

## SHIP MOVEMENTS' ANALYSIS IN A SCALE MODEL

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### ABSTRACT

A set of physical model tests was run in order 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.

Key-words: experimental test / movements of the ship / maritime agitation

### 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.

In this extent, numerical modelling is a common tool to characterize the ship response to the incident sea waves but it has to rely 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 to replicate 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 in order to measure the ship movements when subjected to different incident sea waves (regular and irregular) including different wave angle attacks. 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 to characterize the sea state around the ship.

## **2. PHYSICAL TESTS SET UP**

### **2.1. Description**

The tests were conducted at LNEC, in a tank of approximately 20 m x 35 m (width x length) using a wave generator with a 6-meter wave front. The ship, provided by CENTEC/IST, has a length of 3.45 m, a width of 0.54 m, and a total weight of 214.5 kg (including the measurement equipment and weights put inside the ship). The geometrical scale is 1:50.

Measuring equipment was used to characterize the free-surface elevation around the ship (8 resistive probes and respective power system and Quantum MX data-acquisition system and software) and the ship movements along its six degrees of freedom (fiber-optic gyrocompass and data-acquisition software of the CENTEC/IST). The equipment layout is depicted in Figure 1.

Three directions were tested for the incident waves which correspond to the ship being perpendicular, parallel and oblique to the wave front.

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 on the basis of an empirical JONSWAP spectrum to the irregular waves, with a 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.

## 2.2. Experimental setup

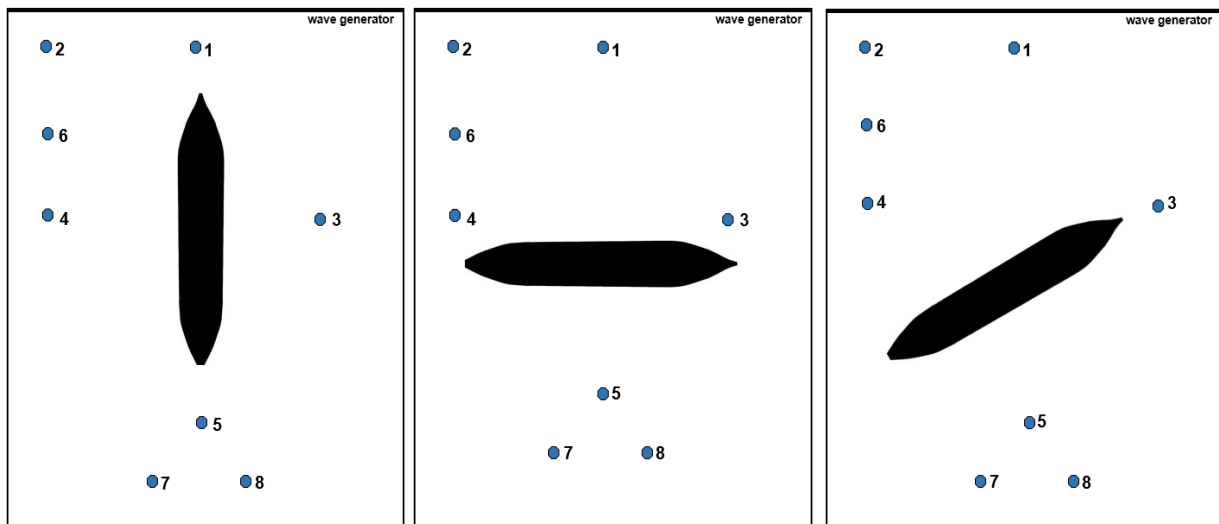
The tests were conducted inside tank 5 of the experimental facility of the Ports and Maritime Structures Division, Figure 1.



Fig. 1 – Layout of the experiments.

Eight resistive probes from LNEC were used for the tests. The ship, as well as the fiber-optic gyrocompass, are from the CENTEC/IST.

