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SHIP MOVEMENTS' ANALYSIS IN A PHYSICAL SCALE MODEL

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ABSTRACT

A set of physical model tests was run in to characterize the ship's response to different wave conditions going from frequently-occurring conditions up to extreme ones. Several wave heights, periods and directions were generated. The waves around the ship were measured with probes and the movements of the ship were measured with a fiber-optic gyrocompass. Transfer functions are established and compared with numerical ones obtained with the WAMIT model.

1. INTRODUCTION

Sea waves can condition different aspects of harbour activities. Among those related to ships, operating conditions regarding ship manoeuvring at entrance channels or when they are moored at a dock are emphasised. In these cases, it is important not only to characterize the wave field in the ship surroundings but also the ship responses to the forces it is subjected to, whether they are common or extreme.

Numerical modelling is a common tool to characterize the ship response to the incident sea waves but it relies on important simplifications and parametrisation of the complex phenomena involved in the ship-wave interactions. Therefore, numerical models of this kind always lack validation and calibration. It is in this sense that physical modelling does represent an extremely important tool allowing replicating complex physical phenomena in an easier and more controlled way.

With the objective of validating and calibrating a numerical model of the behaviour of a free ship, a set of physical model tests was run to measure the ship movements when subjected to different incident sea waves (regular and irregular) including different wave attack angles. It was also measured the waves around the ship. With the data, it was possible to determine the movement of the ship along its six degrees of freedom and to relate them with the characteristics of the incident sea waves. Transfer functions are established and compared with numerical ones obtained with the WAMIT model. The tests also allowed the characterization of the sea state around the ship.

After this introduction, the paper describes: in section 2, the physical model setup; in section 3, the results and analysis; and finally, in section 4, some final remarks and conclusions are shown.

2. PHYSICAL TESTS SET UP

2.1. Description

The objective of the tests was to characterize the free-surface elevation around a ship and the ship movements along its six degrees of freedom.

Three directions were tested for the incident waves which correspond to the ship being perpendicular, parallel and oblique to the wave front. For each direction, the incident sea-wave conditions (regular and irregular) consisted of 3 different periods (8, 12 and 16 s) and 3 different wave heights (2, 4 and 6 m).

The time-series of generated waves were constructed based on an empirical JONSWAP spectrum to the irregular waves, with duration of 300 seconds. The series of regular waves had a duration of 180 seconds.

For each of the above test conditions, a temporal and spectral analysis of both the free surface elevation and ship movements (along its six degrees of freedom) were made, that were measured by using resistive sensors and fiber-optic gyrocompass, respectively.

The ship, as well as the fiber-optic gyrocompass, is from the CENTEC/IST.

2.2. Experimental Setup

The tests were conducted at LNEC, in a tank of the Ports and Maritime Structures Division of the Hydraulics and Environment Department of LNEC using a wave generator with a 6-meter wave front, Fig.1. The dimensions of the tank are approximately 20 m x 35 m (width x length).

Figure 1. Layout of the experiments.

The ship model, Fig. 1, used in the tests is a scale model at 1:100 of the Esso Osaka, a very large crude carrier. The overall length of the ship model is 3.43 m and its width is 0.54 m. It was weighted at 59.06 kgf on a digital scale. To simulate the condition of the ship being moderately loaded, 8 cubic blocks of concrete – representing a total weight of 150 kgf – were placed inside it. The measuring equipment weights 5.44 kgf hence the total weight of the test model (ship+blocks+equipment) is 214.5 kgf. The positions of the blocks were registered to calculate the center of gravity of the ship.

The ship was placed in the middle of the tank, with its axis parallel – then perpendicular, then oblique – to the wave generator, Fig. 2.

To characterize the free-surface elevation around the ship, 8 resistive probes and a Quantum MX data-acquisition system and software were used for the tests. The 8 resistive probes were positioned as shown in Fig.2 and Fig.3. Probe 1 is used to control the generated sea waves while the other probes are used to characterize the wave field in the ship surroundings. Probes 3 and 4 characterize the waves on both sides of the ship, probes 5, 7 and 8 characterize the waves after they passed the ship and probes 2 and 6 are there to identify waves reflected off the ship. The sampling frequency rate was 50 Hz.

