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SHIP IMPACT ON FENDERS. NUMERICAL MODEL VALIDATION USING EXPERIMENTAL MODELLING TESTS

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Abstract. To meet safety criteria for the design of docking structures it is essential to characterize the maximum force applied to an individual fender and the force distribution among a set of fenders. Despite impact forces on fenders resulting from complex hydrodynamics of berthing ships, their design is mostly done using simplified approaches that may neglect important physical effects. Physical model tests showed that, in some circumstances the impact forces can be underestimated by commonly used design guidelines. This paper presents the developments made to the numerical modelling of ship impacts on fenders using physical models results to set the numerical model initial conditions. Then, numerical results are compared with experimental measurements to assess its capability of correctly simulate the impact and the magnitude of instantaneous forces exerted on the fenders. Scale-model tests of the impact of the Gulfstream oil tanker on fenders were carried out at LNEC facilities in still water and for a set of different approach conditions. Numerical model simulations were performed with the MOORNAV package to reproduce the physical tests conditions at the prototype scale. MOORNAV initial conditions were set to a best fit of the moment of first impact velocity and angle of approach measured in the physical experiments. A comparative analysis of force distribution on the fenders and ship motions was performed, which showed good agreement on the maximum force and sequence of fenders activation. However, numerical constraints of the model led to a poorly estimation of yaw motion.

Keywords: *Composite modelling, Fenders, GulfStream Ship, Numerical Modelling, Physical Modelling.*

1. INTRODUCTION

Marine fenders provide the necessary interface between berthing ships and berth structures (PIANC, 2002). Their absence can cause damage to either the quay or the ship or both the quay and the ship, endangering lives, and property. Due to the complex hydrodynamics around berthing ships, the characterization of the maximum force applied to an individual fender and the force distribution among a set of fenders is an essential factor in the design and safety of maritime structures and the fenders themselves, as well as for improving existing ones. This paper aims to describe a combining physical and numerical modelling of a ship impact on fenders, in order to improve the numerical modelling of this problem.

Physical modelling represents a good practice in hydraulic studies, where a scale model is used to reproduce complex dynamic phenomena. However, the use of a sophisticated numerical model (or a package of numerical models) can provide a good means to evaluate the same complex physical processes and, in addition, to design and test a large number of alternatives in a short time span.

Both types of models have their strengths and weaknesses (Gerritsen and Sutherland, 2011). Physical models provide a natural reproduction of complex non-linear physical phenomena, therefore they are well established and considered to be truthful. On the other hand, these models can be expensive and time consuming. In addition, one has to deal with the scale effect and measurement difficulties and errors are frequent. Numerical models in turn are very efficient to simulate rapidly many physical processes and the results can be easily extracted. On the other hand, to improve the reliability of their use in practice, it is necessary to calibrate several parameters through physical model measurements and field experiments.

In order to take advantage of the potentiality of the two models emerged the composite modelling which is the integrated and balanced use of physical and numerical models (Gerritsen and Sutherland, 2011). This technique also costs but provides results with a better quality than those model techniques separately and increases the confidence in the use of numerical models.

The physical modeling consists of a ship scaled model, whose impact on the fenders was performed in a wave basin. Various impact velocities and angles between the ship axis and the fenders alignment were used to represent possible collision conditions. The same conditions were reproduced by a numerical package. The numerical modeling was performed using MOORNAV (Santos, 1994), which estimates the ship motions and the forces exerted on the elements of the mooring system, namely mooring lines and fenders.

2. GULFSTREAM SHIP IMPACT ON FENDERS

Fender forces are influenced by a lot of parameters: the configuration of the berthing site, the geometry and the stiffness of the ship's hull, fenders' properties, the speed of approach, the forces exerted by tugs, wind, current and waves, the mode of motion and the keel clearance (Fontijn, 1988).

2.1 Physical Modelling

The ship model (kindly lent by the Centre for Marine Technology and Ocean Engineering) is a 1:100 scaled version of GulfStream oil tanker (Figure 1). The ship model overall length is 172.5 cm, the width is 24.8 cm, the maximum draft is 14 cm and the weight is 13.124 kg.