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



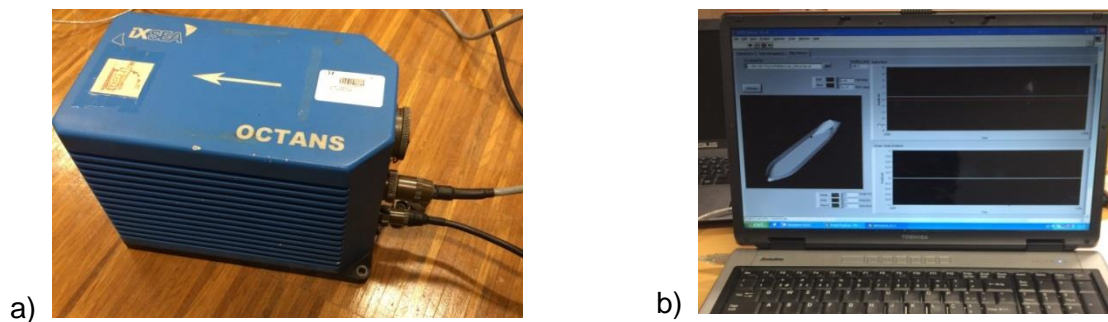
The 8 resistive probes were positioned as shown in Fig. 2.

Fig. 2 – Scheme of the ship positions and the probes layout

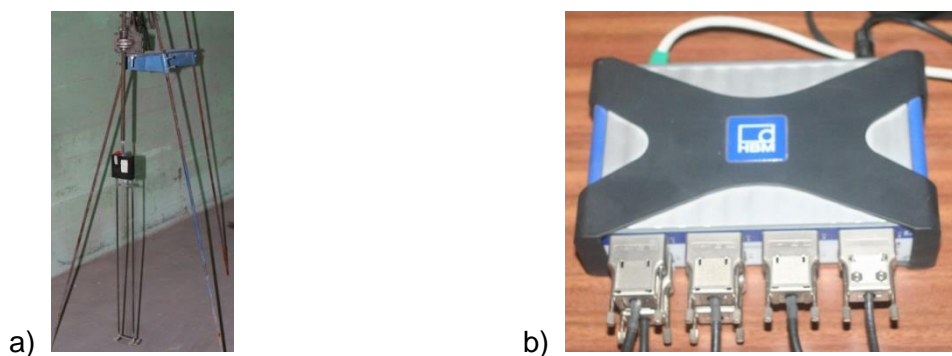
Probe 1 is used to control the generated sea waves while the other probes are used to characterize the wave field in the ship surroundings. Probes 3 and 4 characterize the waves on either side of the ship, probes 5, 7 and 8 characterize the waves after they passed the

ship and probes 2 and 6 are there to identify waves reflected off the ship. The frequency sample was 50 Hz.

An OCTANS fiber-optic gyrocompass 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). In order 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 frequency sample was 20 Hz. Fig. 3 shows the fiber-optic gyrocompass and the software developed, Hinostroza (2014).



**Fig. 3 – a) Fiber-optic gyrocompass, b) Data acquisition software window**



**Fig. 4 – a) Resistive probe, b) Acquisition equipment: Quantum X (BM MX 840A)**

The model 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. In order to simulate the condition of the ship being moderately loaded, 8 cubic blocks of concrete – representing a total weight of 150 kg – were placed inside it. The measuring equipment weights 5.44 kg hence the total weight of the test model

(ship+blocks+equipment) is 214.5 kg. The positions of the blocks were registered in order to calculate the centre of gravity of the ship.

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 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  $\theta=90^\circ$ ;  $T=8$  s;  $H=1.2$  m
- Irregular beam waves with  $\theta=90^\circ$ ;  $T=15$  s;  $H=2.5$  m
- Regular bow waves with  $\theta=135^\circ$ ;  $T=8$  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.

**Table 1 – Wave conditions measured at probe 1**

Test	Wave angle of attack (°)	Wave Type	T, T <sub>p</sub> (s)	H, H <sub>s</sub> (m)	Test	Wave angle of attack (°)	Wave Type	T, T <sub>p</sub> (s)	H, H <sub>s</sub> (m)	
1	180°	Reg	7.7	2.3	28	90°	Reg	15.6	1.7	
2			7.7	3.8	29			15.6	3.1	
3			7.7	4.4	30			15.6	4.6	
4			15.6	1.8	31			11.6	1.4	
5			15.6	3.5	32			11.6	3.1	
6			15.6	5.0	33			11.6	4.6	
7			11.6	1.4	34-43			7.7	1.2	
8			11.6	3.1	17-26			Irreg	14.9	2.5
9		11.6	4.7	27	Irreg		11.3	2.9		
10		Irreg	7.5	2.0	44-46		135°	Reg	7.7	1.5
11			7.5	3.9	47				11.6	1.2
12			7.7	5.4	48				11.6	2.7
13			11.2	4.0	49				11.6	4.0
14			11.2	5.7	50				15.6	1.8
15			14.8	4.0	51				15.6	3.5
16			14.5	6.1	52				15.6	5.0

### 3. RESULTS AND ANALYSIS

#### 3.1. Free Surface elevation and ship motions

Measurements were transformed first into prototype values 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. 5 and Fig. 6 present the time series of the free surface elevation and the respective spectra for test number 13. Fig. 7 presents the ship motions time series while the Fig. 8 presents the power density spectrum of the ship motions.

