Experimental Study of Sloshing Effect on Added Resistance in Head Waves

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1 INTRODUCTION

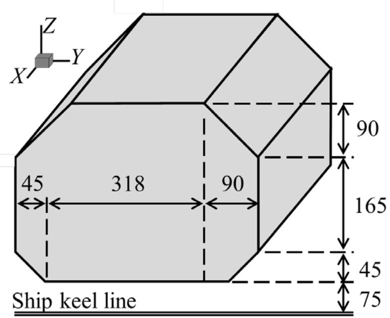
Ship motion coupled with inner sloshing flow has been widely studied in recent decades. The coupling phenomenon shows that ship motion excites the sloshing flow in inner tanks, and tank sloshing-induced force and moment can affect ship motion at the same time. Typical cases are anti-rolling tank and FPSO unit, and these studies normally consider the zero-speed ship under beam wave condition (Kim et al., 2007; Nam et al., 2009; etc.). Recent studies (Seo et al, 2017; Li et al, 2019) have applied potential-based methods to investigate the sloshing-coupled effect considering forward ship in head waves. From practical engineering viewpoint, studying the sloshing-coupled ship moving in head waves can provide useful information to ship sea trials. If the coupling effect was not significant for a forward moving ships, for example container ship, then certain sea trails can be more flexible and economic by using water-filling tanks rather than massive solid cargoes. In this study, a series of experiment has been carried out in order to investigate the sloshing-coupled effect at different tank filling levels. Ship moves in various wavelength conditions with free motion in surge, heave, and pitch.

2 EXPERIMENTAL SETUP

2.1 Experiment Models

This study applies the blunt modified Wigley hull (Kashiwagi, 2013) which is a mathematical hull of fore-aft symmetry. Ship model is equipped with two identical inner tanks that are symmetrically distributed around midship section. Main dimension of prismatic inner tank is 600×408×300 (length L_0 × breadth B_0 × height H_0, unit: mm), and details can be further found in Fig. 1(c). Standing wave theory is used to calculate the natural frequency of inner tank, $\omega_0 = \sqrt{\left(g\pi \tanh(\pi h_0 / L_0)\right)/L_0}$, where h_0 is tank filling height and L_0 is tank length.

(a) View on top



(b) Dimension of inner tank (unit: mm)

Fig. 1 Ship model with inner tanks

Table 1 Model particulars w.r.t. tank filling heights

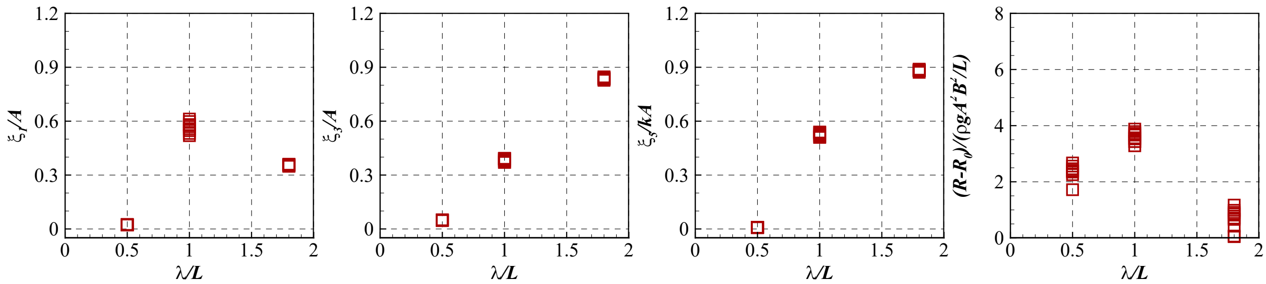
Tank filling height h_0		$0.3H_0$	$0.5H_0$	$0.7H_0$
Ship length/beam L/B	[m]	3/0.6		
Ship draught d	[m]	0.1482	0.1692	0.1899
Mass of total model	[kg]	146.7	176.1	205.5
Mass of filling water m_w	[kg]	20.8 × 2	35.5 × 2	50.2 × 2
Natural frequency of inner tank ω_0		4.750	5.804	6.412

To identify the effect of sloshing flow on ship motion, the experiment has established two types of test cases: "with sloshing cases" and "without sloshing cases". "with sloshing case" is that ship is equipped with partially filled tanks, while "w/o sloshing case" indicates that the two tanks are replaced by equally distributed weights. Sloshing-coupled effect is observed with respect to three different tank filling levels, therefore model particulars can be different depending on the filling levels. Two inner tanks always keep same filling conditions, and model principle particulars are summarized in Table 1. The static inclining test and swing test which are used to measure ship center of gravity and gyrational radius are carried out by "w/o sloshing case" rather than "with sloshing case".

