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Experimental Study on the Effect of Coupled Motions on the Sloshing in Rectangular Tank

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Abstract

Intensive experimental investigation has been conducted on the characteristics of model tank with intruded flow. The remaining flow inside tank contribute to the dynamic behavior and further closely related to the stability of vessel as well. To understand the importance of the trapped flow and its dynamic effects, a series of systematic tests were conducted using a bench tester that could generate periodic roll motion and also complex motions of combined roll-heave-sway. To accommodate experimental conditions and to create three degree freedom of motions, a bench tester was fabricated and verified. Having similarities in terms of flow trapped inside tank, theoretical approaches for A.R.T. were applied to the study. The major parameters including roll angle, period and flow height were varied in the experiments to obtain the characteristics of model tank.

Keywords: bench tester, A.R.T., model tank, intruded flow

1 Introduction

Safety of ship is a great concern not only to loaded vessels but also vessels being exposed to intruding water. The trapped water in the vessel can significantly affect on the dynamic behavior and its stability as well. To reduce the dynamic motions caused by continuously changing environmental conditions, various devices including bilge keels, fin stabilizers, A.R.T. etc. were created and adapted to ocean vessels. Even substantial efforts have been burned to find clear interactions of trapped flow with vessel motion, the complexity of the subject make difficult to obtain a complete understanding by its nature. In this research, extensive experiments were conducted to examine dynamic behavior of vessels and resultant moments with various phase angles and flow heights. Also it was observed the effects of the major parameters on the dynamic motions of model tank (Adee and Caglayan 1982). For large vessels, the water trapped on deck effects on the stability and the green water as in head seas would results in structural damage (Caglayan and Storch 1982). The water on deck has been considered as passive tank stabilizer to reduce roll motion by early researchers (Bosch and Vugts 1966).

Generally, pseudo-static heel becomes higher in high frequency range since it is caused by the increased asymmetry of wave height in roll period. The mechanism of inflow on deck could act as a passive stabilizer reducing roll motion. They revealed from systematic experiments that the most important parameters are amount of water in tank characterized by water level and roll frequency. Additional parameters are breadth of tank, amplitude of motion.

In 1990s, a number of numerical and experimental researches have been carried out on the coupled motions caused by the interaction between vessel and liquid inside tank. From the series of researches, the non-linear damping and restoring terms were explained (Francescutto and Contento 1994). Also Lee and Vassalos (1995) also published a paper on the anti-roll tank effects. Jeung and Woo (1997) studied on coupled motion of a free surface tank. However, Most of existing mathematical approaches in sloshing motion provide limited solutions for strict conditions. Those models can only provide restricted solutions and generally are based on a single degree of freedom motion. Therefore the complex behaviour of the inflow has to be investigated.

2 Experiment apparatus

Series of experiments have been carried out systematically with an advanced bench tester and hydraulic control system that can simulate complicated tank motions and corresponding water behaviour. The bench test was 100cm long with 20 cm width and depth. It has two hydraulic cylinders at the corners of tester that can generate pure and combined roll and heave motions. Each hydraulic cylinder has LVDT so that the position of cylinder can be presented in electric signal. Also the moment and force are measured by load cells placed on the bottom of tester.

2.1 Model tank

The general characteristics of the parent ship and the model tank are shown in Table 1.

Table 1: Particulars of parent ship and model tank

Model	Ship	Tank
Particulars	$120m \times 20m \times 6.75m \times 5.5m$ $(L \times B \times D \times S_d)$ Full Displacement = 9,711 ton KG = $7.45m$ GM = $1.72m$ T_s = 13.15 sec (ω_s = 0.48 rad/sec) $k = 0.43 \times B$ b_s = 0.10, 0.15	(Scale 1:20) $100cm \times 20cm \times 20cm$ $(L \times B \times d)$ T_t = 11.54 sec (ω_s = 0.54 rad/sec) inflow holes: diameter = 1 cm numbers = 10 intervals = 1 cm

2.2 Experimental conditions

Table 2 shows experimental conditions and input data used for the series of experiments. It is seen that variations of tank simulations, such as inflow height and motion type are given to study their effects as well.