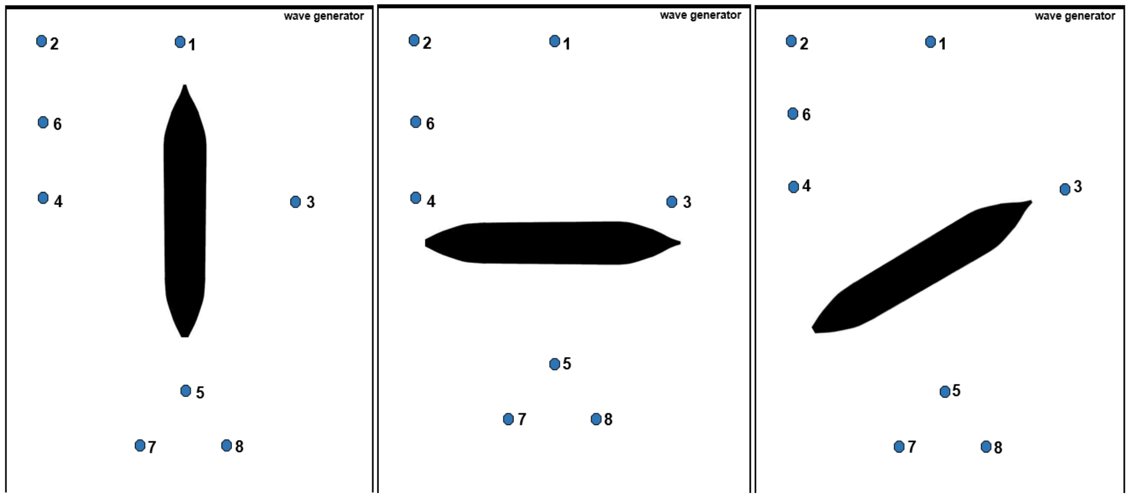
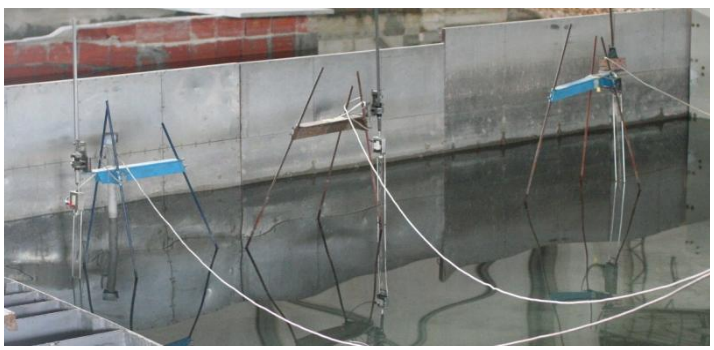


Figure 2. Scheme of the ship positions and the probes layout


a)

b)
Figure 3. a) Resistive probe, b) Acquisition equipment: Quantum X (BM MX 840A)

An OCTANS fiber-optic gyrocompass, Fig. 4, was used to measure the ship motions along its 6 degrees of freedom. The gyrocompass is capable of measuring true-heading, roll, pitch, yaw, heave, surge, sway rates of turn and accelerations. The equipment was placed onboard of the ship model as close as possible to the center of gravity (centered as regard to its longitudinal and transversal axis). To synchronize, acquire and store data from the gyrocompass a software architecture was programmed in LABVIEW software. The software architecture consists of several programs loops, communication, real-time monitoring, data saving, etc. The sampling frequency rate was 20 Hz. Fig. 4 shows the fiber-optic gyrocompass and the one of the user interfaces of the developed software, Hinostroza (2014).

a)


b)

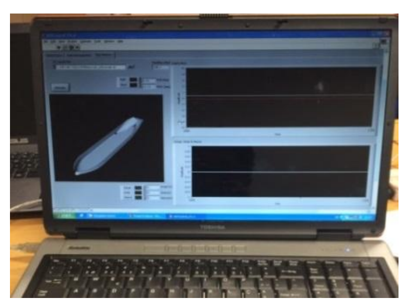



Figure 4. a) Fiber-optic gyrocompass, b) Data acquisition software window

The tests were carried out using the following procedure:
1) Weighting of the ship based on two points;
2) Weighting and placement of the concrete blocks;
3) Adjustment of the water level inside the tank;
4) Calibration of the resistive probes;

5) Regular waves tests;
6) Irregular waves tests.

