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Experimental Study Of Sloshing Effects In Roll Motion Of Floating Units

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ABSTRACT
Usually, the hydrodynamic loads due to sloshing are considered in the design of liquid cargo ship or floating units concerning the structural. Owing to the increasing size of these structures, resonant sloshing motions may occur and result in the amplification or attenuation of motion of the vessel. In order to assess the effect of sloshing, traditionally the motion of the vessel is calculated at first without considering the dynamic of the liquid inside the tank. After that, this motion of the vessel is inputted as excitation motion acting on the tank and, finally, the sloshing effect is evaluated. In the other words, the coupling effects of sloshing and sea wave in the vessel's motion are ignored. A bibliographical survey shows that there are few studies that consider the effect of sloshing on the ship motion, acting as a passive device of absorption of the movements. The main goal of this research is to investigate experimentally the roll motion amplification and reduction due to sloshing. The coupling effects of sloshing and sea wave in the vessel's motion are taking into account by recording the motions, in regular waves, of a free floating model with a partially filled liquid tank. For this purpose, a two-dimensional model is designed to carry out measurements with fixed cargo and partially filled liquid cargo. The experimental results are evaluated by comparing the measured motion of the free-floating model with fixed cargo against the results obtained by traditional approach. Then, the effects of sloshing on floating units are shown by comparison of the measurements from free-floating model with fixed cargo and liquid cargo. The results shown herein provide data for the validation of new numerical approaches for the study of the coupled motions of the floating units and sloshing.

KEYWORDS
Sloshing, experimental results roll motion, floating units.

1. INTRODUCTION
The sloshing is violent liquid motion inside a recipient. Traditionally, the hydrodynamic loads due to sloshing are considered in the design of liquid cargo ship or floating units concerning the structural and several experimental studies and numerical methods were reports in [1] and [2].

In order to assess the effect of sloshing, usually the motion of the vessel is calculated at first without considering the dynamic of the liquid inside the tank. After that, this motion of the vessel is inputted as excitation motion acting on the tank and, finally, the sloshing effect is evaluated. In the other words, the coupling effects of sloshing and sea wave in the vessel's motion are ignored. However, owing to the increasing size of the tanks, in case of liquid cargoes, and the possibility of variation of liquid levels, in case of the change of ballast water in seaways, resonant sloshing motions may occur and result in the amplification or attenuation of motion of the vessel. A bibliographical survey shows that there are only few studies that consider the effect of sloshing on the ship motion in [3], [4] and [5], acting as a passive device of absorption of the movements in reference [6]. On the other hands, there are almost no numerical approaches that consider the coupling effects of sloshing and sea wave neither the experimental data for the development and validation of new ones.

Within this context, the main goal of this research is to investigate experimentally the motion amplification and reduction due to liquid sloshing, and to provide data for the validation of the numerical methods under development. The coupling effects of sloshing and sea wave in the vessel's motion are taking into account by recording the motions, in regular waves, of a free floating model with a partially filled liquid tank. For sake of simplicity, two-dimensional roll motion is considered in the present study.

At the fist, a free-floating model is designed to carry out measurements with fixed cargo and partially filled liquid cargo. The prismatic shaped free-floating model is made of acrylic and its ratio of length by width is set obtain distinct resonance frequencies on both directions. Also, the model has double-skin bottom and removable longitudinal bulkhead that allow the change of the tank's internal dimensions. Rate-gyro, accelerometers and a video camera are used to record the model's motion data.

The experimental results obtained by the present study are evaluated by comparing the measured motion of the free-floating model with fixed cargo against the results obtained by traditional approach, under different wave period. Then, the effects of sloshing on floating units are shown by comparison of the measurements from free-floating model with fixed cargo and liquid cargo.

In what follows, the development of the experimental model, the configuration of the experimental apparatus, the results and discussions about sloshing effects on the roll motion are given.

2. EXPERIMENTAL MODEL AND APPARATUS

This item describes the development and assembly of the experimental apparatus used by the present study, which was carried out in a small towing tank of the laboratory of the Department of Naval Engineering of EPUSP.

Figure 1 shows the small towing tank used by the present study. The tank has length of 24.0 meters, which includes a beach of 3.0 meters. The width is 1.0 meter each and depth of the tank is 0.8 meters. Figure 2 shows the main dimensions of the tank.