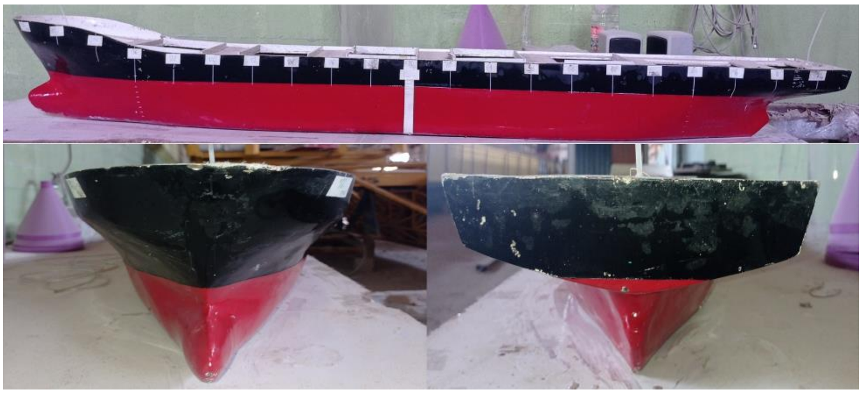


Figure 1. CENTEC scaled version of the GulfStream oil tanker

Physical tests were conducted in an area of 4 m x 4 m of a 22 m x 23 m (width x length) tank of the Ports and Maritime Structures Unit of the Hydraulics and Environment Department of the National Civil Engineering Laboratory (LNEC). The water depth in all tests was 39.5 cm. The mooring system comprises four fenders, equally spaced 40 cm apart, supported by a porous structure.

The ship was manually pushed against the fenders to induce a range of different velocities and ships' headings. Ship’s motions were recorded using an Optitrack® multi-camera motion capture system. A set of markers was placed on the top of the ship and the full body tracking was performed to acquire the motion of the free ship in its six degrees of freedom. From this, velocity and heading are computed at every instant of the test. The impact forces were measured using four force sensors attached to plates and a Quantum MX data-acquisition system with CatmanEasy® DAQ Software. Figure 2 shows the measuring equipment used in the physical tests of the GulfStream oil tanker impact on fenders.

Figure 2 - Physical model setup. Left: GulfStream ship scaled model and force sensors. Right: Optitrack cameras setup.

The physical tests were conducted in still water. Different conditions were performed, namely, the ship’s mass ranging from ballast condition to fully loaded, the ship’s approach heading ranging from strictly parallel to the quay to large angles, and the ship’s approach velocity ranging from normal docking speeds to accidental impacts speed.

The test series were grouped based on the similar docking angles and energy, where the differences between them arise from the human factor slightly influencing the speed and angle of the ship on impact (Table 1). In this paper, only the results for test series T10 is presented, which corresponds to an accidental docking with a small angle of attack and the ship loaded at 3/4 of its maximum capacity. The physical model tests conditions were reproduced by the numerical model according to Froude's similarity.

2.2 Numerical Modelling

The MOORNAV package is an integrated tool consisting of the WAMIT and BAS numerical models. The numerical model WAMIT (Korsemeyer *et al.*, 1988), acronym for WaveAnalysisMIT, is a program based on a three-dimensional panel method which evaluates, in the frequency domain, the radiation and diffraction velocity potentials and the hydrodynamic parameters of the free-floating ship.

The hull's paneling of the GulfStream oil tanker resulted from a 3D scan of the scale-model ship, then converted to prototype scale. Nautical Pre-Processor (Santos, 1994) was used to generate the panels on the hull's surface.

Table 1 – Physical model test conditions.