Table 1. Wave conditions measured at probe 1

Test	Wave angle of attack (º)	Wave Type	T, Tp (s)	H, Hs (m)
1	180º		7.7	2.3
2			7.7	3.8
3			7.7	4.4
4			15.6	1.8
5		Reg.	15.6	3.5
6			15.6	5.0
7			11.6	1.4
8			11.6	3.1
9			11.6	4.7
10			7.5	2.0
11			7.5	3.9
12			7.7	5.4
13		Irreg.	11.2	4.0
14			11.2	5.7
15			14.8	4.0
16			14.5	6.1

Table 1. (cont.) Wave conditions measured at probe 1

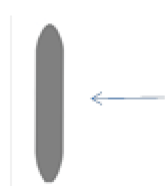
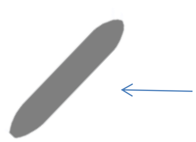
Test	Wave angle of attack (º)	Wave Type	T, Tp (s)	H, Hs (m)
28	90º		15.6	1.7
29			15.6	3.1
30			15.6	4.6
31		Reg.	11.6	1.4
32			11.6	3.1
33			11.6	4.6
34-43			7.7	1.2
17-26		Irreg.	14.9	2.5
27	135º	Irreg.	11.3	2.9
44-46			7.7	1.5
47			11.6	1.2
48			11.6	2.7
49		Reg.	11.6	4.0
50			15.6	1.8
51			15.6	3.5
52			15.6	5.0

Table 1 presents the characteristics (wave period and wave height) and type (regular or irregular) of the waves generated for each test. The duration of the test was 300 s for irregular waves and 180 s for regular waves.

Three wave conditions were chosen to test the repeatability of the results, namely:

- Regular beam waves with θ=90º; T=8 s; H=1.2 m
- Irregular beam waves with θ =90º; T=15 s; H=2.5 m
- Regular bow waves with θ =135º; T=8 s; H=1.5 m

Because of the electronic equipment inside the ship (namely the fiber-optic gyrocompass) the irregular cases had to be limited to large periods for beam and bow waves due to the possibility of water overtopping the ship's hull.

3. RESULTS AND ANALYSIS

3.1. Free surface elevation and ship motions

Measurements were transformed first into prototype values (that is why the maximum abscissa in the graphics of Fig. 5 and of Fig. 7 is around 2000 s), and then were sent through a set of algorithms that operate a spectral analysis and plot both the original time series and spectra for the wave probes and the ship motions (surge, sway, heave, yaw, roll, pitch and yaw). Fig.4 and Fig.5 present the time series of the free surface elevation and the respective spectra for test number 13. Fig. 6 presents the ship motions time series while Fig. 7 presents the power density spectrum of the ship motions.