Table 2: Experimental conditions

Item		Validation Runs	Exp.
Depth of Tank Water (*cm*)		10	2, 6, 10 (h/d=0.1, 0.3, 0.5)
Roll	Angle (*deg*)	3.8	5
	Period (*sec*)	1.5 ∼ 4.0 (0.25 interval)	
Heave	Amplitude (*cm*)	4	
	Period (*sec*)	1.6	
Sway	Amplitude (*cm*)	4	
	Period (*sec*)	1.6	
Uncoupled Motion	Roll only	○	○
Coupled Motion	Roll+Heave +Sway	○	○

2.3 Verification of bench tester

The apparatus of bench tester as shown in Figure 2 are fabricated to simulate roll and also coupled motions including roll, heave and sway. To verify the performance of the bench tester, the results of Bosch and Vugts (1966) are used for comparison with the experimental results. As previously done by early researchers, the inflow depth was set to 10 cm to begin with. In the model tank the heave and sway and roll conditions were similarly set for the verification. Roll and coupled motion including roll and heave and sway were generated. As indicated in Figure 3, the test results of moment and phase angle agree well with those of Bosch and Vugts (1966). Figure 4 shows the characteristics of tank flow with various modes of motion.

2.4 Roll and coupled motions

Coupled motions in 3-degree of freedom comprising roll, heave and sway, are examined. Furthermore, important parameters are incorporated in the study and the results from roll motion and coupled motion are presented and discussed.

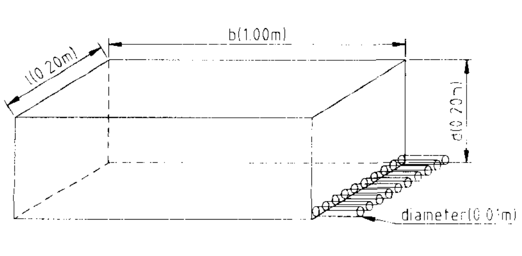


Figure 1: Features of model tank

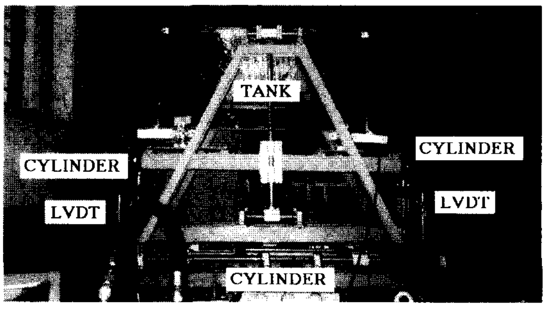
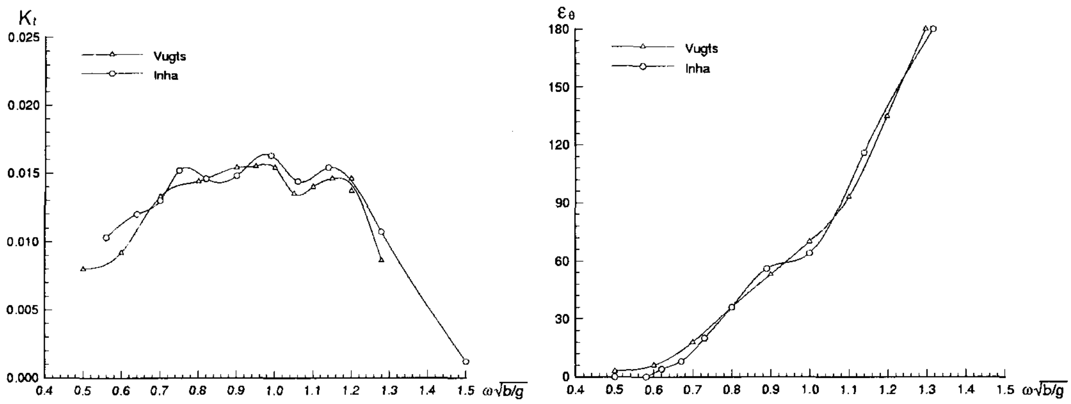