Loading condition	Docking speed type	Docking angle type	Test series	nº tests
3/4 Loaded	Normal docking	Lateral	1 - 2	10
		Small angle	3 - 4	10
		Large angle	5 - 6	10
	Accidental docking	Lateral	7 - 8	10
		Small angle	9 - 10	10
		Large angle	11 - 12	10
Fully loaded	Normal docking	Small angle	13 - 14	14 to 16
		Large angle	15 - 16	15 to 17
		Stern	17 - 18	15
	Accidental docking	Lateral	19 - 20	16 to 18
		Small angle	21 - 22	15 to 16
		Large angle	23 - 24	16 to 15
Half loaded	Normal docking	Lateral	25 - 26	10 to 15
		Small angle	27 - 28	12 to 14
		Large angle	29 - 30	13 to 15
		Stern	31 - 32	14 to 17
	Smooth docking	Lateral	33 - 34	14 to 16
		Small angle	35 - 36	15 to 17
		Large angle	37 - 38	12 to 14
Ballast	Smooth docking	Small angle	39 - 40	13 to 16
		Large angle	41 - 42	15 to 16
		Stern	43 - 44	15 to 17

The ship's submerged hull was discretized into 279 planar rectangular/ triangular panels and the geometric and inertia characteristics were computed. This information constitutes the main input data for the WAMIT model, along with water depth and the range of periods and incident wave angles to be simulated. The water depth was set at 39.5 m and a range of 89 frequencies and 5 angles were considered. WAMIT computes damping coefficients (Figure 3), added mass coefficients (Figure 4) and response amplitude operators (RAOs).

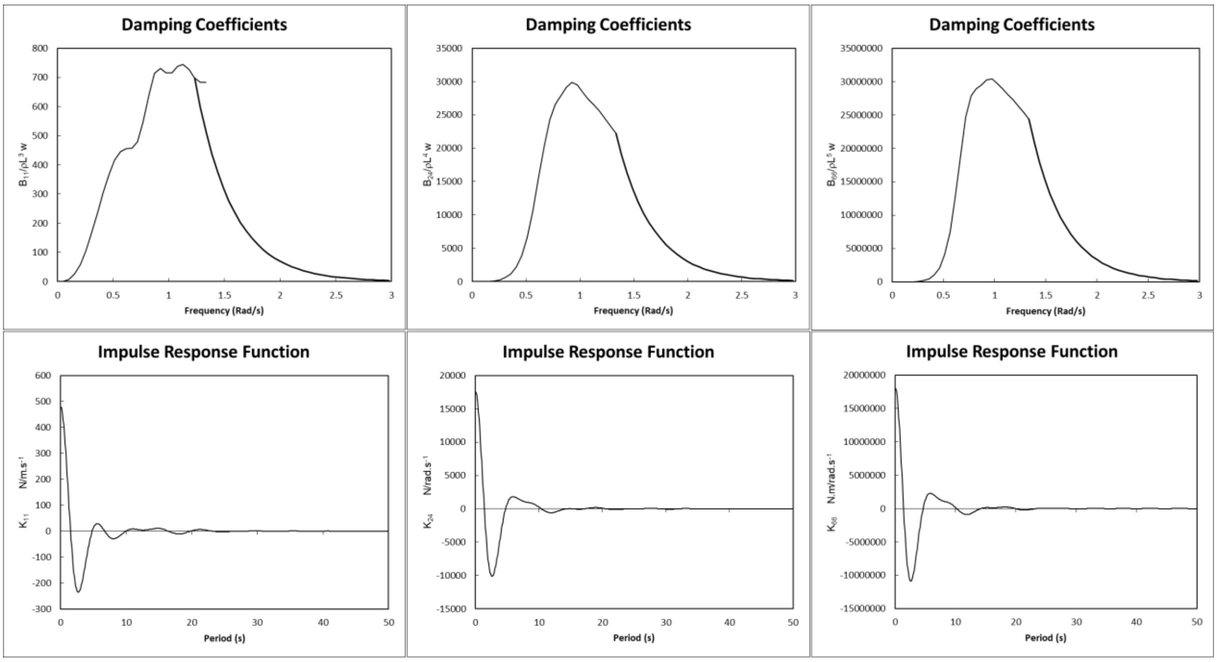
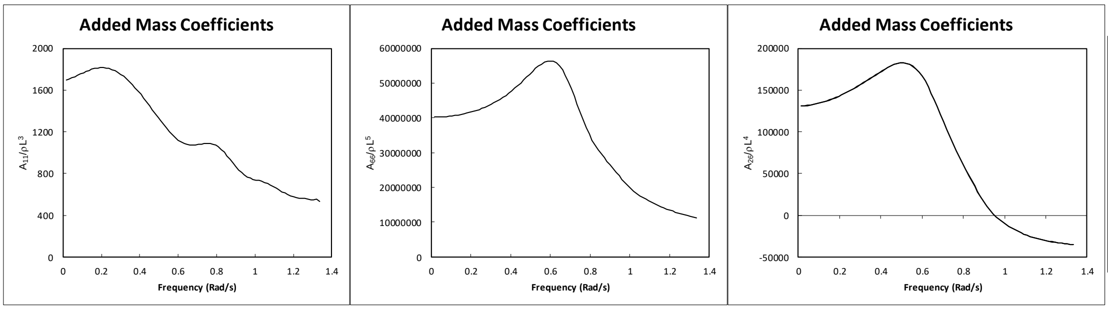