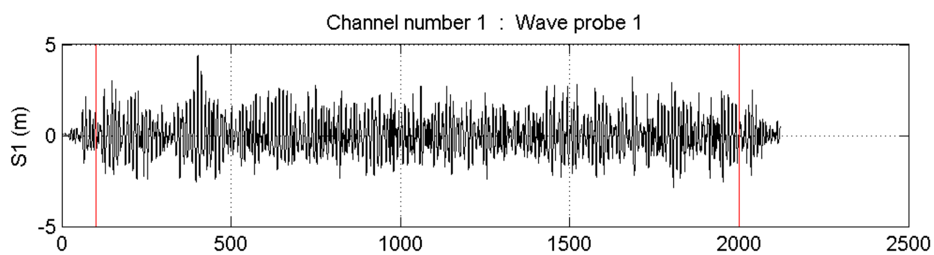


Figure 5. Time series of the wave probe 1 for test number 13

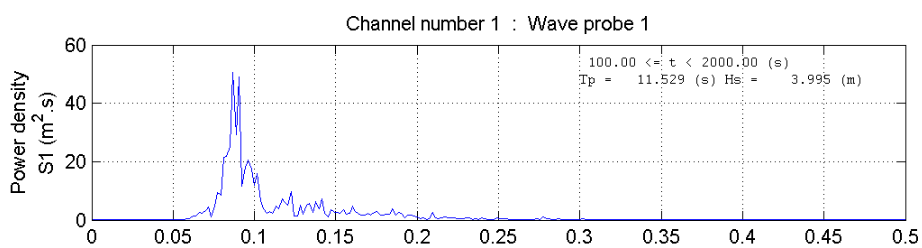


Figure 6. Power density spectrum wave probe 1 for test number 13

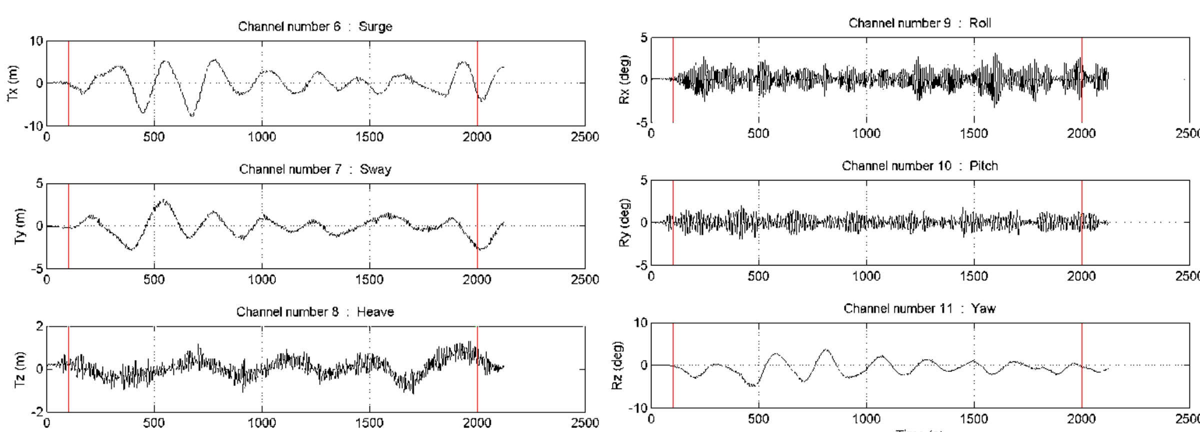


Figure 7. Time series of the ship motions for test number 13

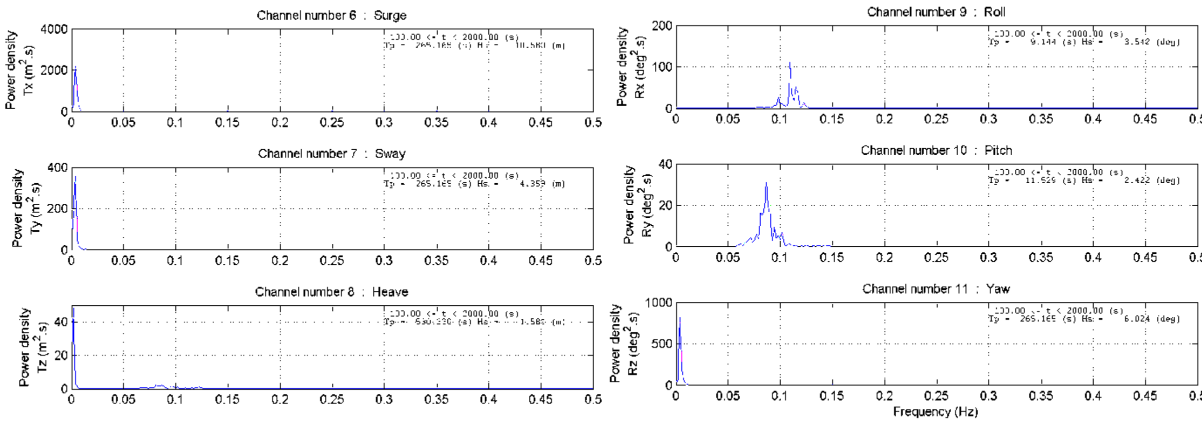


Figure 8. Power density spectrum of the ship motions for test number 13

3.2. Free surface elevation and ship motions

From the measurements of all the tests it was determined the transfer function associated with each test. A transfer function, also known as response amplitude operator (RAOs), is a measure of the effect that a sea state will have upon the motions of a ship. The transfer function is frequency dependent. The ship motions are assumed to be linear, and the transfer function is given by:

$$TF(\omega) = \frac{x(\omega)}{H_{s1}(\omega)} \tag{1}$$

where x is a degree of freedom (e.g. a vector of rigid body motions) and H_{s1} is the wave height measured at probe s1. The phase shift between the excitation and the ship motions is not considered in this work, therefore only the absolute value of the transfer functions is considered:

$$\mathrm{x} = \left[\mathrm{H_{Tx}}, \mathrm{H_{Ty}}, \mathrm{H_{Tz}}, \mathrm{R_x}, \mathrm{R_y}, \mathrm{R_z}\right] \tag{2}$$

H_{Tx} and H_{Ty} components are a result of the Fourier transform of the time series of the wave height measured in probe s1 and the movements time series from which the significant wave height and motion amplitude is extracted, respectively.

WAMIT numerical model results are also presented and compared to the experimental results. WAMIT (Korsemeyer *et al*. 1988) solves in the frequency domain, using a panel method, the radiation and diffraction problems associated to the interaction between incident waves and a free-floating body to obtain frequency domain added masses, damping coefficients and transfer functions. The ship's hull was discretized with 6037 panels, Fig.8. Frequencies ranging from 3.67 Hz to 628.31 Hz were simulated.