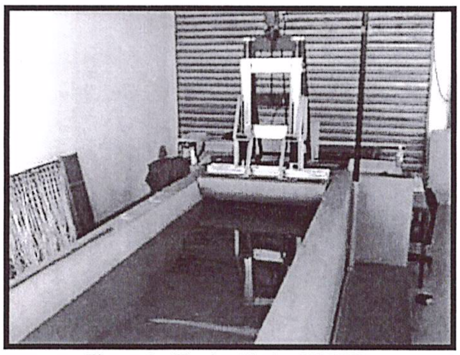

Figure 1 – Towing Tank of EPUSP.

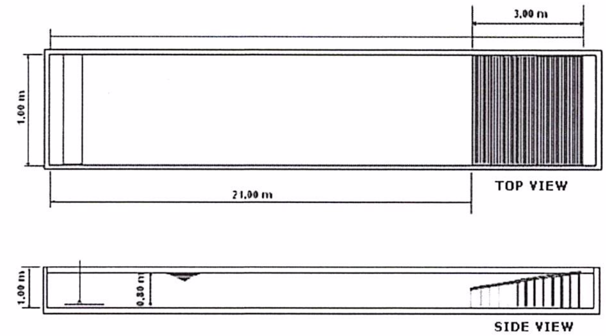

Figure 2 - Size of Physical Tank.

The wave generator of the tank is wedge type with vertical movement. The frequency range that the wave generator can operate is from 0.5 to 3.0 Hz.

The requirements for the design of the experimental model are:

• Study of 2D phenomena, focusing on the roll motion;
• Free-floating structure with an internal liquid tank;
• Ratio of length by width that avoids three-dimensional motions such as swirling;
• Natural frequency of sloshing within the frequency range of the wave generator;
• Natural frequency of sloshing close that of the motions of the free-floating model.

For sake of simplicity, a rectangular box shape is adopted for the model. Based on the above the requirements and constraints, and setting a clearance of 4 cm in the both ends of the model to avoid the collision with the walls of the towing tank, a parametric approach to assess the dimensions of the model was created.

In order to record the motion of the liquid inside the model's tank by using video camera, acrylic plates were adopted for the construction of the model.

The estimate of the first natural frequency of sloshing of a rectangular tank can be made by applying:

$$f = \frac{1}{2\pi}\sqrt{(\frac{\pi g}{b})\tanh(\frac{\pi h}{b})} \quad (1),$$

where:
f: natural frequency of the tank;
b: width of the tank;
h: height of the free surface.

Thus, the frequency of the sloshing was calculated for filling heights, ranging from 5% to 95% with the variation of 5% regarding the total height of the model's tank.
The natural period of roll motion of the model it self is calculated by:

$$T_{roll} = 2.\pi.\sqrt{\frac{Ixx.(1+C_{mad-roll})}{K_{roll}}} \quad (2),$$

where:
$C_{mad\text{-}roll}$ - Added mass coefficient of the roll motion;
K_{roll} - Restoration of the roll motion;
Ixx - Inertia of roll.

With the variation of the parameters of model test got up an alternative capable of meeting all requirements, including the superposition of frequencies of sloshing and roll to an average height of the water in the tank model, as shown in
Figure 3 shows the results of the parametric analysis. The dimensions that meet all requirements, including the superposition of frequencies of sloshing and roll to an average height of the water inside the model's tank are defined.

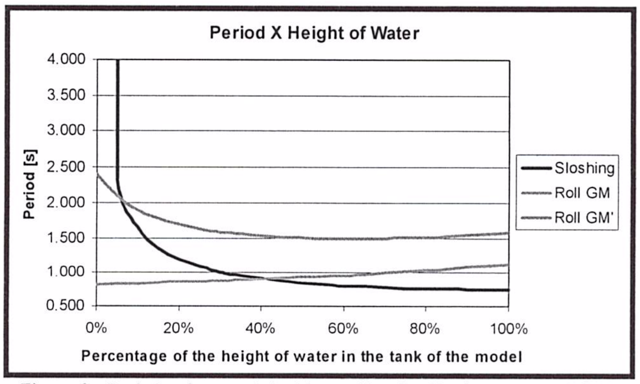

Figure 3 - Periods of natural sloshing, roll and roll using corrected GM.