2.3 Evaluation of Type A Standard Uncertainty

According to the ITTC Recommended Procedures and Guidelines (2008a) which is based on ISO's methodology (1995), experimental uncertainty can be classified intro three categories: standard uncertainty, combined uncertainty, and expanded uncertainty. Standard uncertainty can be further divided into Type A and Type B depending on the method of evaluation. Type A standard uncertainty is determined using statistical analysis of repeated observations, while Type B standard uncertainty is evaluated by wide information other than repeated observations. The wide information includes previous measurement, past experience, general knowledge, calibration data etc. Combined uncertainty and expanded uncertainty are relatively small in present experiment. Based on well calibrated facility and DAQ system (Park et al., 2015), present experiment only considers type A standard uncertainty through a series of repeat tests. Repeat test considers ship "sloshing case" in three different wave conditions: short wave, medium wave, and long wave. Constant wave height H/L=0.008 is applied. Filling height of inner tanks $0.5H_0$, where $0.5H_0$ indicates that tank filling height is half of tank height H_0. For each wave condition 10 repeats are observed.

Fig. 2 are the repeat results on ship motion and added resistance. Generally ship motion shows small discrepancy except for the ship surge response in medium wave case. Because the medium wave case has a wave encountering frequency that is close to the natural frequency of inner tank, inducing strong harmonic sloshing phenomenon as well as surge uncertainty. However, sloshing-induced uncertainty is not significant on added resistance, showing weak surge effect on ship added resistance.



(a) Surge motion (b) Heave motion (c) Pitch motion (d) Added resistance

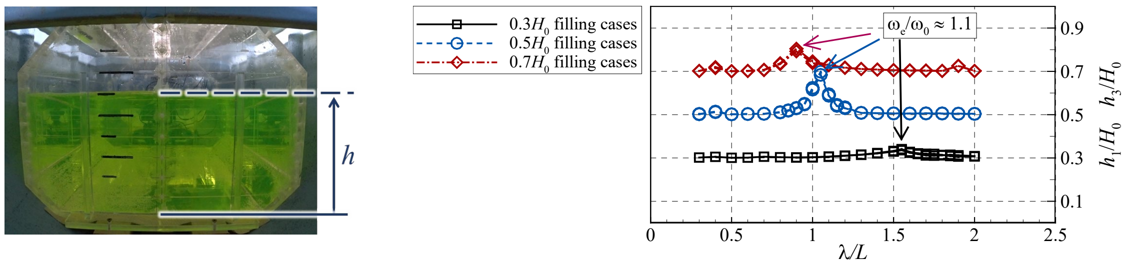
Fig. 2 Repeat results on ship motion RAOs and added resistance
(10 repeats, $0.5H_0$ filling tank, wave height H/L=0.008, ship Fn=0.2)

3 RESULTS AND DISCUSSION

Experiment has been carried out for three different tank filling conditions, $0.3H_0$, $0.5H_0$, $0.7H_0$. To identify sloshing free-surface, capacity probes are equipped at the frontal wall of inner tank in order to measure the elevation (h) of inner sloshing free-surface, as shown in Fig. 3 (a). There are two inner tanks symmetrically distributed around midship, so h_1 and h_3 indicate the free-surface elevation at the front walls of two different tanks. From Fig. 3 (b) it can be observed that two inner tanks have similar sloshing behaviour regardless of incoming wave condition. Fig. 3 (b) also shows that inner tank has sloshing behaviour only near the resonance point where encountering wave frequency ω_e is close to tank natural frequency ω_0, while inner free-surface is calm at out-of-resonance region. Moreover, $0.3H_0$ filling case has relatively calm free-surface even near resonance point. This is because the mass of filled water is relatively low compared with total ship structure mass, causing inner tanks behaviour like "anti-surge" tanks. Compared with $0.5H_0$ filling case, $0.7H_0$ case has relatively mild sloshing free-surface because $0.7H_0$ filling level has more inertia effect so that much more energy is required to excite sloshing.