Figure 3 – Damping coefficients and corresponding impulse response functions.



Added mass coefficients for infinite frequency	
A11	800
A13	600
A15	121300
A22	11500
A24	16100
A26	24000
A33	45600
A35	-127500
A44	513000
A46	414000
A55	60900000
A66	21800000

Figure 4 – Added mass coefficients and all the added mass coefficients estimated for infinite mass.

BAS numerical solver solves the motion equations of the ship in time domain (Eq. 1).

$$\sum_{j=1}^{6}\left[\left(M_{kj}+m_{kj}\right)\ddot{X}_j(t)+\int_{-\infty}^{t}K_{kj}(t-\tau)\dot{X}_j(\tau)d\tau+\ C_{kj}X_j(t)\right]=F_k^d(t)+F_k^w(t)+F_k^c(t)+F_k^m(t)+F_k^f(t) \quad (1)$$

where j, k = ship's modes of motion; M_{kj} = ship's inertia matrix; m_{kj} = infinite frequency added-mass matrix; K_{kj} = impulse response matrix; C_{kj} = hydrostatic restitution coefficients matrix; X_j *(t)* = ship’s oscillating motion; F_k^d = incident wave force; F_k^m = Forces on the mooring lines; F_k^f = Forces on the fenders; F_k^w = wind forces; F_k^c = current forces; and t = time.

So, a frequency to time domain conversion is made and corresponding impulse response functions and infinite added mass coefficients are computed for all 6DoF.

The HYDRO routines (Hurdle, 1987 and Schuurmans, 1991) gather all the hydrodynamic matrices and creates a structured file in the convenient format to be used by BAS.

BAS pre-processing routines prepare the time series of the external forces from waves, wind and currents. Finally, BAS computes time series of the ship motions and forces on existing mooring lines and fenders.

For this analysis, no waves or wind were introduced, just a steady flow current, pushing the ship towards the dock. The current force exercted on the ship was calibrated in order to induce a ship velocity equal to the one measured in the physical model in each test.

No mooring lines were introduced, just the 4 fenders with a $\sum_{j=1}^{6}[(M_{kj}+m_{kj})\ddot{X}_j(t)+\int_{-\infty}^{t}K_{kj}(t\text{-}\tau)\dot{X}_j(\tau)d\tau+C_{kj}X_j(t)]=F_k^d(t)+F_k^w(t)+F_k^c(t)+F_k^m(t)+F_k^f(t)$linear compression and a maximum force of 24500 kN for a deflection of 123.5 mm (matching the force sensors characteristics).

3 RESULTS AND DISCUSSION

In this section, physical and numerical results are presented, as well as comparative analysis between the two models' outputs. **Error! Reference source not found.** presents the physical test results of the test series T010, i.e., the ship's center of gravity movements recorded with the Optitrack® system, it's impact forces on fenders measured with the four forces sensors. Additionally, the ship's angle and velocity time-series were calculated and plotted.