The Table 1, Table 2 and Table 3 summarize the dimensions and other variables of the model used in the present study.

Table 1 - Main Dimensions.

Main Dimensions		
Parameter	Value	Unit
Length	0.920	m
Breadth	0.420	m
Depht	0.315	m
Double Botton	0.050	m

Table 2 - Thickness.

Thicknesses		
Parameter	Value	Unit
Botton	0.010	m
Top	0.005	m
Front	0.010	m
Back	0.010	m
Left	0.010	m
Right	0.010	m
Double Botton	0.010	m

Table 3 - General.

General		
Parameter	Value	Unit
Acrylic Density	1190.000	Kg/m³
Water Density	1000.000	Kg/m³
Gravity	9.786	m/s²
Ballast Weight	30.000	Kg

Figure 4 shows the cross section of the model and the arrangement of the acrylic plates.

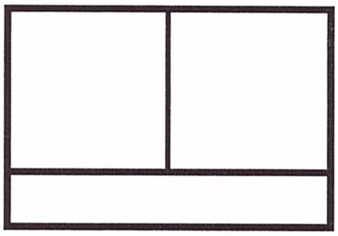

Figure 4 - Cross section of arrangement of acrylic plates.

The model in the water of the tank can be seen in Figure 5.

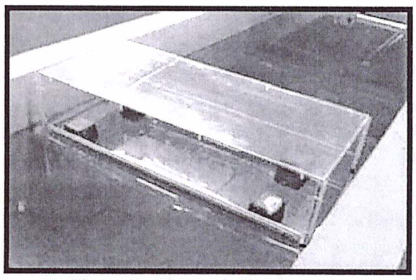

Figure 5 - The model in the tank.

4. EXPERIMENTAL CONDITIONS

In both experiments with fixed and liquid cargoes, the initial inertia and center of gravity of the model are the same, as shown in Table 4, and they were adjusted by positioning the ballast in the fixed cargo model to be the same of liquid cargo.

Table 4 – Mass Properties of the model.

Properties of Mass		
Parameter	Value	Unit
Mass	21.22	Kg
VCG	126.38	mm
TCG	0.00	mm
LCG	0.00	mm
Ixx	6.71E-01	Kg.m²

Experimental equipment

In the physical experiments were used three types of equipments.

A piezoelectric vibrating gyroscope, brand and model Murata ENV-05D-52, its output is an analogue voltage proportional to the sensed angular rate at a frequency of 2 kHz. The voltage output at zero rate is unit-dependent and ranges from 2.2 to 2.8 V with a mean of 2.5 V. The maximum angular velocity that can be sensed is 80 deg/s.

A capacity acceleration transducer, brand and model Kyowa AS-2GA, use a strain gage as the sensing element, this equipment was designed to measure small levels of acceleration. The Table 5 shows other characteristics about this equipment.

Table 5 - Characteristics of the capacity acceleration transducter.

Model	Resonance frequency [Hz]	Frequency response	Rated capacity [m/s²]
AS-2GA	100	5%	+/-19.61 (+/-2G)

And a wave probe designed by IPT-USP, through of the variations in the potential in its stems is calculated the height of generated wave by wave batter. The conversion of volts signal to wave height is made by software through the transfer function obtained in calibration of equipment.

The case of tests

In the present study, filling height of 10.8 cm, which corresponds to 45% of the height of the internal tank of the model, is adopted (see Table 6).

Table 6 – Filling height and the estimated motion parameters.

% of height (%)	Height of water (m)	Sloshing Freq. (Hz)	Roll Freq. (Hz)	Draft (m)	GMT (m)
45	0.108	1.16	1.09	0.23	0.09

The height of water in tank was chosen in 10.8 centimeters because it shows that the analytical result is close to the requirements for testing of sloshing.

In the case of fixed cargo, the water was replaced by ballast and was used the same frequencies of the case sloshing.