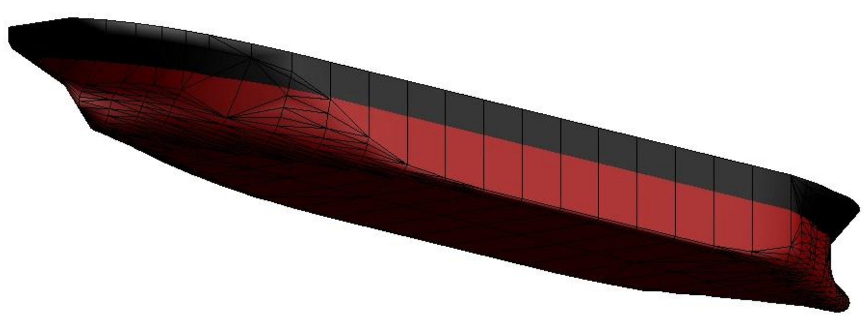


Figure 9. Discretization of the ship's hull in panels.

Fig. 10 to Fig. 12 present the transfer functions (experimental and numerical) for all regular incident waves for the six ship movements. In those figures, there is a black continuous line corresponding to the computed transfer function for the assumed angle between the ship longitudinal axis and the wave propagation direction, whereas the dashed lines represent the computed transfer functions for variations of some degrees in that angle. This analysis permits to infer about the uncertainty of the actual wave attack angle in the experimental tests.

For beam waves (90º), surge and roll transfer functions obtained experimentally fit very closely the numerically obtained curve. Yaw is under predicted compared with the numerical results. Sway, heave and pitch, in average, fit well with the numerical simulation.

For bow quartering waves (135º), surge and roll transfer functions have the best fit to the numerical results. Heave is under predicted compared with the numerical results as well as pitch and yaw rotation movements, especially for the smaller frequency. All movements, on average, fit fairly well the numerical simulation.

For head waves (180º), the surge, sway and yaw transfer functions obtained experimentally fit very closely the numerically obtained curve. Heave is underpredicted when compared with the numerical results. Roll has a wide range of RAO for the same frequency but, in average, it fits the numerical simulation.

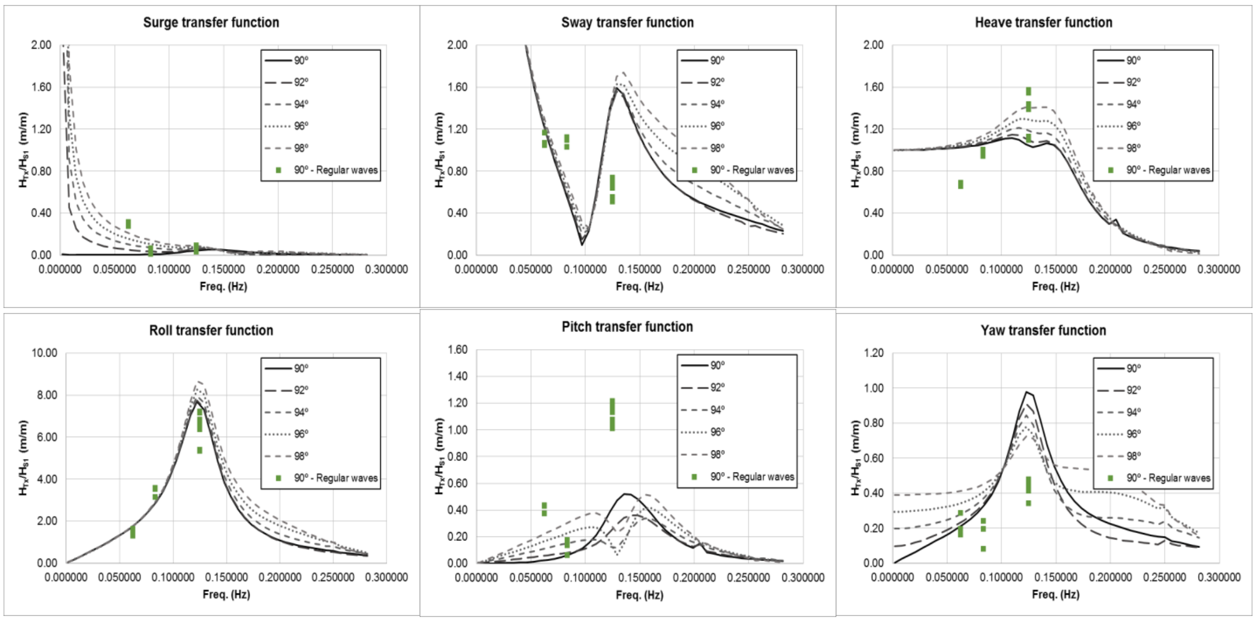


Figure 10. Regular waves transfer functions for beam waves (90º).

