Nonlinear Effects of Sloshing Flows on Ship Motion

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Introduction

Sloshing flow in ship cargo is excited by ship motion, but the sloshing flow itself affects the ship motion in return. This coupling effect is sometimes critical in ship design and/or motion control, and also may be important in the accurate prediction of slosh-induced loads on tank structure. There are some existing studies on the coupling analysis, e.g. Dillingham (1981), Kim (2002), Rognibakke and Faltinsen (2003), and Newman (2005). We can consider two approaches in the coupling problem: the frequency-domain approach (e.g. Newman, 2005) assuming linear sloshing flow, the time-domain approach adopting nonlinear sloshing flow (e.g. Kim, 2002). The choice of solution method is dependent on the degree of nonlinearity of sloshing flow. This study aims to observe the importance of the nonlinear effects of sloshing flows in the problem coupled with ship motion.

In the present study, the linear ship motion coupled with nonlinear sloshing problem is solved. In particular, an impulse-response function (IRF) is adopted for the time-domain analysis of ship motion. For simulating nonlinear sloshing flow, the numerical method used by Kim (2001, 2004) is applied. This method concentrates on the simulation of global fluid motion, including impact occurrence during violent sloshing. The developed IRF scheme is verified by comparing the motion RAOs with the frequency-domain solution. The nonlinear effects of the coupled problem are observed in the roll motion of a modified S175 hull equipped with a rectangular passive-type anti-rolling tank(ART). The present analysis shows that the nonlinearity of sloshing flow is of an essential part in the coupled analysis,

IRF Method for Ship Motion

The equation of ship motion can be written to the following convolution form:

$$\sum_{j=1}^{6}\left[(m_{ij}+a_{ij}(\infty))\ddot{\xi}_j(t)+\int_0^t R_{ij}(t-\tau)\dot{\xi}_j(\tau)d\tau+c_{ij}\xi_j(t)\right]=F_i^{ext}(t)+F_i^{slosh}(t) \qquad (1)$$

where m_{ij}, $a_{ij}(\infty)$, and c_{ij} represent the total ship mass including fluid mass inside the tank, the infinite-frequency added mass, and linear hydrostatic coefficient, respectively. $R_{ij}(t)$ is so called retardation function. $F_i^{ext}(t)$ is the wave excitation force acting externally on hull, while $F_i^{slosh}(t)$ is the sloshing-induced force acting internally on the tank. In this formulation, $F_i^{slosh}(t)$ can be computed by subtracting mass-inertia component from total roll moment. The fundamental properties of the retardation function for the radiation force are that these functions are real, and, from the principle of causality, they must vanish for t<0. The formulas for $a_{ij}(\infty)$ and $R_{ij}(t)$ are given by

$$R_{ij}(t) = \frac{2}{\pi}\int_0^\infty b_{ij}(\omega)\cos(\omega t)d\omega = -\frac{2}{\pi}\int_0^\infty \omega\{a_{ij}(\omega) - a_{ij}(\infty)\}\sin(\omega t)d\omega \tag{2}$$

$$a_{ij}(\infty) = a_{ij}(\omega) + \frac{1}{\omega}\int_0^\infty R_{ij}(t)\sin(\omega t)dt \tag{3}$$

where $a_{ij}(\omega)$ and $b_{ij}(\omega)$ are added mass and damping coefficients, respectively. In the present computation, the damping coefficients are used to obtain the retardation function.

In an actual numerical computation of the retardation function, truncation error is inevitable since the integral of motion equation (1) is generally carried out in a finite frequency range. To minimize this truncation error, a special treatment similar to Lee & Newman (2005) is applied. For a sufficiently large truncated frequency, Ω, the retardation function with a correction of the truncation error can be approximated as follows:

$$R_{ij}(t) = \frac{2}{\pi}\int_0^\Omega b_{ij}(\omega)\cos(\omega t)d\omega + \varepsilon_{ij}(t) \tag{4}$$

where

$$\begin{aligned}\varepsilon_{ij}(t) &\equiv \frac{2}{\pi}\int_\Omega^\infty b_{ij}(\omega)\cos(\omega t)d\omega \\ &\simeq -\frac{2}{\pi}R'_{ij}(0)\int_\Omega^\infty \frac{\cos(\omega t)}{\omega^2}d\omega = -\frac{2}{\pi}R'_{ij}(0)\frac{\cos(\Omega t) + \Omega t\,\mathrm{si}(\Omega t)}{\Omega}\end{aligned} \tag{5}$$

and $\mathrm{si}(z)$ is the sine integral. Furthermore, $R'_{ij}(0)$ can be calculated by numerical difference if the time step is sufficiently small.