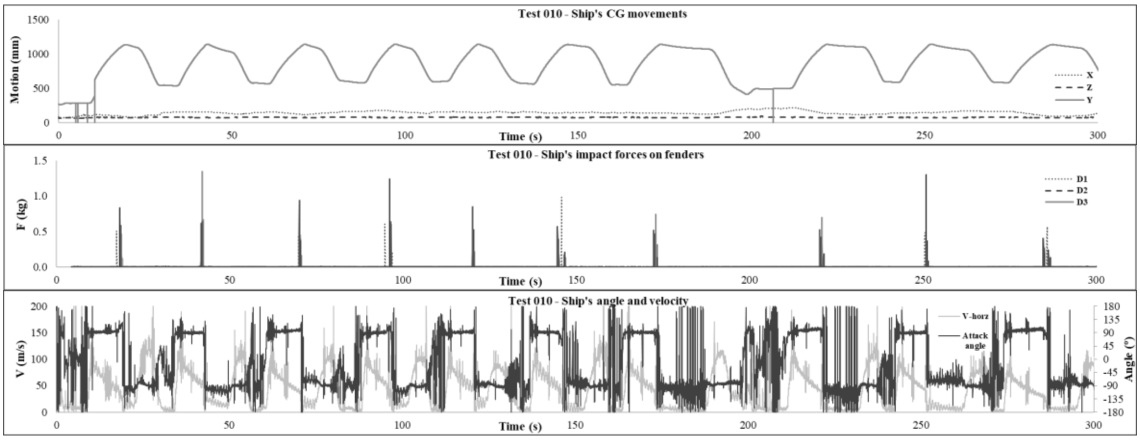


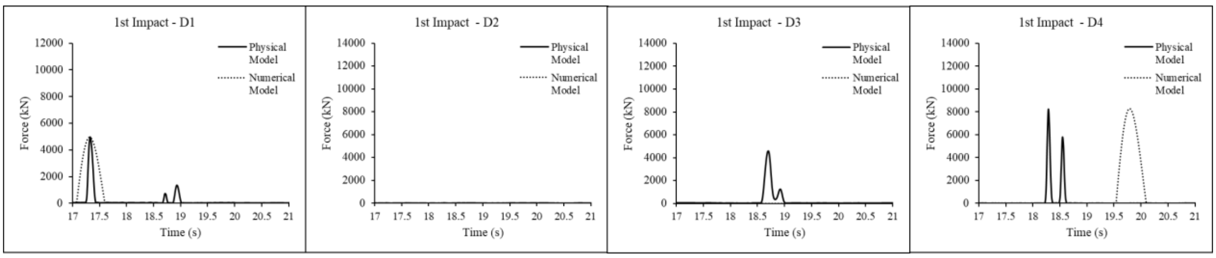
Figure 5 - Physical test series T010 measurements.

T10 is made of 10 repetitions of approximately the same docking impact. The first and last moments of the ship's impact on the fenders were identified, as well as it's intensity and the angle and velocity of the ship on the first moment of the impact.

Error! Reference source not found. presents the physical and numerical impact forces on the four fenders. The timeline of the numeric results was adjusted to coincide with the experimental one.

Numerical modelling has accurately estimated the force exerted by the Gulfstream tanker on the first fender it hits. Nevertheless, it did not accurately reproduce the time lapse between the impacts on different defenses. This can be due to scale effects or a poor representation of the yaw motion (rotation of the ship on the XY plane) due to the fact that a constant current force continues to push the ship after the first impact.

The first four impacts of the physical test series T010 are presented in Figure 5, Table 2 and **Error! Reference source not found.**.



