

The frequency and wave length of surface wave can be related using Eq. (7).

2.2 Wave maker theory

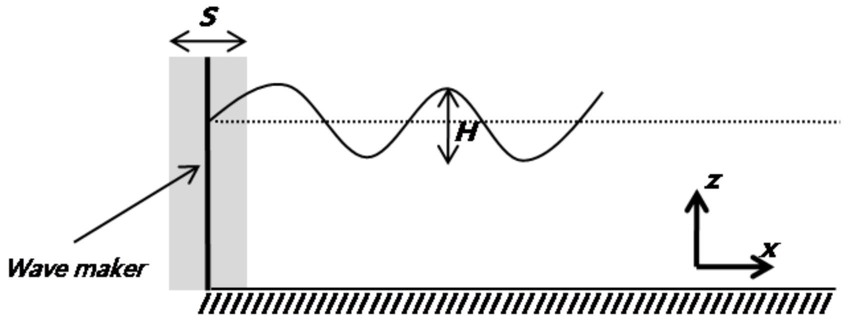


Fig. 2 A wave maker and surface wave

Theory for a wave maker is also described in detail in Dean & Dalrymple (2000). Fig. 2 shows a schematic view of a wave maker and surface wave. Theory of a wave maker is similar to the theory of surface wave except for the lateral boundary condition. The lateral boundary condition is induced from the stroke equation of a wave maker and the kinematic boundary condition at the wave maker. The stroke equation is written as

$$x = \frac{S(z)}{2}\sin\sigma t \tag{8}$$

Taking time-derivative of both sides of Eq. (8) leads to

$$u(0,z,t) = \frac{S(z)}{2}\sigma\cos\sigma t \tag{9}$$

Then, the following potential function can be derived using Eqs. (1)~(4) and (9)

$$\begin{aligned}\phi &= A_p \cosh k_p(h+z)\sin(k_p x - \sigma t) \\ &\quad + \sum_{n=1}^{\infty} C_n e^{-k_s(n)x}\cos[k_s(n)(h+z)]\cos\sigma t\end{aligned} \tag{10}$$

The surface wave is described as

$$\begin{aligned}\eta &= \frac{1}{g}\frac{\partial\phi}{\partial t}\bigg|_{z=0} = -\frac{A_p}{g}\sigma\cosh k_p h\cos(k_p x - \sigma t) \\ &= \frac{H}{2}\cos(k_p x - \sigma t)\end{aligned} \tag{11}$$

The ratio of the stroke of a wave maker to the height of surface wave leads to

$$\frac{H}{S}=\frac{2(\cosh 2k_p h-1)}{\sinh 2k_p h+2k_p h}, \text{ for a piston-type of wave-maker} \qquad (12)$$

This equation means that the stroke of a wave maker can be determined if the required amplitude of surface wave is specified.

3. SURFACE WAVE

3.1 Numerical model

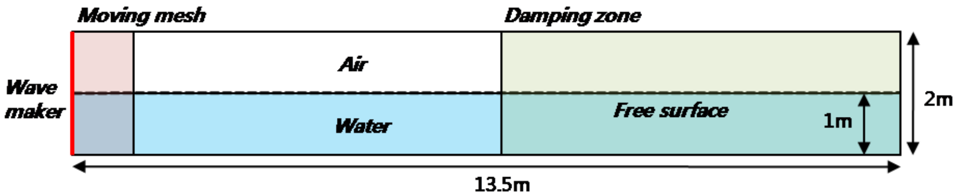


Fig. 3 Schematic view of the entire computation domain for a flume

Fig. 3 shows the entire computation domain to simulate surface wave in a flume. The dimension of the flume is 13.5m 2m, and water depth is 1m. To reduce numerical damping of moving meshes and the possible contamination from reflected surface wave, the computation domain is divided into three parts. The first part is a moving mesh zone to generate surface wave by the waver maker. To reduce damping of moving mesh in this region, the length of first part is set 1m. The second part is the physical computation domain where amplitude of surface wave is computed and actual numerical tests are performed to assess effects of a TLD as well as surface wave on movement of a floating body. The third part is a damping zone to reduce effect of reflected wave on the computation domain. This is realized by increasing mesh sizes gradually in a downstream direction. Meshes are densely clustered around the free surface region to accurately compute the amplitude of surface wave.