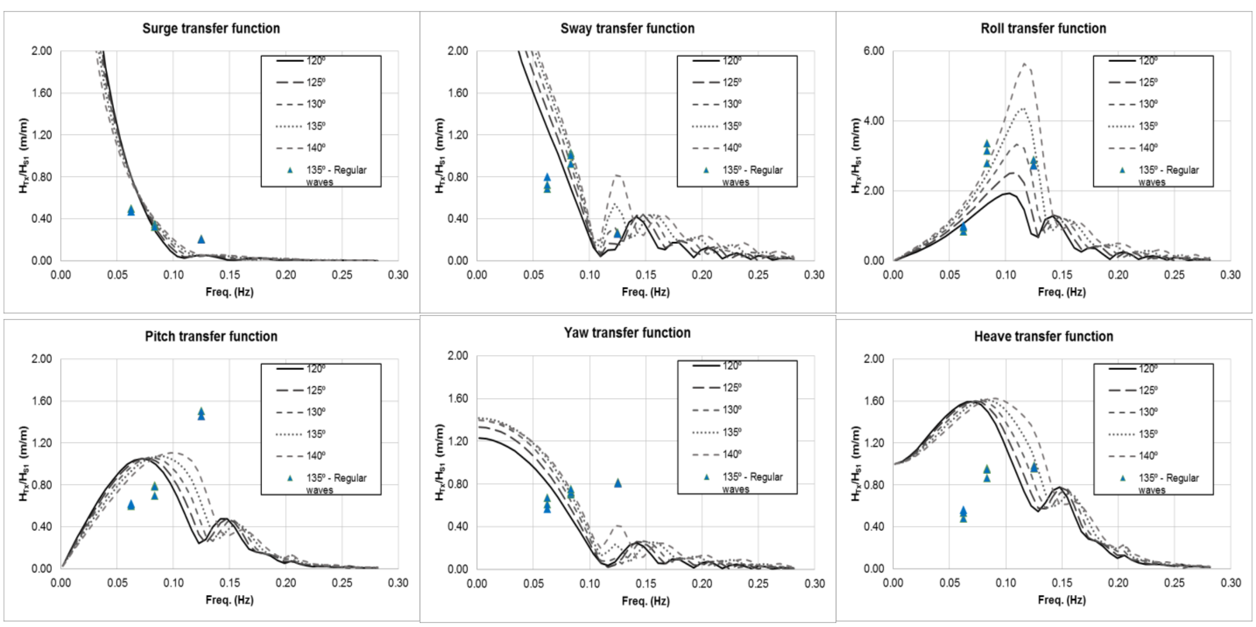


Figure 11. Regular waves transfer functions for bow waves (135º).