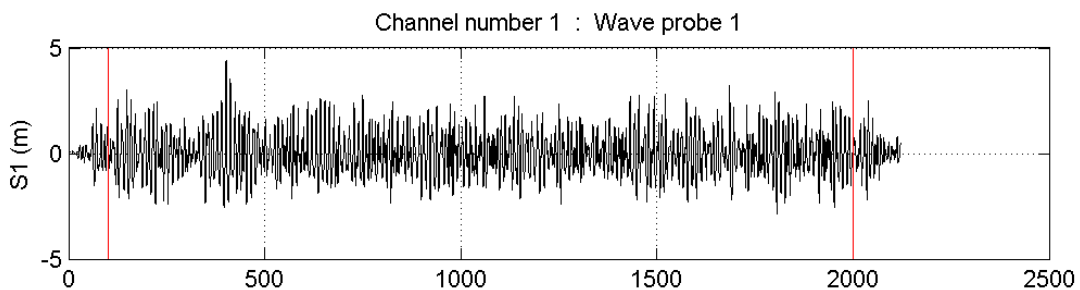


Fig. 5 – Time series of the wave probe 1 for test number 13

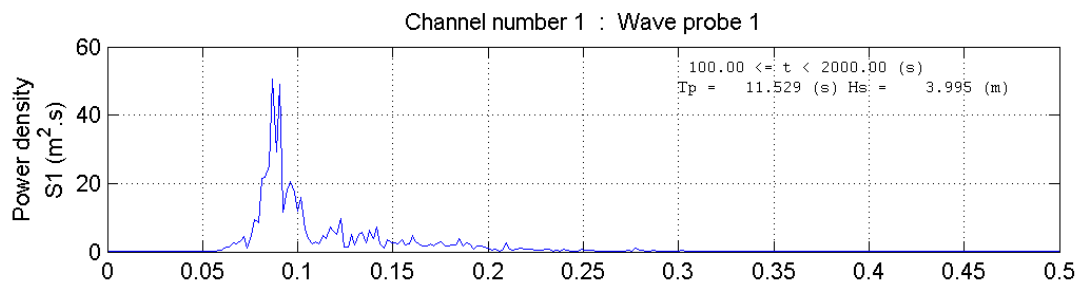


Fig. 6 – Power density spectrum wave probe 1 for test number 13

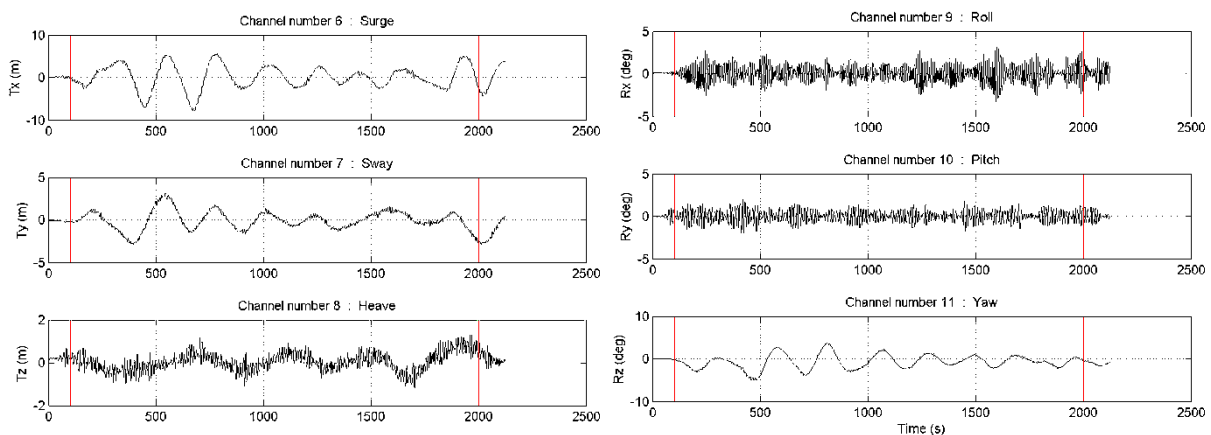


Fig. 7 – Time series of the ship motions for test number 13

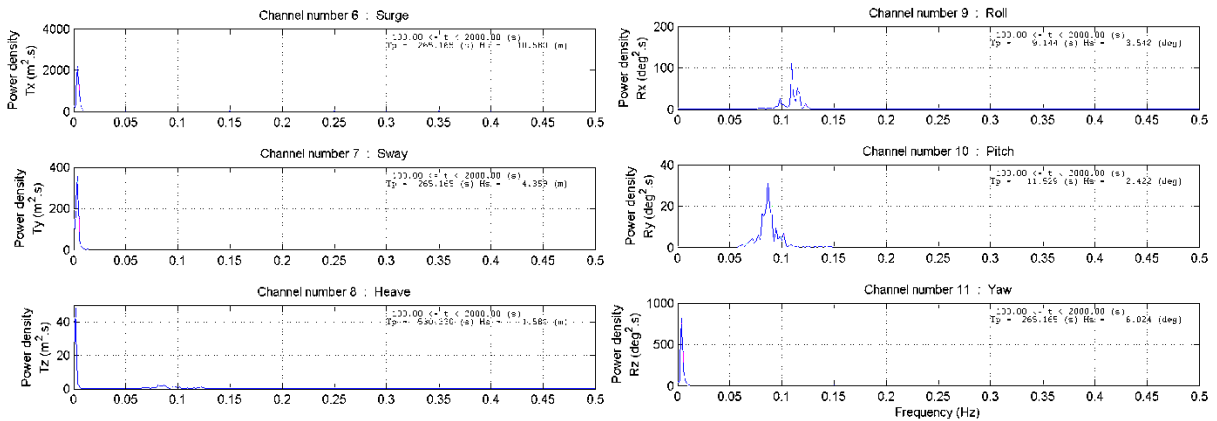


Fig. 8 – Power density spectrum of the ship motions for test number 13

### 3.2. Transfer functions

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:

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

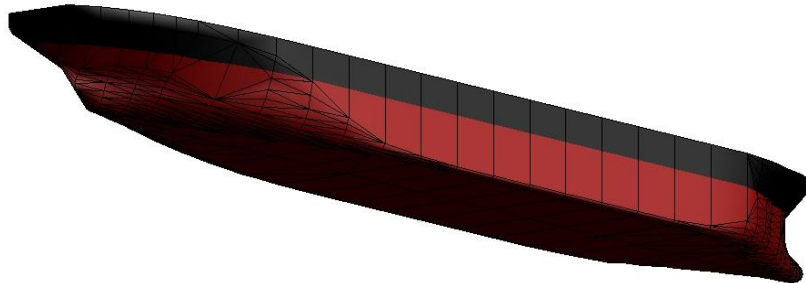
where  $x$  is a degree of freedom (e.g. a vector of rigid body motions) and  $H_{s1}$  is the wave height measured at probe s1. The phase between the excitation and the ship motions are not considered in this work, therefore only the absolute value of the transfer functions is considered:

$$x = [H_{Tx}, H_{Ty}, H_{Tz}, R_x, R_y, R_z] \quad (2)$$

$H_{s1}$  and  $x$  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.

In order to assess the quality of the experimental results, WAMIT numerical model results are also presented. WAMIT (Korsemeier *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. 9. Frequencies ranging from 3.67 Hz to 628.31 Hz were simulated.



**Fig. 9 – Discretization of the ship's hull in panels.**

Fig. 10 to Fig. 15 present the transfer functions (experimental and numerical) for all regular and irregular incident waves for the six ship movements. In those figures, in black, it is presented the transfer functions for a head waves ( $180^\circ$ ), in red, it is presented the transfer functions for beam waves ( $90^\circ$ ) and in green, it is presented the transfer functions for bow waves ( $135^\circ$ ).

For head waves ( $180^\circ$ ), surge, sway and yaw transfer functions obtained experimentally fit very closely the numerically obtained curve. Heave is under predicted compared with the numerical results. Roll has a wide range of RAO for the same frequency but, in average, fits the numerical simulation. Surge, sway and yaw have higher response amplitudes if the waves are irregular. The opposite happens for pitch motion.