The Reynolds-averaged Navier–Stokes equations (RANS) are solved as the governing equations. Free surface is tracked using the Volume of Fluid (VOF) method (Hirt, 1989). You can refer to the references (Ha et al., 2013a; 2013b) for the detailed numerical methods.

3.2 Grid refinement study

A motion of floating body is greatly affected by the amplitude of surface wave which is in turn found to be greatly affected by the grid size. Therefore, a grid refinement study is carried out to guarantee grid-independent numerical solution in predicting the amplitude of surface wave.

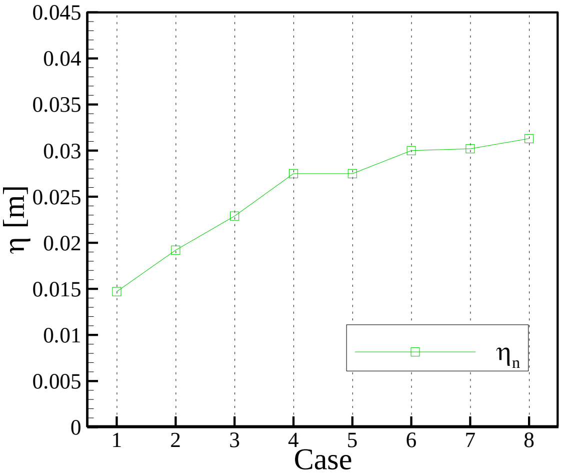


Fig. 4 Predicted amplitude of surface wave according to grid resolution
(The higher case number means the simulation result using denser grids)

Fig. 4 shows predicted amplitudes of surface wave by varying the computation meshes: the higher case number means the computation result using more highly fine grid. It is seen that the amplitude is converged over the Case 6. Based on these results, the mesh used for the Case 6 (Δx=0.02m, Δy=0.0025m) is used in all the following computations.

3.3 Amplitude of surface wave versus excitation frequency

The dispersion-relation of Eq. (7) relates the frequency of surface wave to the wave length of surface wave. To prevent the breaking of surface wave, the stiffness of wave that is the ratio of wave length to wave height needs to be kept low. Therefore, wave amplitude is reduced as the frequency increases to keep the stiffness to be constant of lower value. The natural frequency of liquid sloshing inside a rectangular floating body is 8.6rad/s. We select five different excitation frequencies of which the center value matches the sloshing natural frequency.

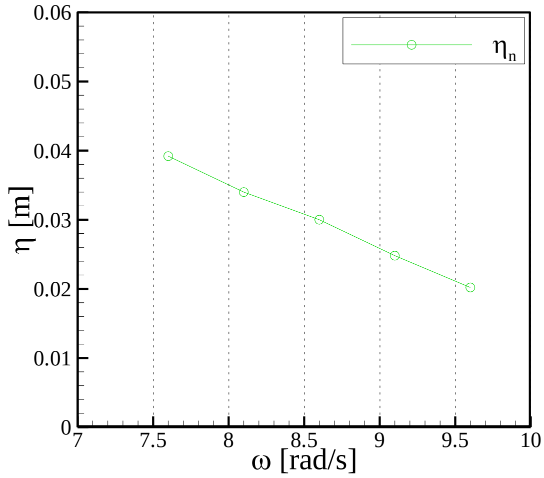


Fig. 5 Variation of amplitude of surface wave according to the excitation frequency

Fig. 5 shows the variations of computed amplitudes of surface wave at the monitoring point by varying the excitation frequency of the wave maker. The amplitude of surface wave is found to decrease as the frequency increases. The current result is used to normalize the motion of a floating body in the next section.