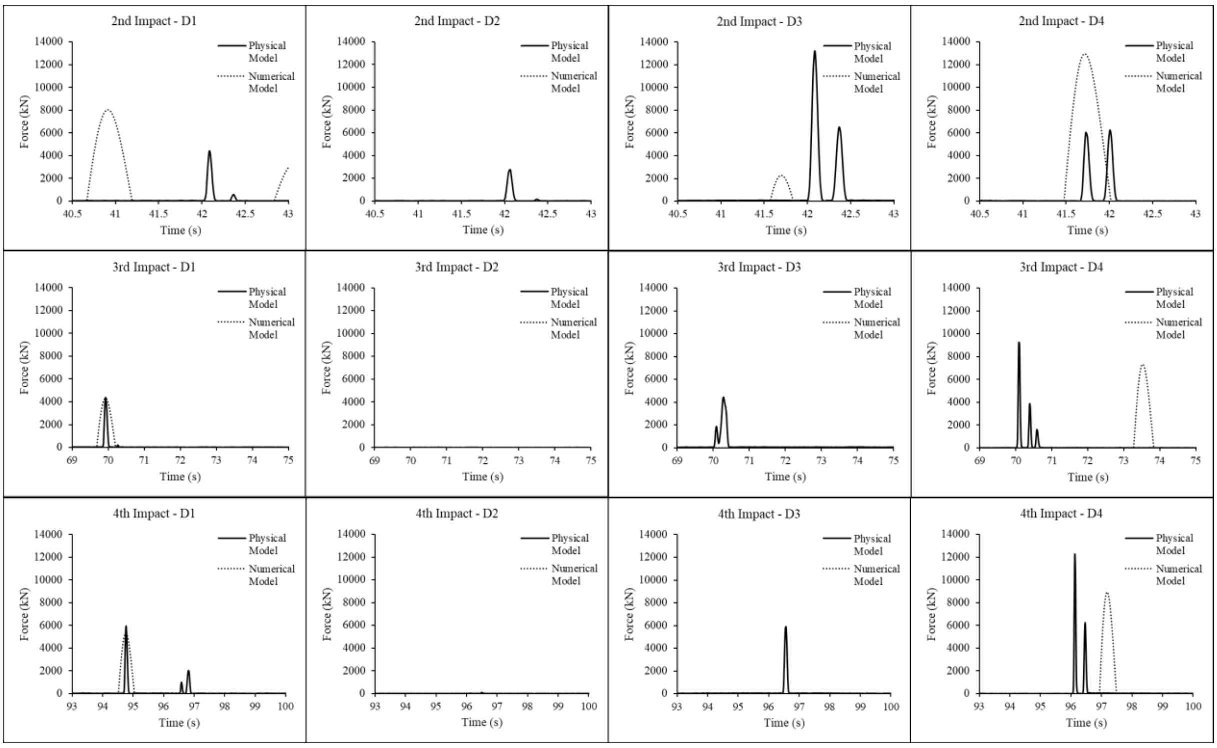


Figure 5 - Physical and numerical first impact of the GulfStream oil tanker on fenders.

Table 2 - Test series T010 physical results (converted to prototype scale).

Impact #	Angle of Attack (°)	Horizontal Velocity (m/s)	1st Impact		Max. Impact		$\frac{(F_{max}-F_1)}{F_1}$ (%)
			F_{max} (kN)	Defense	F_1 (kN)	Defense	
1	90.5	46.2	5070	D1	8370	D4	65%
2	84.4	56.9	4500	D1	13490	D3	200%
3	92.5	42.9	4470	D1	9420	D4	111%
4	90.1	53.4	6060	D1	12440	D4	105%

Table 3 - Test series T010 numeric results (prototype scale).

Impact test #	Angle of Attack		Horizontal Velocity		1st Impact			Max. Impact			$\frac{(F_{max}-F_1)}{F_1}$ (%)
	(°)	Deviation (º)	(m/s)	Deviation	(kN)	Defense	Deviation	(kN)	Defense	Deviation	
1	93.2	2.69	48.4	5%	4959	D1	-2%	8282	D4	-1%	67%
2	87.8	3.42	55.9	-2%	8039	D1	79%	12953	D4	-4%	61%
3	96.3	3.85	42.1	-2%	4325	D1	-3%	7327	D4	-22%	69%
4	93.8	3.70	53.4	0%	5332	D1	-12%	8933	D4	-28%	68%

The velocity of the ship, at the moment of the first impact, is the calibration parameter used, therefor the deviations between numerical results and physical tests are very small (<5%). The impact angle results from the slight deviations that occur during the ship’s trajectory before hitting the defenses (Table 3, **Error! Reference source not found.**). The impact angle deviation is about 3º to 4º, which is an acceptable difference but can nevertheless affect the outcome of the model.

In terms of sequence of impacts, the ship is supposed to dock laterally to the structure and the slight deviation from 90º will be determinant on the order of contact of the fenders. The first impacted fender is fender D1 both on numeric calculations and on physical model. The magnitude of this first impact is well simulated (deviations <12%), except on the test #2 where the deviation is 79% in relation to the physical test.