For beam waves ( $90^\circ$ ), 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 fairly well with the numerical simulation. Surge, sway and heave have higher response amplitudes if the waves are irregular. For the rotation movements the response is very similar for regular and irregular waves.

For bow waves ( $135^\circ$ ), 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. Surge, sway and heave have higher response amplitudes if the waves are irregular. For the rotation movements the response is lower when the waves are irregular.



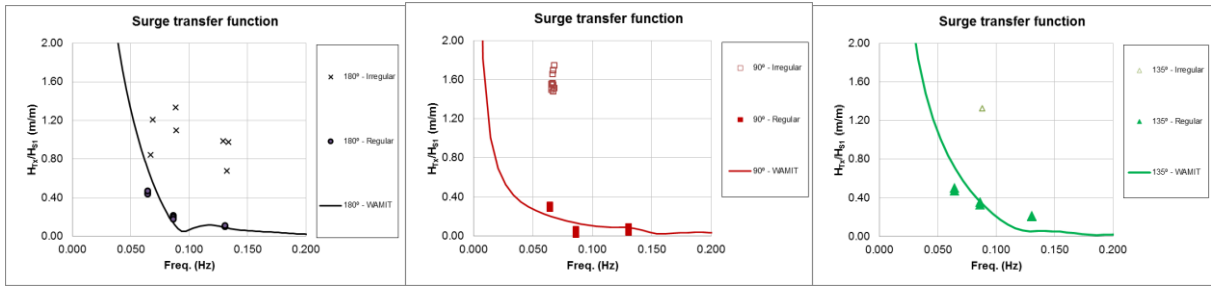


Fig. 10 – Regular and irregular waves SURGE transfer functions

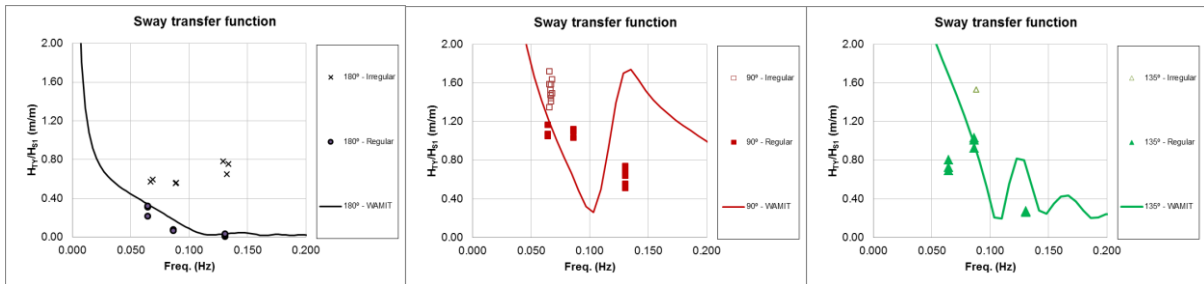


Fig. 11 – Regular and irregular waves SWAY transfer functions

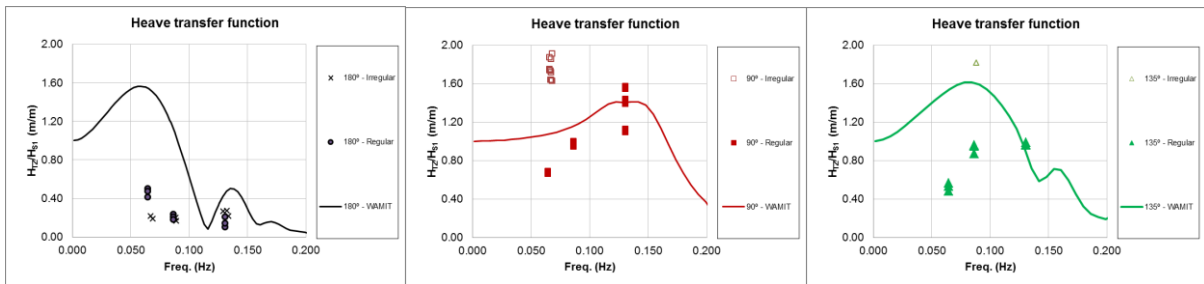


Fig. 12 – Regular and irregular waves HEAVE transfer functions

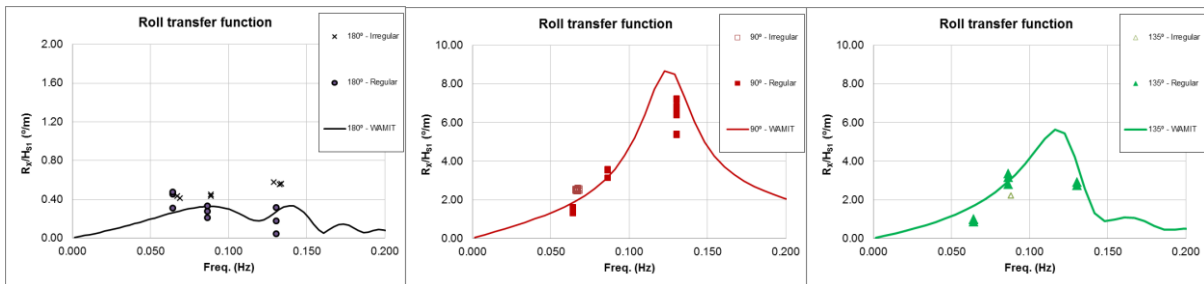


Fig. 13 – Regular and irregular waves ROLL transfer functions

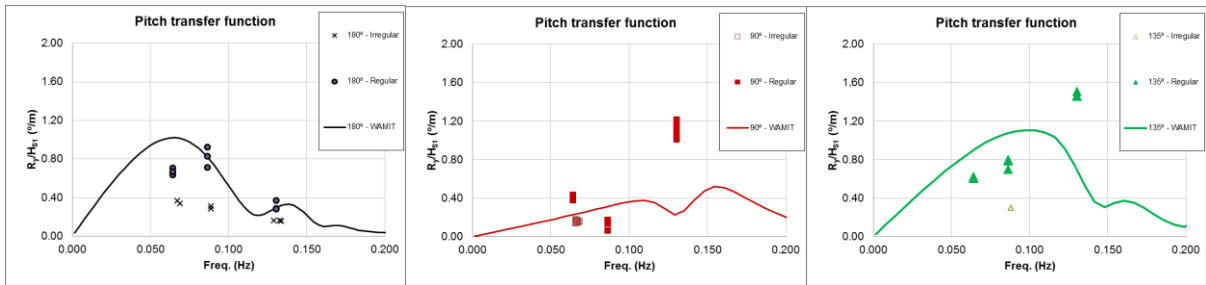