Figure 2: Apparatus of bench tester



(a) K_t(tank moment) due to $\omega\sqrt{b/g}$ (b) ε_θ(phase angle) due to $\omega\sqrt{b/g}$

Figure 3: Verification of bench tester (roll angle 3.8 deg.)

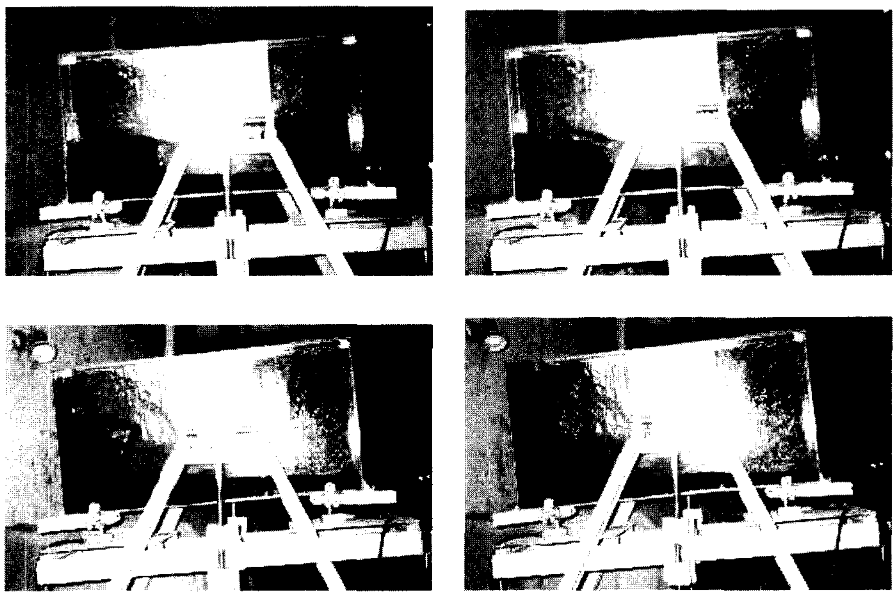


Figure 4: Example of a flow pattern in experiment

As shown in Figure 5, the data aquisition system and its corresponding program collect the electric signals from the hydraulic control system and those from load cells attached under the tank. From the obtained data, the motions and moments and phase angles with time are analyzed.

3 Results and discussion

From the experimental output on tank moment and phase angle, it show that K_t due to coupled motion is greater than that of roll motion, particularly in low wave frequencies. It is demonstrated