Regarding the maximum impact, the numerical model captured fairly well the magnitude of it (deviations < 28%) and the corresponding fender. Regarding fender D3, the numerical modelling made it possible to identify a slightly deviated positioning of the fender on the physical model.

The important thing to notice here is the fact that both physical and numerical model showed that the first impact is not the most energetic one. In fact, the second impact, after the rotation of the ship around its z-axis, carries more impact energy than the first one (65 to 200% in the physical tests and 61 to 69% in the numerical tests).

In fact, docking structures design guidelines rely on the calculation of the fist impact force and physical model tests showed that the second impact is more energetic and should be the one considered in design. This work also proved that numerical model is capable of correctly estimate the magnitude of the second impact force, which can be very useful for design engineers.

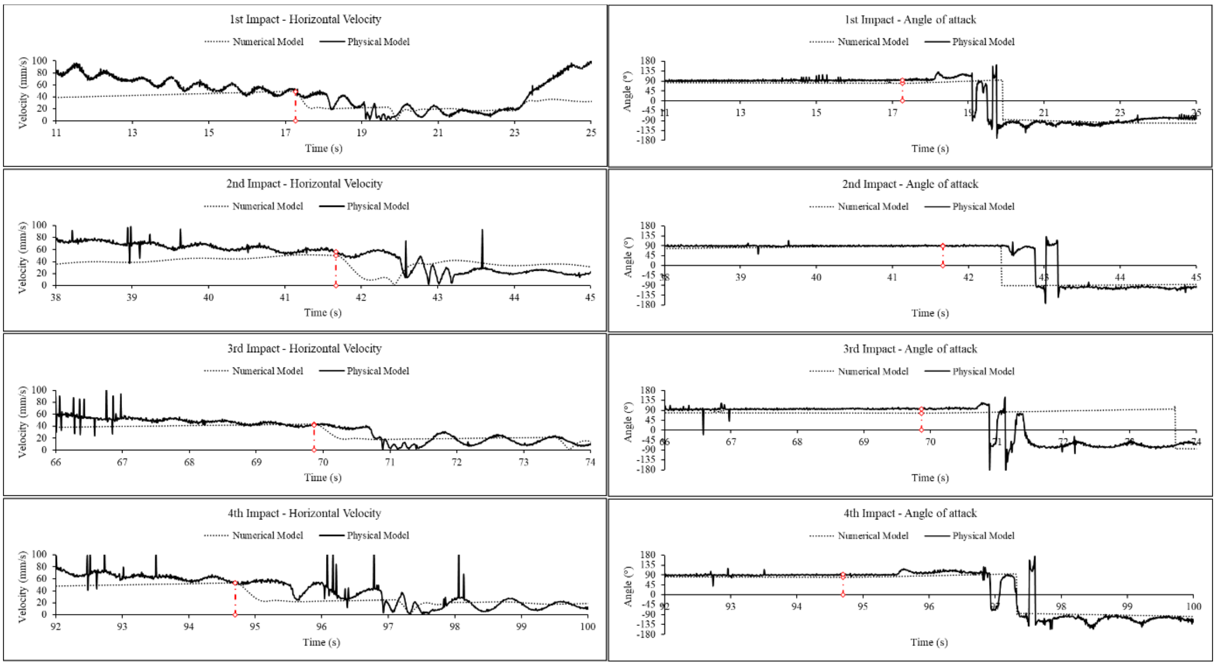


Figure 6 - GulfStream oil tanker impact angle and velocity comparative analysis.

Regarding the time series of the GulfStream ship's motions, horizontal movements, surge, sway and yaw are the most significant movements and the ones that most influence the forces exerted on the fenders. Surge and sway, because it directly determines the speed of the ship motion, and sway because it determines the energy of the second impact.

A comparative analysis was performed. Figure 7 presents the plot of the GulfStream ship sway and yaw motions resulted from both physical and numerical modelling of the first impact. Surge is not depicted because the motion is approximately perpendicular to the dock. In the graphs the first impact instants are marked and the yaw motion graphs have two y-axes, the left one is for the physical modelling results and the right one for the numerical modelling results.

