NONLINEAR SLOSHING EFFECTS ON THE SWAY MOTION OF 2D RECTANGULAR CYLINDERS IN REGULAR WAVES

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Summary In this paper, we investigated the contribution of high-order nonlinear sloshing components on the sway motion of two-dimensional rectangular cylinders in regular waves. The sway motion becomes small and then increases largely near the lowest natural frequency of each model. The multi-modal theory predicts the sway motion quite well except some frequencies, where the free surface becomes rather complicated. The theoretical result can be significantly improved by using higher-order multi-modal method with a small computational burden.

RESEARCH BACKGROUND

As clean energy became an important global issue, the demand for natural gas has largely increased. Natural gas is normally liquefied for transportation in the form of LNG. During transportation and also offloading, LNG may undergo violent motions in the cargo tank, which is well known as sloshing. Sloshing may cause serious damage on the tank wall. In new LNG-related structures like LNG-FPSO and LNG-FSRU, sloshing may invoke more serious problems because the filling ratio of LNG changes continuously during the offloading process. Therefore an accurate prediction of floater's motion in waves including sloshing effects is critical to the safe operation of such structures.
As a first step toward it, we considered the sway motion of two-dimensional rectangular cylinders of different draft with varying filling ratios in regular waves theoretically and experimentally.

EXPERIMENT

Experiments were carried out in a flume, which is 20.0m long, 0.5m wide and 1.0m deep. Regular waves were generated by a piston-type wave maker in water of 0.71m deep. Two rectangular box-shaped models were constructed. The length and width of two models were the same as 400mm and 495mm, respectively, while the draft was 200mm for the larger model in front of the smaller model with the draft of 100mm. The gap between the flume and the model is quite small on both sides. The inside of the models was divided into three compartments, where the center part was filled with water of different levels and the other two were used for ballast. The models were connected firmly to a cart moving freely on the rail by rigid frames and thus they were allowed to move only in the horizontal direction, and all other motions were restricted for the sake of simplicity. The steepness of incident waves was maintained at 1/40 for most wave frequencies except for some high frequencies. In order to prevent the drift of models, a spring system with a total stiffness of 34.6 N/m was introduced. The sway motion was measured by a self-developed non-contact video camera. Experimental details are described in [1].
Extended experiments were made for several cases where the larger model was 50% filled and the smaller model was 18%, 24% and 30% filled. The lowest natural frequency for each case is 8.62rad/s, 5.83rad/s, 6.58rad/s and 7.16 rad/s in this order.

MULTI-MODAL METHOD

The sway motion in the time domain can be described by

$$(M + A_{22}(\infty))\ddot{\eta}_2 + B_{22}^{visc}\dot{\eta}_2 |\dot{\eta}| + \int_0^t h_{22}(\tau)\dot{\eta}_2(t-\tau)d\tau = F_2^{exc} + F_2^{tank} + F_2^{friction} \quad (1)$$

In the above, M is the mass and $A_{22}(\infty)$ is the infinite frequency limit of the sway added mass. B_{22}^{visc} corresponds to the viscous damping and $h_{22}(t)$ to the time memory function. F_2^{exc}, F_2^{tank} and $F_2^{friction}$ are the wave excitation force, the sloshing-induced force and the friction on the tank rail. Hydrodynamic forces were calculated by the in-house code [2], while the sloshing induced force was estimated by using multimodal method under the assumption that there were no overturning waves and no tank roofs.

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The free surface elevation is represented in terms of Fourier series. To limit the number of modes, β_i, a smallness parameter ε is introduced as the ratio of the excitation amplitude to the tank length. The structure of the equation system depending on ordering is extensively described in Faltinsen [3]. The leading order solution is obtained under the assumption of magnitude as follows; $\beta_1 = O(\varepsilon^{1/3})$, $\beta_2 = O(\varepsilon^{2/3})$, $\beta_3 = O(\varepsilon)$, $\beta_i \le O(\varepsilon), i \ge 4$, while higher order terms than those of $O(\varepsilon)$ are neglected. It is shown that this solution predicts the sway motion qualitatively well, but it deviates from the experiment near the second natural frequency of the smaller model. In order to overcome this problem, we applied higher order multimodal method. Herein Model 2 is meant the next order solution derived under the assumption of magnitude, $\beta_1 = O(\varepsilon^{1/3})$, $\beta_2 = O(\varepsilon^{1/3})$, $\beta_3 = O(\varepsilon)$, $\beta_i \le O(\varepsilon), i \ge 4$, while Model 3 corresponds to the case, $\beta_1 = O(\varepsilon^{1/3})$, $\beta_2 = O(\varepsilon^{1/3})$, $\beta_3 = O(\varepsilon^{1/3})$, $\beta_i \le O(\varepsilon), i \ge 4$. Higher order multi modal solutions contain a lot of terms compared to the leading order solution, but the computational burden is still small.

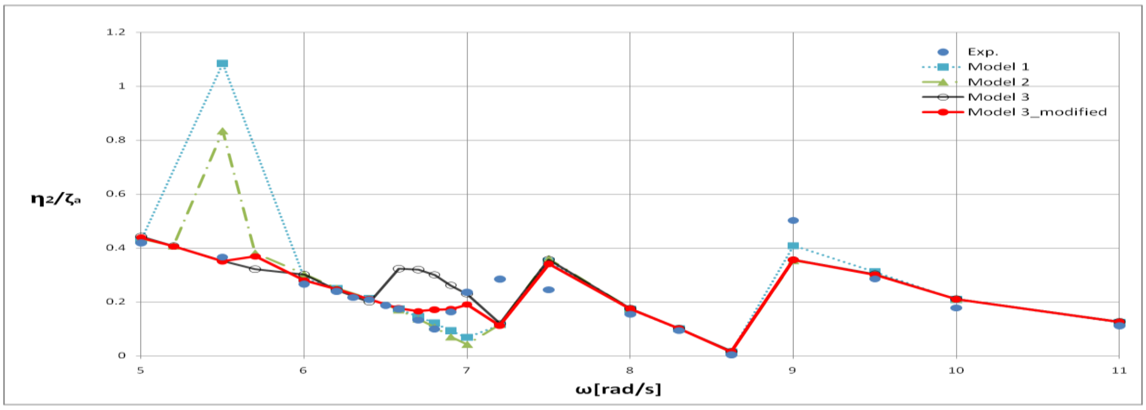

Fig.1 Comparison of numerical results with experimental data of the sway transfer function for 50%-filled larger model with 24%-filled smaller model

Fig.1 shows the comparison of numerical results with experimental ones, when the larger model was 50% filled and the smaller was 24% filled. It is observed that the sway motion becomes small and then increase largely near the natural frequency of each model, ω=6.58rad/s and 8.62rad/s. The theory generally predicts well except two frequency regions. The first one is near 5.5 rad/s, which corresponds to the second natural frequency of the smaller model. The second one happens near 7.0rad/s, where the gap flow between two models becomes rather complicated. It is to note that Model 1 and Model 2 over predict the sway motion near the second natural frequency of the smaller model, while Model 3 does not. If Model 3 is modified by increasing the viscous damping arbitrarily, the numerical result becomes even closer to the experiment as shown in the figure.

CONCLUSIONS

The sway motion of two rectangular cylinders is strongly affected by the fluid motion inside the tank and also between two models. It becomes smaller and then increases largely near the lowest natural frequency of each model. Multi modal method is very economic in computation and predicts the sway motion quite well in general. However, it deviates clearly from experimental data, when the fluid motion on the free surface becomes complicated, which can be improved partly by using higher-order multi-modal method with a small computational burden.

References

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