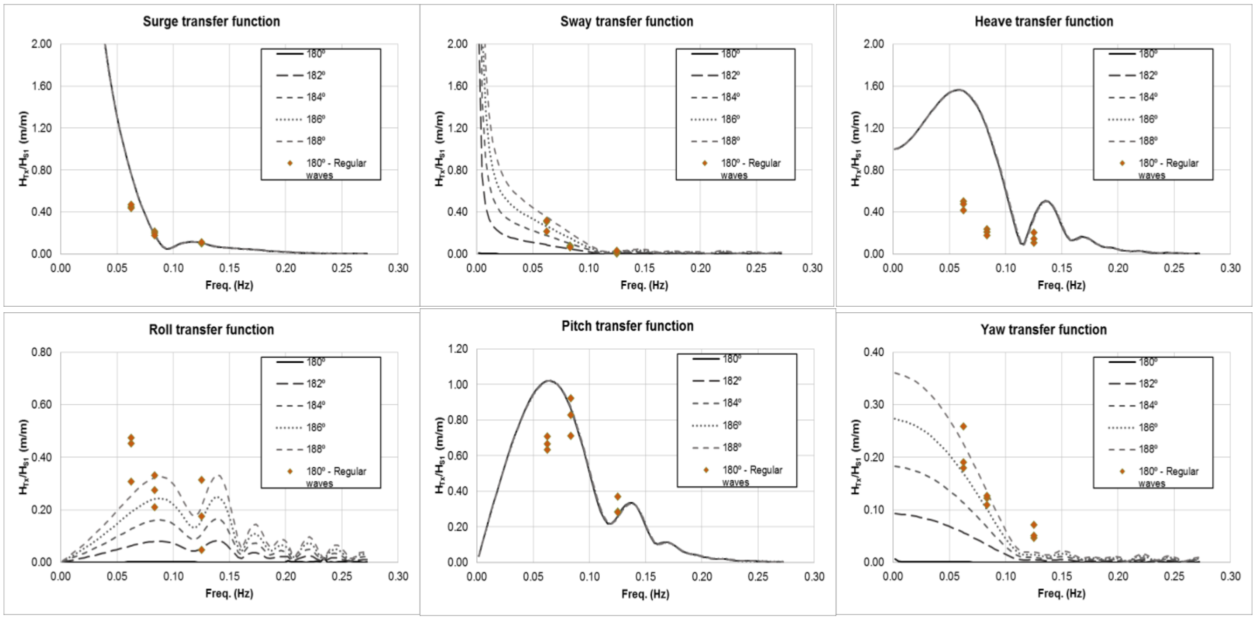


Figure 12. Regular waves transfer functions for head waves (180º).

Each of the dots in the above figures represent one test. For the same wave frequency, three different wave heigths were generated. That is why three dots appear aligned in the same frequency. In order to analyse the variation of results in terms of wave heights, Fig. 13 presents for the head waves (180º) cases, the comparison between the motion amplitude registered in the physical tests and the one obtained with the linear transfer function from WAMIT model. Each frequency is now represented by a different color.

For surge and heave movement, the angle variation does not affect significantly the amplitude of the motion, as can be seen in fig. 12. Whereas sway and yaw modes are activated if the angle of attack is slightly off. For this reason, based on the Fig.12, a deviation of 6º from the targeted angle is considered to best fit experimental results.

The variation of motion amplitudes, assumed to be linear, is in fact very close to a linear function in all cases. Despite that, higher frequencies are better estimated than lower ones.

Surge and Heave have mostly lower amplitudes than the numerical model would predict.

Sway and Yaw (that in perfect conditions would be null) are effectively well predicted by the numerical model if an offset of about 6º is introduced.

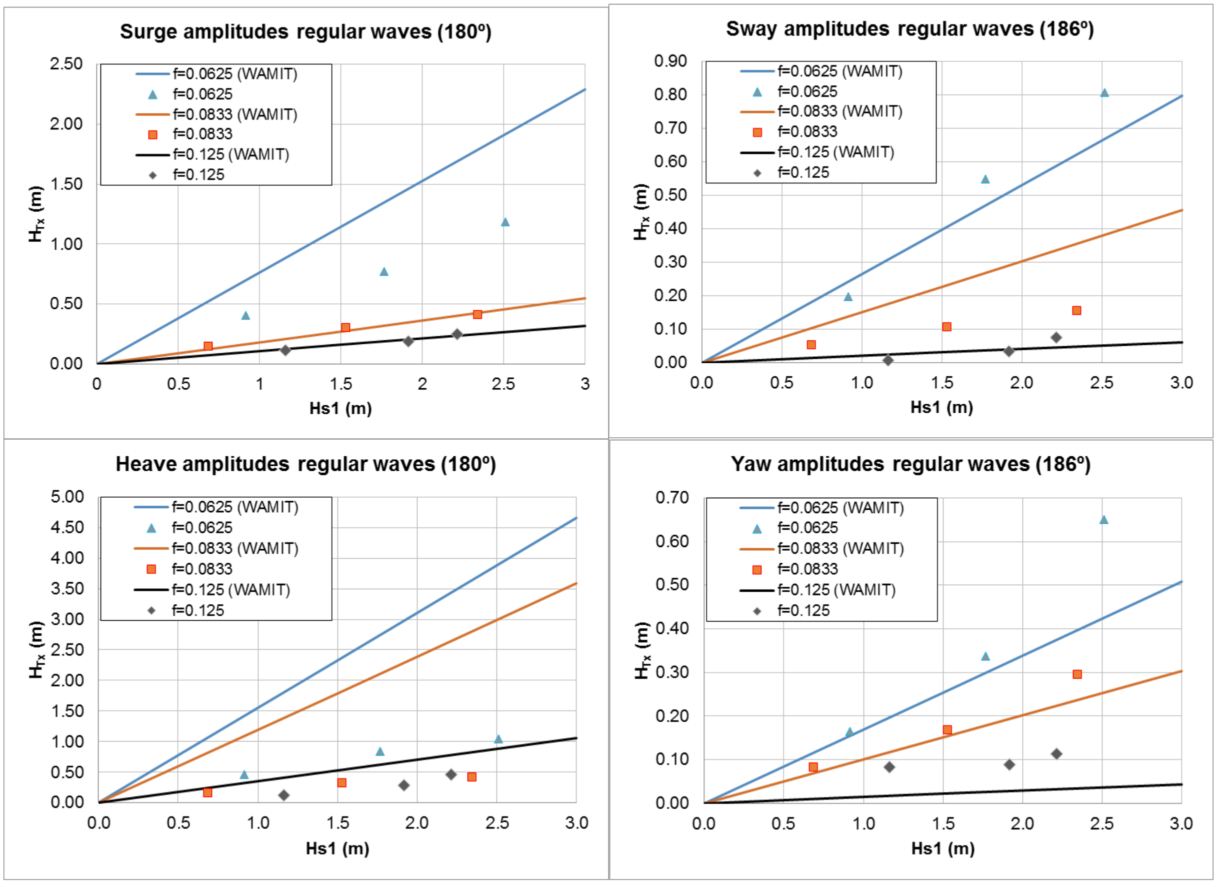
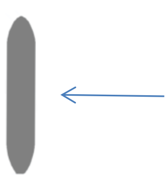
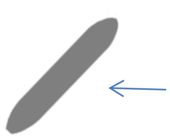