In order to obtain a RAO, a series of frequencies were tested according to Table 7 and Table 8. These tables shown too that in order to check the non-linear effects, for the frequencies of 1.0 Hz, 1.08Hz, 1.16Hz and 1.33Hz, which are near to the resonance, the experiments were carried out for two different wave heights.

5. RESULTS

Table 7 - Test Cases for Fixed Cargo.

Test Cases		
Frequency (Hz)	Height (m)	
	Lower	Higher
0.67	0.030	-
0.71	0.042	-
0.77	0.034	-
0.83	0.016	-
0.91	0.022	-
1.00	0.026	0.044
1.08	0.020	0.030
1.16	0.036	0.040
1.33	0.044	0.054
1.67	0.008	-
2.00	0.004	-

Figure 7 shows the time series of wave probe and roll motion for the wave of 1.0 Hz, which is very close to the estimated resonant frequency, and amplitude of 0.013 m. In order to assess the amplitudes of the wave and the motion, two methods were considered: the analysis of peaks, for calculating the amplitude of the wave, and the power spectrum, through FFT (Fast Fourier Transformation). The intervals selected for the analysis are shown in red.

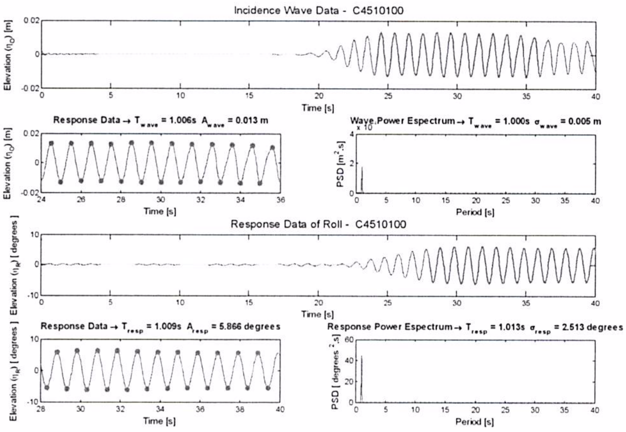

Figure 6 – Test Analysis for 45% loading of Fixed Cargo with Frequency 1Hz and wave amplitude of 0.013m.

Figure 8 shows the time series of wave probe and roll motion for the wave of 1.0 Hz and amplitude of 0.022 m, which is higher and aims to detect the non-linear effects.

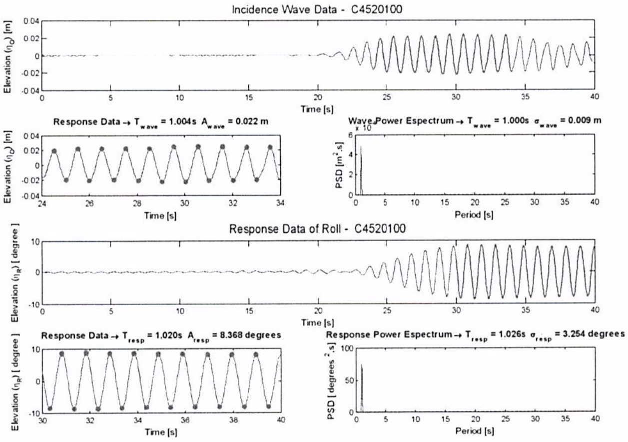

Figure 7 - Test analysis for Fixed Cargo with 45% loading, frequency 1Hz and wave amplitude of 0.022m.

Figure 8 shows the RAO calculated, respectively, by the analysis of peaks, in the upper graphics, and by power spectrum, in the lower graphics, and also the comparison between the calculated with the series of lower height and the series of higher height.

In order to check the accuracy of the experimental results, comparisons were made with the numerical results obtained by WAMIT are also shown in Figure 8. To simulate 2D phenomena by using WAMIT, a 3D hull with length 100 times longer than the length of the model were used.