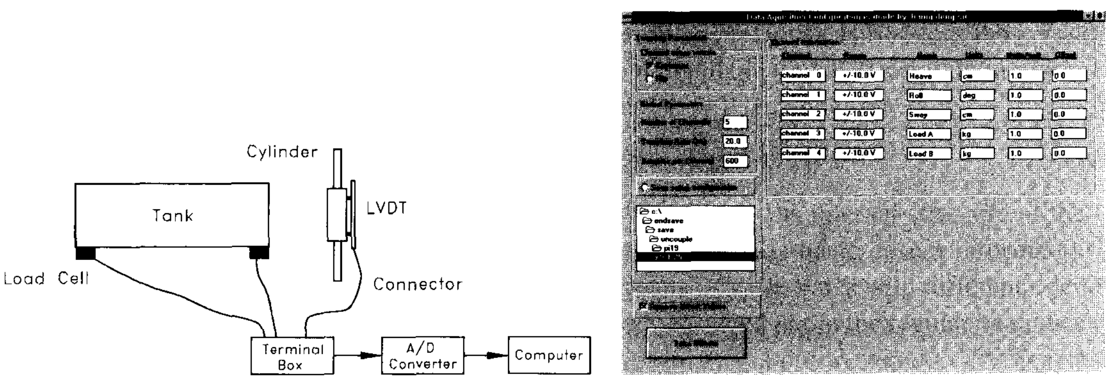
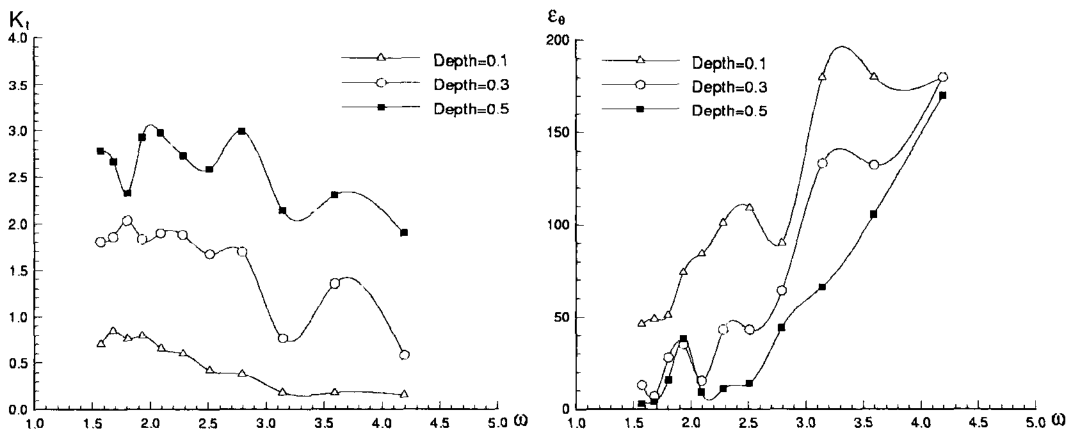


Figure 5: Data aquisition system and program

that coupled motion causes complex and non-linear characteristics of flow. The differences of ε_θ between roll and coupled motions does not show any persistent trends. It could confirm that phase angle is very sensitive, depending on the parameters, such as volume, frequency, mode of motion, etc. of the flow.

3.1 Water depth

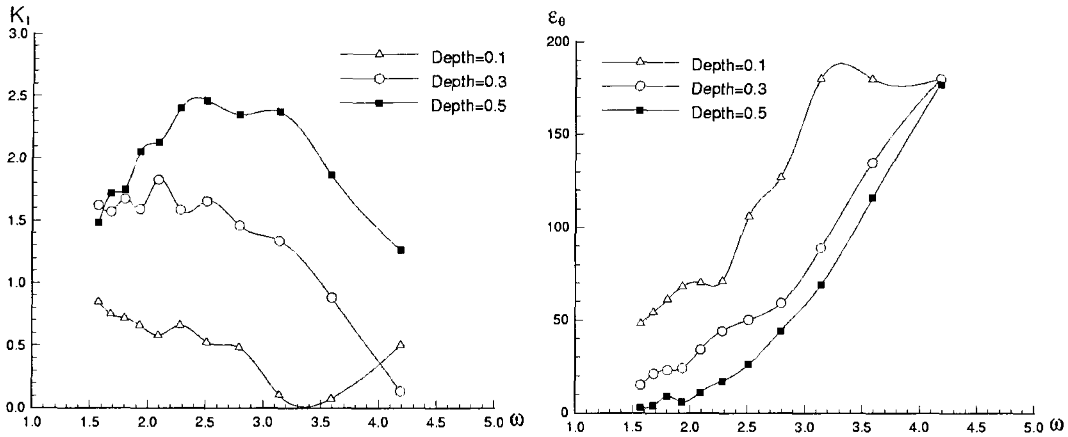
The effects of inflow depth on K_t and ε_θ are evident and show persistent trend in either motion mode. As inflow depth increases, corresponding magnitudes of K_t increase, whereas those of ε_θ decrease. Figures 6 and 7 show the effects of inflow depth to moment and phase angle for roll and coupled motions at roll angle 5°.