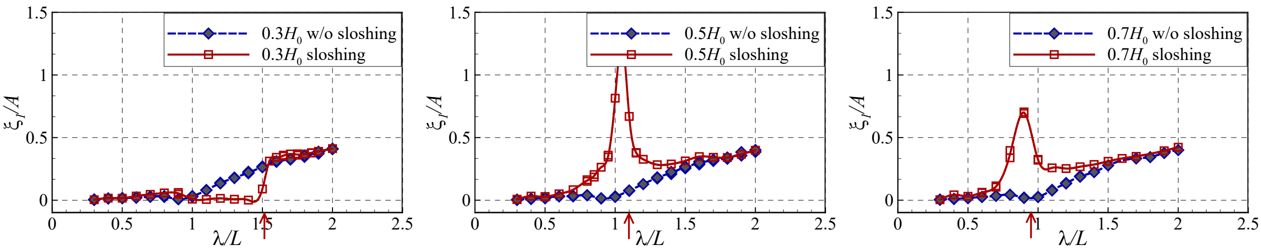
This similar tendency can also be observed in ship surge motion as shown in Fig. 4. For $0.3H_0$ filling case in medium incoming wave condition, ship surge motion is obviously restricted with 90° phase difference between sloshing free-surface h_1 and ship surge, as shown in Fig. 5(a). But that phase difference is almost zero for $0.5H_0$ and $0.7H_0$ cases near tank resonance region, which is regarded to be the reason that resonant sloshing increases surge motion. Moreover, Fig. 5(b) shows the phase difference between h_1 and ship pitch, with obvious phase shift observed near each resonance point.

Results of short incoming wave (λ/L<0.6) are not shown in Fig. 5. Because either inner sloshing or ship motion response is very weak, resulting in large measurement uncertainty as well as negligible coupling effect.



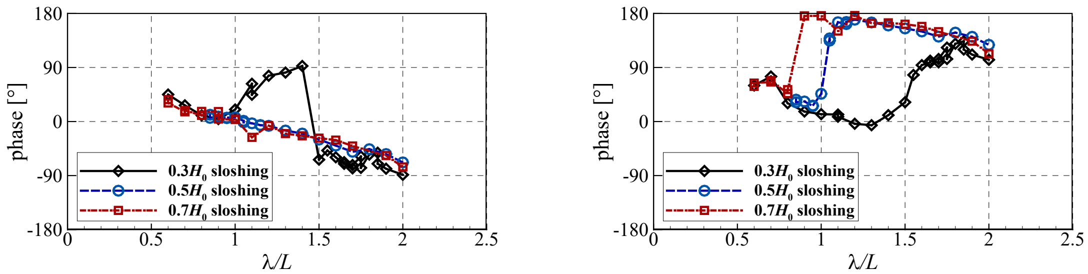
(a) Definition of free-surface elevation (h) at tank front wall (b) h results w.r.t. ship incoming wavelength

Fig. 3 Elevation of inner free-surface (ω_e: freq of ship encountering wave, ω_0: natural freq of inner tank)



(a) 0.3H_0 case (b) 0.5H_0 case (c) 0.7H_0 case

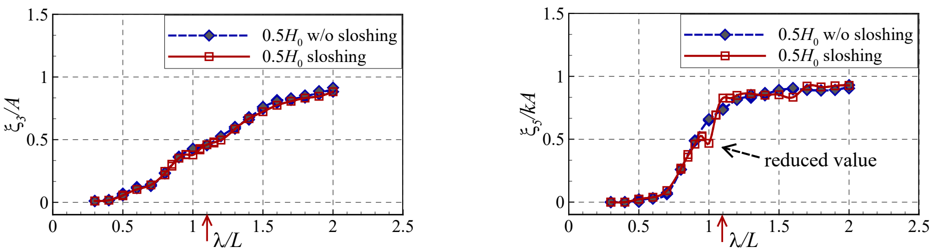
Fig. 4 Ship surge motion (each figure has an arrow that indicates ω_e/ω_0=1.1)