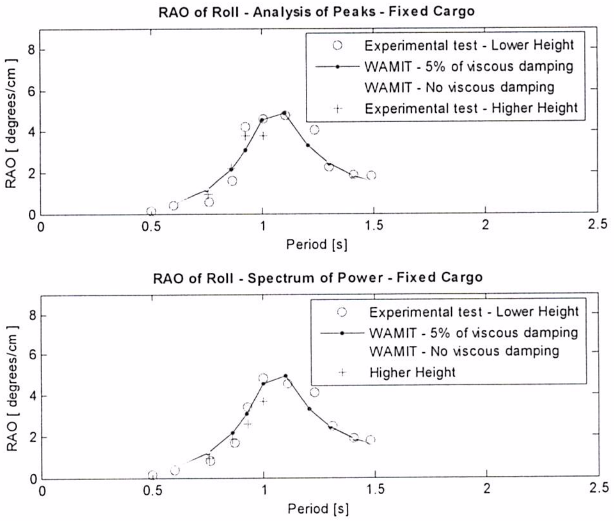

Figure 8 - RAO Fixed Cargo - Experimental Test.

As illustrated by Figure 8, the viscous damping has relevant effects on the responses near to resonant frequency. However, in both cases, without and with 5% of viscous damping the experimental and the numerical results agree very well.

Also, the non-linear effects of the motion due to larger wave amplitudes are not remarkable in the case analyzed herein.

Table 8 - Test Cases for Liquid Cargo.

Test Cases		
Frequency (Hz)	Wave Amplitude (m)	
	Lower Height	Higher Height
0,67	0,028	-
0,71	0,046	-
0,77	0,038	-
0,83	0,018	-
0,91	0,020	-
1,00	0,038	0,048
1,08	0,022	0,036
1,16	0,042	0,044
1,33	0,046	-
1,67	0,008	-
2,00	0,008	-

In Figure 9 and in Figure 10 there are the time series of wave and the selected interval of the series for some frequencies of waves, in red, to the analyses. Following is the analysis of peaks, for calculating the amplitude of the wave, and the power spectrum, through FFT (Fast Fourier Transformation), the selected time period. Following is the same time series, and spectrum analysis of peak power for the model response in roll.

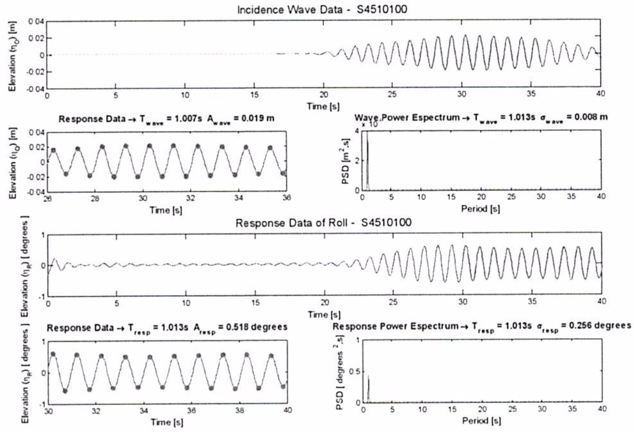

Figure 9 – Test analysis for Liquid Cargo with 45% loading, frequency 1Hz and wave amplitude of 0.019m.

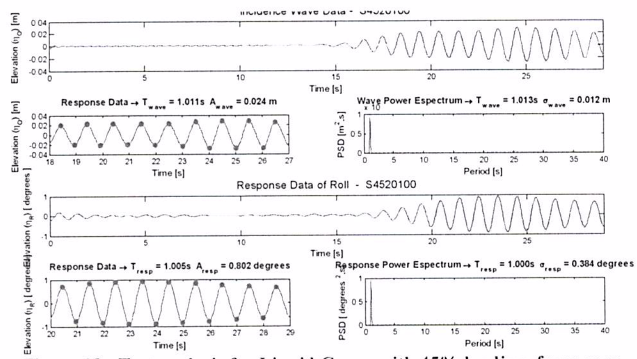

Figure 10 - Test analysis for Liquid Cargo with 45% loading, frequency 1Hz and wave amplitude of 0.024m.

Figure 11 gives the RAO calculated, respectively, through the analysis of peaks in the spectrum of power.