(a) Tank moment due to wave frequency

(b) Phase angle due to wave frequency

Figure 6: Pure roll motion: moments and phase angles



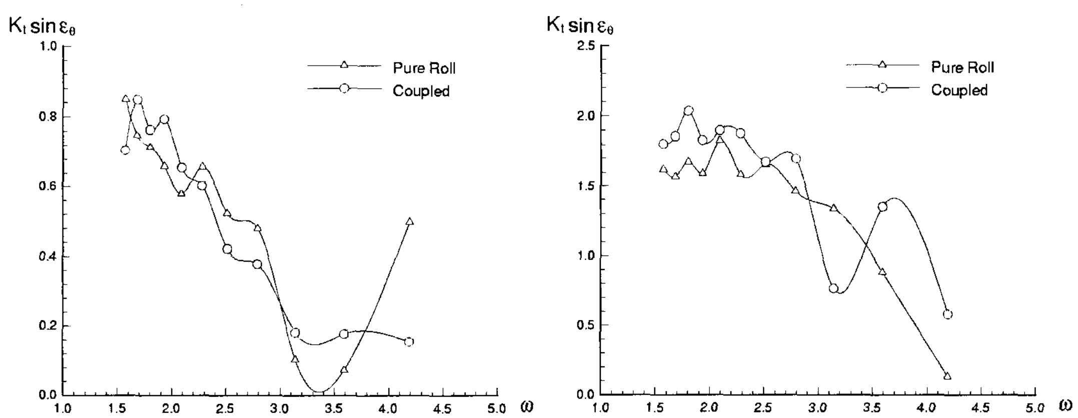
(a) Tank moment due to wave frequency

(b) Phase angle due to wave frequency

Figure 7: Coupled motion: moments and phase angles

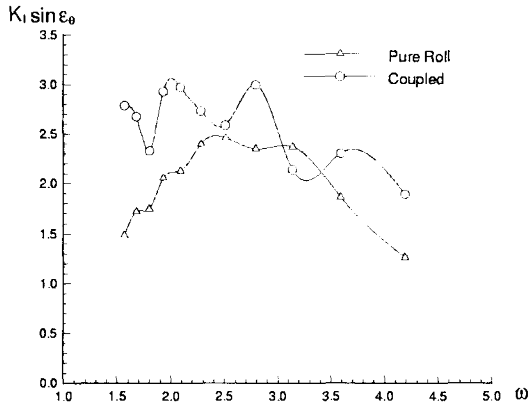
3.2 Comparison of $K_t \cdot \sin \varepsilon_\theta$

The difference in magnitude of $K_t \cdot \sin \varepsilon_\theta$ can be seen in Figure 8 at variable water depth. It is observed that phase angle ε_θ, plays an important role and the value of $K_t \cdot \sin \varepsilon_\theta$ increases significantly with water depth at high frequencies at roll angle of 5°. In particular, coupled motion gives more fluctuating results at low frequencies.



(a) h/d = 0.1

(b) h/d = 0.3



(c) h/d = 0.5

Figure 8: Comparison of $K_t \cdot \sin \varepsilon_\theta$ between pure roll and coupled motions

4 Conclusions

It is confirmed that coupled motion causes the flow in tank to be of complexity and non-linearity. The phase angle and moment are very sensitive in coupled motions. The moment from coupled motion is generally greater than that of roll motion, particularly in low motion frequencies. Also moment increases as inflow depth increases. The difference of phase angles between roll and coupled motions is significant as inflow depth becomes shallow.

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