Figure 13. Regular waves motion amplitudes for head waves (180º).

Some of the tests where repeated several times to assess the repeatability of the experimental results. In Table 2 the mean values and standard deviations of these repetitions are presented as well as the standard error with respect to the mean value.

Table 2. Repeatability of Results: Transfer functions (HT/Hs1) or (R/Hs1).

Test	Wave angle of attack (º)	Type	Mode	N. tests	Mean	Min.	Max.	Std dev.	Std. Error
17-26	90º 	Irreg	Surge	10	1.58	1.48	1.75	0.09	6%
			Sway	10	1.52	1.35	1.72	0.11	7%
			Heave	10	1.75	1.62	1.91	0.10	6%
			Roll	10	2.50	2.42	2.60	0.06	2%
			Pitch	10	0.16	0.14	0.18	0.01	8%
			Yaw	10	0.38	0.34	0.51	0.05	14%
34-43		Reg	Surge	10	0.08	0.03	0.09	0.02	23%
			Sway	10	0.64	0.51	0.74	0.08	13%
			Heave	10	1.35	1.09	1.57	0.18	13%
			Roll	10	6.36	5.33	7.21	0.73	11%
			Pitch	10	1.12	1.01	1.21	0.07	6%
			Yaw	10	0.44	0.34	0.48	0.04	9%
44-46	135º 	Reg	Surge	3	0.21	0.20	0.21	0.00	2%
			Sway	3	0.27	0.26	0.27	0.00	2%
			Heave	3	0.97	0.96	0.99	0.01	2%
			Roll	3	2.79	2.73	2.90	0.09	3%
			Pitch	3	1.47	1.46	1.51	0.03	2%
			Yaw	3	0.81	0.81	0.82	0.01	1%

For the tests that were repeated, the variation of results is not significant, mostly less than 10%. Irregular waves show less variability. Wave obliquity with the longitudinal axis of the ship also leads to less variability of results. In fact, when there is some degree of symmetry (as in the cases of 180º and 90º angles of attack) experimental biases and unpredictability have a larger impact on the expected results.

4. CONCLUSIONS

In this paper, a set of physical model tests was performed to characterize the ship's response to different incident wave conditions (regular and irregular), including different angle attacks. For each wave condition, the free surface elevation around the ship was measured with resistive wave gauges while the movements of the ship were measured with a fiber-optic gyrocompass. Transfer functions are established and compared with numerical ones obtained with the WAMIT model.

Surge and roll are the most important movements and are the ones that have the best fit to the numerical simulation, for all the tested conditions.

The variation of motion amplitudes, assumed to be linear, is in fact very close to a linear function in all cases. Despite that, higher frequencies are better estimated than lower ones.

Surge and heave movement have mostly lower amplitudes than the numerical model would predict and the angle variation does not affect significantly the amplitude of the motion.

Sway and Yaw are well predicted by the numerical model if an offset of about 6º is introduced.

Consequently, one can say that oblique waves are better reproduced in experimental tests because the errors and biases associated to laboratory introduce effects on all the movements of the ship perfect symmetry are very difficult to reproduce in the lab.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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Hinostroza, M. A., 2014. "Parametric Estimation of the Directional Wave Spectrum from Ship Motions". Thesis to obtain the Master of Science Degree in Naval Architecture and Marine Engineering. Instituto Superior Técnico.

7. RESPONSIBILITY NOTICE