(a) Phase difference between h_1 and ξ_1 (b) Phase difference between h_1 and ξ_5

Fig. 5 Phase difference between sloshing free-surface elevation (h_1) and ship motions (surge ξ_1, pitch ξ_5)

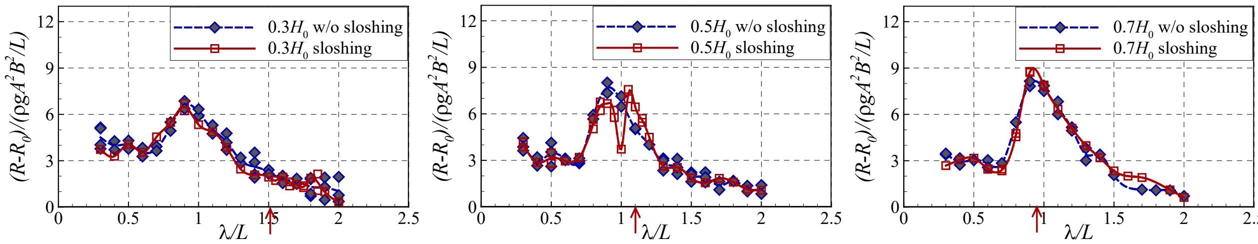
However, ship heave motion and pitch motion are generally insensitive to sloshing effect. Only one special case is the λ/L=1.0 case of 0.5H_0 filling conditions (Fig. 6). This is caused by sloshing-coupled effect, inner sloshing is so strong that it reduces ship pitch response with a 180° phase difference, as the phase difference already shown in Fig. 5(b). Ship heave motion has no clear difference because present experiment hull, blunt modified Wigley, is a fore-aft symmetric hull of weak heave-pitch coupling effect.



(a) Heave (b) Pitch

Fig. 6 Ship heave and pitch motions at 0.5H_0 case

Furthermore, ship added resistance shows similar tendency as its pitch motion. Only one special case is the λ/L=1.0 case of 0.5H_0 filling conditions, with a significantly reduced added resistance which is caused by reduced pitch response, as shown in Fig. 7. This reduction is contributed by sloshing-coupled effect rather than experimental uncertainty, since uncertainty results have already be confirmed in previous Fig. 2(d). Other cases generally show similar tendency for both “sloshing case” and “w/o sloshing case”.



(a) 0.3H_0 case (b) 0.5H_0 case (c) 0.7H_0 case

Fig. 7 Ship added resistance

4 CONCLUSIONS

This study has carried out a series of experiment to identify coupling effect between inner sloshing and ship forward motion in waves. Conclusions can be made as follows:

- Inner tank has different sloshing behaviours depending on filling levels. Low filling case has calm free-surface while medium filling case has most severe sloshing free-surface. The reasons are inertia effect and phase difference.
- In medium filling case (0.5H_0), inner tank resonance shows the strong coupling effect that can reduce ship pitch response and added resistance, which has be identified through repeated observation.
- However, generally sloshing-coupled effect is weak for ship heave, pitch, and added resistance, particularly at tank out-of-resonance region. It provides information so that water-filling tanks rather than solid cargoes can be considered for certain types of sea-trials.

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REFERENCES

Kim, Y. et al., 2007. Study on coupling effects of ship motion and sloshing, *Ocean Engineering*, 34, 16, 2176-2187.

Nam, B.W. et al., 2009. Experimental and numerical studies on ship motion responses coupled with sloshing in waves, *Journal of Ship Research*, 53, 68-82.

Seo, M.G. et al., 2017. Effect of internal sloshing on added resistance of ship, *Journal of Hydrodynamics*, 29, 13-26.

Li, Y. L. et al., 2019. Numerical research on time domain ship motions coupled with sloshing at different liquid levels and forward speeds, *Ocean Engineering*, 178, 246-259.

Kashiwagi, M., 2013. Hydrodynamic study on added resistance using unsteady wave analysis, *Journal of Ship Research*, 57, 220-240.

ISO, 1995. Guide to the expression of uncertainty in measurements. International Organization for Standardization, Geneva, Switzerland.

Park, D.M. et al., 2015. Uncertainty analysis for added resistance experiment of KVLCC2 ship, *Ocean Engineering*, 95, 143-156.