4. A FLOATING BODY

4.1 Numerical model

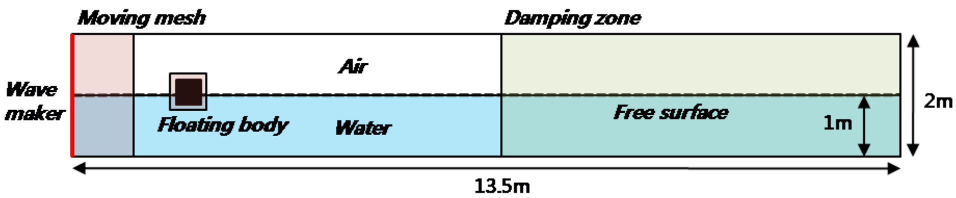


Fig. 6 Schematic view of the entire computation domain for a flume with a floating body

Fig. 6 shows the entire computation domain for a flume with a rectangular-shaped floating body. The only difference compared to that in Fig. 3 is that there is a floating body in the flume. The length and thickness of the floating body is 0.4m and 0.01m, respectively. The water depth inside the floating body is 0.19m and the draft is 0.2m. To prevent the floating body from drifting off, springs with stiffness 0.875N/m in both of the surge and pitch directions are added, respectively.

4.2 Motion of a floating body with and without water

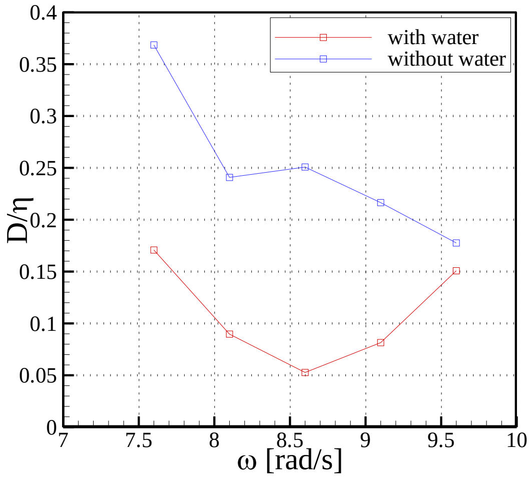


Fig. 7 Non-dimensional amplitudes of surge motion of a floating body
with and without water

Fig. 7 shows the numerical results of the surge motion of the floating body. In the case without water, non-dimensional surge motion generally decreases as the frequency increases. In the cases including sloshing water, however, non-dimensional surge motion is smaller than that in the cases without water. The minimum surge motion occurs at the excitation frequency that equal to the sloshing natural frequency, 8.6Hz. Note that the total mass of the floating body with and without water is kept the same as each other.