Fig. 14 – Regular and irregular waves PITCH transfer functions

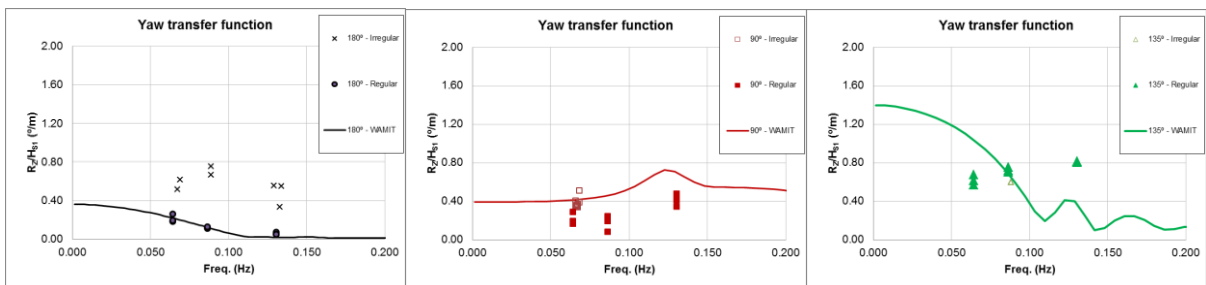


Fig. 15 – Regular and irregular waves YAW transfer functions

Some of the tests were 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	90º	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. Obliquity of waves also leads to less variability of results. In fact, when there is some degree of symmetry (as in the cases of 180° and 90° 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.

In general, translational movements increase in amplitude when the wave field is irregular. Rotation movements however don't seem to change significantly from regular to irregular waves.

Irregular and 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 whereas regular waves and perfect symmetry are very difficult to reproduce in the lab.

The more realistic are the experimental tests, the more likely they are to predict the amplitudes of the movements of the ship.

#### **ACKNOWLEDGEMENTS**

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