To include viscous roll damping, an equivalent linear damping coefficient is applied. In the case of surge, sway, and yaw motions, the concept of soft spring is adopted to prevent the monotonously increasing or decreasing motion.

Finite Difference Method for Sloshing Problem

The finite difference method used by Kim(2001) is applied in the present time-domain analysis. This method concentrates on global fluid motion, hence the numerical computation ignores some local phenomena, e.g. turbulence boundary layer, local wave breaking, and air trapping. Although the local flows are sometimes important, the global flow plays a more important role in most sloshing problems in ship cargo.

The present method is based on the SOLA-SURF scheme, adopting staggered grids in a rectangular Cartesian grid system. The Euler equation is considered, and the free surface is assumed to be single-valued profile. In particular, the concept of buffer zone is applied for the prediction of impact loads on tank ceiling, and the attachment and detachment of fluid on tank ceiling is carefully treated to avoid the non-physical attachment of some amount of fluid. The sensitivity study on computational parameters of the present method has been introduced in the Workshop by Lee at al. (2004).

Results and Discussion

The computer program based on the IRF method is validated by comparing the motion RAOs with the frequency-domain solution when the motion is not coupled with sloshing, and a very fair agreement is observed. The effects of nonlinear slosh-induced moment are observed for the modified S175 hull introduced by Kim (2002). A passive flume-type ART is equipped at Z=0.045L near midship, and its dimension normalized with respect to ship length is 0.05882(length)*0.2878(breadth)*0.0504(height). To concentrate on roll motion, only beam sea is considered in this computation. The viscous roll-damping coefficient of the ship is fixed to 3.0% of the critical roll damping. The natural frequency of the fundamental sloshing mode varies in the range of 1.5~1.7, depending on filling ratio.

Fig.1 and 2 show the motion RAOs for different wave slopes and filling conditions. Due to the difference of sloshing natural periods as well as the magnitude of sloshing-induced moment, the motion responses are strongly dependent on filling condition. Furthermore, the motion response shows a dramatic dependency on the wave slope. Although the ship motion is assumed to be linear, the nonlinear sloshing flow can result in different motion responses for different wave slope. This implies that the slosh-induced moment does not linearly vary with respect to motion amplitude. These figures show that the slosh-induced moment plays an important role when the wave slope is small, but wave excitation becomes dominant as the wave slope is larger. Therefore, the motion RAOs at larger wave slope (figure (b)) show a trend similar to the case without ART. The results of the present study show that it is essential to consider the nonlinearity of sloshing flow in the ship motion problem coupled with sloshing.

References

Cummins, W.E., 1962. The impulse response function and ship motions. Symposium on Ship Theory.

Dillingham, J., 1981. Motion studies of a vessel with water on deck. Marine Technology 18.

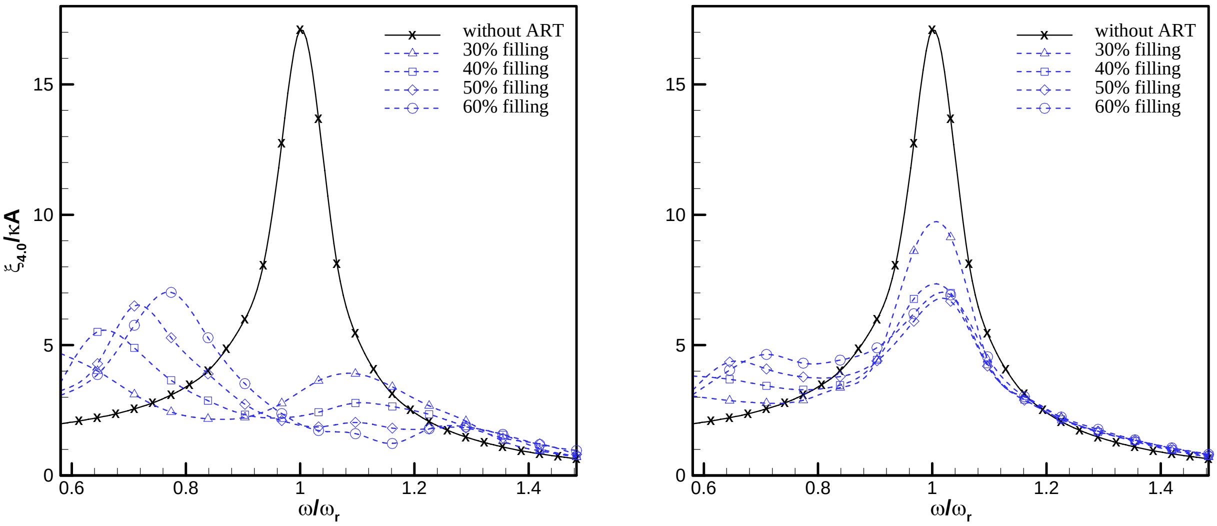
Kim, Y., 2001. Numerical simulation of sloshing flows with impact load. AOR 23.