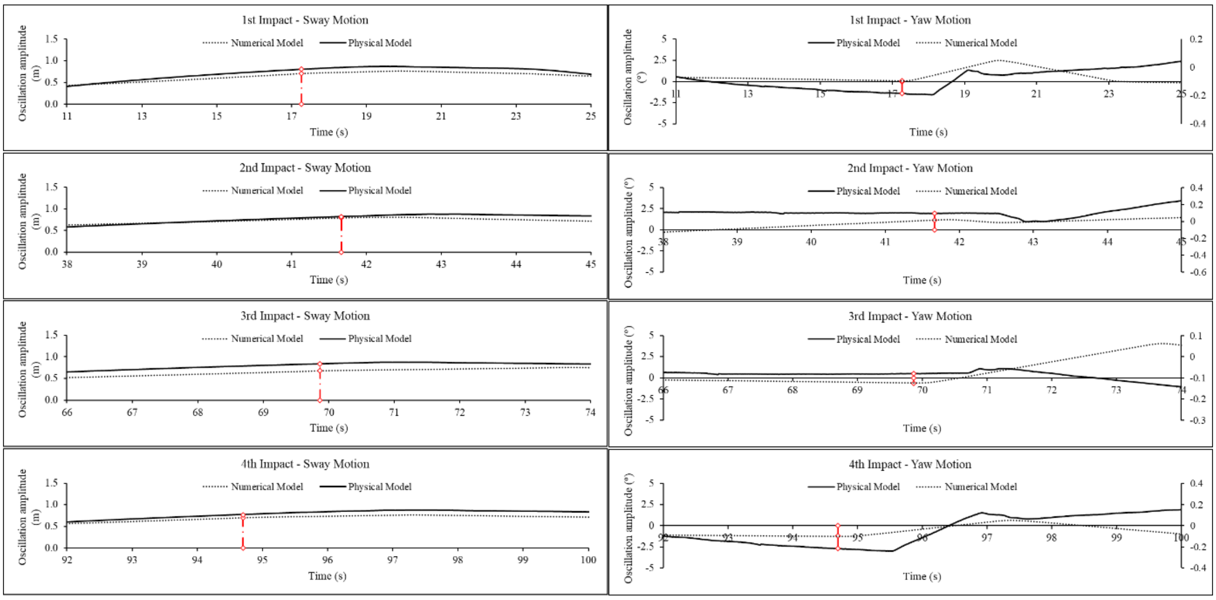


Figure 7 - GulfStream oil tanker sway and yaw motions comparative analysis.

The numerical model was able to provide accurate estimates of the sway motion amplitude but not so much for the yaw motion amplitude.

The discrepancy between the physical modelling and numerical modelling of the Gulfstream oil tanker on fenders can be associated to physical effects that were not accounted for in the numerical modelling such as viscosity. A viscosity calibration can be made in the future to improve numerical results. Another cause can be the current force that is constant and continues pushing the ship towards the fenders, even after the impact occurs. This is an improvement that needs to be addressed in the numerical model, i.e., use an external force source more similar to the human "*push-and-let-go*" used in physical model tests.

Future work will include the numerical simulation and analysis of the remaining physical scale model tests.

4 CONCLUSIONS

A physical modelling of the 1:100 scaled Gulfstream oil tanker was performed in still water to evaluate the forces exerted on fenders by the ship. MOORNAV numerical package was adapted to reproduce some of the physical tests available. Ship's velocity and angle of attack to the dock on the moment of first impact where the calibration parameters.

A comparative analysis between physical and numerical results after the first impact was performed. The order of fenders contacts with the ship and the magnitude of the forces where compared.

The analysis of results allowed a better understanding of the physics of the ship impact on fenders, namely the magnitude of the impact forces, their sequence and the importance of accounting for all possible physical phenomena in the numerical simulations.

This work proved that numerical model is capable of correctly estimate the magnitude of the first and second impact forces, which can be very useful for design engineers. Both physical and numerical model showed that the second impact carries more energy than the first, with force magnitude going 60 to 200% higher than the first impact, suggesting that docking structures design guidelines should take this effect into account.

Further developments on this docking impact investigation must be performed to improve and validate further the numerical modeling of ship impacts on fenders.

Acknowledgements

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