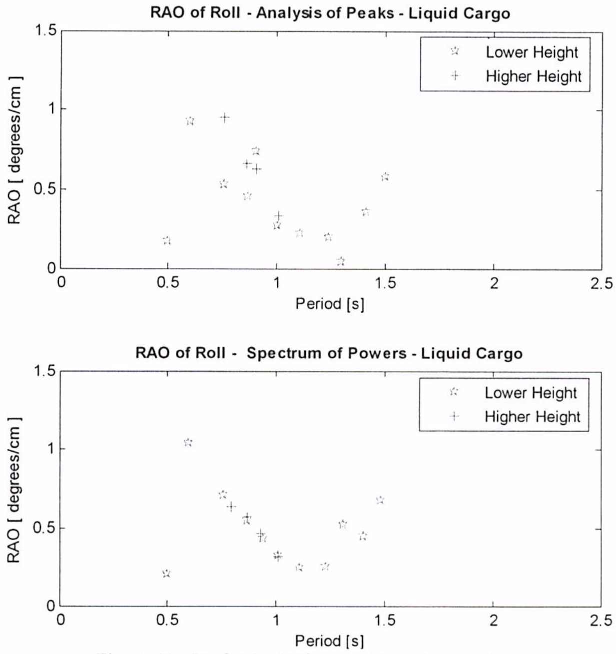

Figure 11 - RAO Liquid Cargo - Experimental Test.

Figure 12 are plotted the RAOs of both tests of lower wave for comparison.

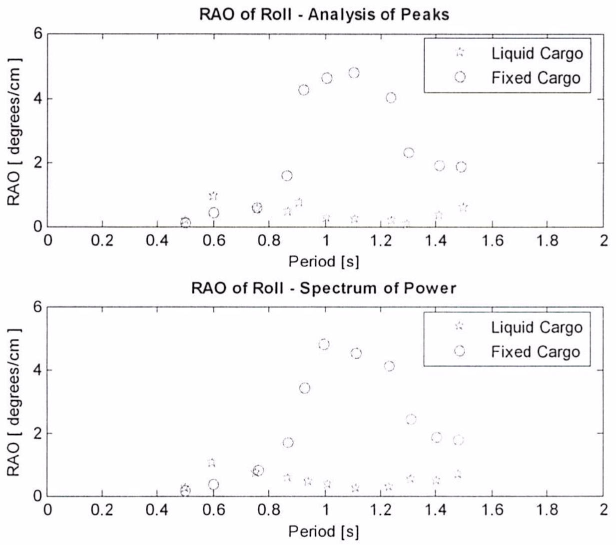

Figure 12 - Comparison RAO – Liquid Cargo and Fixed Cargo, Experimental Test.

7. CONCLUSIONS

This paper presented some results of a experimental study on the effect of the sloshing on the motion of the floating units. In order to take into account the coupling effect of the sloshing and wave motions, free-floating models with an internal liquid tank was used. The roll motion of the model with fixed cargo was measured and compared with WAMIT, which shows very good agreement between the experimental and the numerical results. In the experiments with liquid cargo, the results show that the main effects of sloshing is on the roll motion of the model: for the frequencies close to the resonant liquid motion, the sloshing reduced remarkably the roll motion of the model. Also, in the case analyzed herein, the non-linear effects of the motion due to larger wave amplitudes are not remarkable The results shown herein provide data for the validation of new numerical approaches for the study of the coupled motions of the floating units and sloshing.

NOMENCLATURE

- EPUSP: Escola Politécnica da Universidade de São Paulo;
- *f*: Natural frequency of the tank;
- *b*: Width of the tank;
- *h*: Height of the free surface;
- $C_{mad\text{-}roll}$: Added mass coefficient of the roll motion;
- K_{roll}: Restoration of the roll motion;
- *Ixx*: Inertia of roll;
- GM: Metacentric height;
- VCG: Vertical center of gravity;
- TCG: Transversal center of gravity;
- LCG: Longitudinal center of gravity;
- Ixx: Moment of inertia around x-axis;
- IPT-USP: Instituto de Pesquisa Tecnólgicas da Universidade de São Paulo;
- GMT: Transversal Metacentric height;
- RAO: Response amplitude operator;
- FFT: Fast Fourier Transformation;
- T_{wave}: Wave period;
- A_{wave}: Wave amplitude;
- s_{wave}: Wave variance;
- T_{resp}: Response period;
- A_{resp}: Response amplitude;
- s_{resp}: Response variance;
- PSD: Power spectral density;
- WAMIT: Wave analysis at Massachusetts Institute of Technology.

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