Kim, Y., 2002. A numerical study on sloshing flows coupled with ship motion-the anti-rolling tank problem. JSR 46.

Kim, Y., Shin, Y.S., Lee, K.H., 2004. Numerical study on slosh-induced impact pressures on three-dimensional prismatic tanks. AOR 26..

Lee, Y.B, Kim, Y., Kim, Y.S., Shin, Y., 2004. Sensitivity study on slosh-induced impact

pressures. IWWWFB.
Newman, J.N., 2005. Wave effects on vessels with internal tanks. IWWWFB.
Rognebakke, O.F., Faltinsen, O.M., 2003. Coupling of sloshing and ship motions. JSR 47.



(a) A/L=0.010 (b) A/L=0.025

Fig.1 Comparison of roll RAOs for different filling and wave slope: modified S175

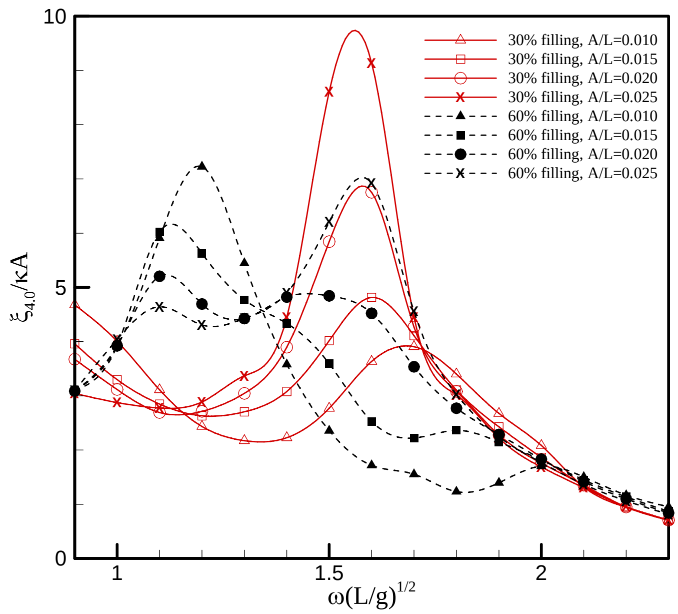


Fig.2 Comparison of roll RAOs at 30% and 60% filling condition with different wave slope: modified S175

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Discusser - M. Kashiwagi:

You mentioned a conclusion that the time history of the pressure computed by SPH is spiky but the integrated force is reasonable. This fact is well recognized by numerical results done by Sueyoshi and Koshiizuka. On the other hand, in the computation by FDM, the sharpness of the interface is very important for resolving the impulsive pressure. What king of scheme is used for the interface capturing in your computations by FDM?

Reply:

Thank you for your comment. We are aware of the works of Sueyoshi, and the conclusion for integrated force is similar to that of Dr.Sueyoshi. For the FDM of our computation adopts the mixed first and second-order scheme.It is no question that the sharpness of free surface during is important.However, the degree of importance depends onnumerical scheme. Our approach is intended to simulate the global fluid motion, and we found that our scheme provides reasonable results.

Discusser - K. Takagi:

The influence of the mooring is supposed to be important when you estimate the coupled sway/yaw and roll motion. Do you have any comment on it?

Reply:

The coupled motion of sway/yaw and roll is important in actual problem. In our computation, we considered only roll since we have exeprimental data similar to the computational model, which only roll motion was allowed. In real shipproblems, the mooring (or restained) effect is significant in many cases. Also the heave sometimes play a critical role during impact occurrence.