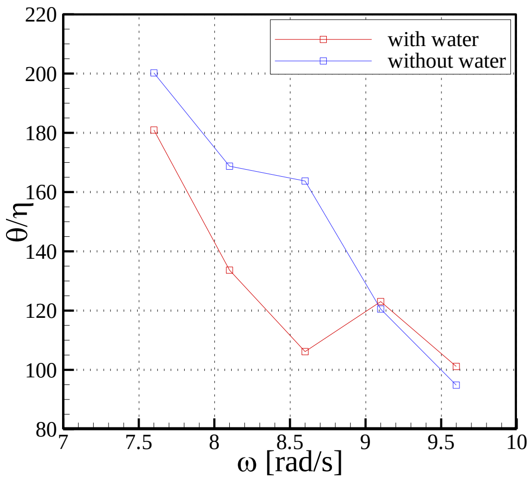
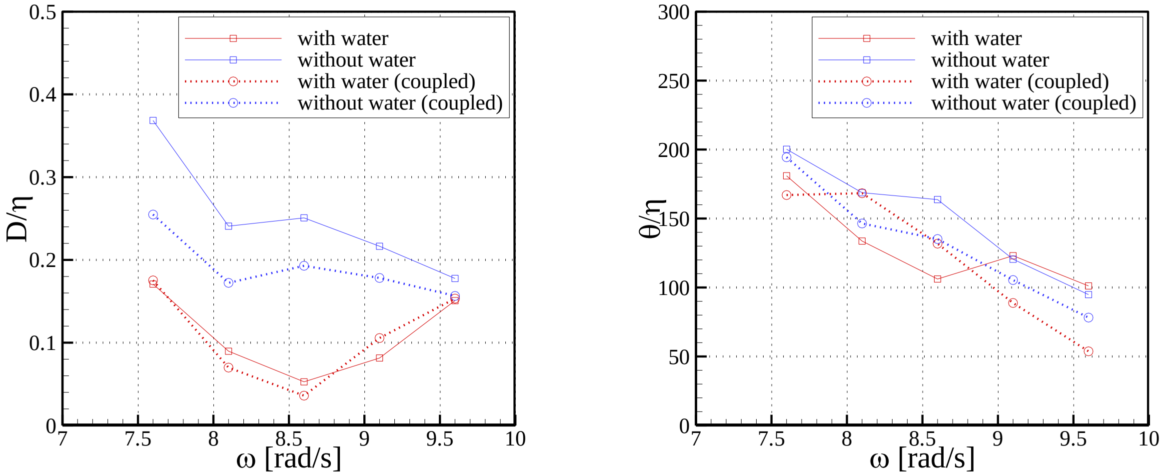


Fig. 8 Non-dimensional pitch motion of a floating body
with and without water

Fig. 8 shows the numerical prediction results of the pitch motion of the floating body. In the cases without water, the frequency dependence of the pitch motion is similar to that of the surge motion. Also, in the cases including sloshing water, the amplitude of pitch motion is smallest at the sloshing natural frequency in the range below 9.1Hz.

However, the amplitude of the pitch motion of the floating body with water is higher than that without water at the highest frequency, 9.6Hz.



(a) surge (b) pitch

Fig. 9 Non-dimensional coupled surge and pitch motions of a floating body with and without water

Fig. 9 shows non-dimensional amplitudes of the coupled surge and pitch motions of the floating body with and without water. The numerical prediction results of the surge motion are similar to those using the decoupled simulation in Fig. 7, whereas that of the pitch motion shows different frequency dependence from that of the decoupled simulation in Fig. 8. The effect of resonance phenomenon observed in Fig. 8 disappears in Fig. 9b. However, the surge and pitch motions of the floating body with water are generally smaller than those without water.

5. CONCLUSION

Effects of the TLD employed in a floating substructure on its motions are numerically investigated. For simplicity, a two-dimensional rectangular tank partially filled with water is considered. First, a grid refinement study is carried out to ensure that the specified amplitude of surface wave is created by a wave maker at the location where the rectangular tank is placed. Then, the amplitude of surface wave is calculated by varying the excitation frequency of the wave maker, which is used to normalize the amplitude of the motion of the rectangular tank. Next, the surge and pitch motions of the rectangular tank with and without water are investigated by varying frequency. It is found that the motion of rectangular tank can be reduced using liquid sloshing phenomena inside the floating body. Also, when the external excitation frequency is coincident to the sloshing natural frequency, the motion of rectangular tank is minimized. Finally, the coupled surge and pitch motions of the rectangular tank with and without water are investigated by varying the excitation frequency. Predicted frequency dependence of the surge motion is similar to the uncoupled result. However, the predicted amplitude of the pitch motion seems to be independent with the sloshing natural frequency. However, overall, it is confirmed that the surge and pitch motion of a floating body subject to the external surface wave can reduced by using internal liquid sloshing phenomena, and the reduction can be maximized by matching the natural frequency of liquid sloshing to the external frequency.

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