ON THE ASSESSMENT OF SHIP SQUAT AND VERTICAL WAVE MOTIONS FOR DTC CONTAINER CARRIER IN SHALLOW WATER IN A REAL TIME MANEUVERING SIMULATOR

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SUMMARY

The accurate prediction of ship squat and vertical wave motions is important to assess ship underkeel clearance in shallow water and to define the maximum draft (or the minimum depth) for a safe navigation. Although the real-time ship maneuvering simulators are not the most adequate tool to the vertical design of the nautical access, they are used to check the vertical maneuvering margin and to execute tests with the aid of pilots and captains to verify the proposed nautical layout. Therefore, the simulators must have reasonable and realistic models of vertical movements, considering the limitations imposed by the real-time calculation. This paper presents the mathematical models for vertical motions (squat and wave motions) adopted in the Brazilian simulator SMH, and a comparison with benchmark data from (Van Zwijnsvoorde et al., 2019), comprising model tests conducted with the DTC container carrier.

NOMENCLATURE

B	Vessel's beam (m)
C_B	Vessel's block coefficient
C_S	Coefficient of ICORELS regression
F_S	Equivalent squat force (N)
F_{nh}	Froude number $(adim.)$
g	Gravitational acceleration (m/s^2)
h	Water depth (m)
k	wave number $(1/m)$
K_{ij}	Hydrostatic restoring matrix
L_{pp}	Vessel's length between perpendiculars (m)
$S_{s,b}$	Stern / Bow squat (m)
x_3	Vessel's vertical displacement (m)
x_5	Vessel's pitch angle (rad)
Z VA	Running sinkage at aft perpendicular (mm)
Z VF	Running sinkage at fore perpendicular (mm)
∇	vessel's displacement (ton)
λ	wavelength (m)
ω	wave frequency (rad/s)
ω_e	wave encounter frequency (rad/s)
CONAPRA	Brazilian Maritime Pilots Association
DTC	Duisburg Test Case (container carrier)
RAO	Response Amplitude Operator
SMH	USP Maritime and Waterways Simulator
TPN	Numerical Offshore Tank Laboratory
USP	University of São Paulo

1 INTRODUCTION

The accurate prediction of ship squat and wave motions is important to assess ship underkeel clearance in shallow water. The dimensions of the new large containerships operating in ports are beyond the design ship of these locations, which require advanced analysis and simulations to improve the navigation safety and efficiency. The limiting environmental conditions (due to waves and tide) for safe navigation are obtained from accurate mathematical models of vertical forces and motions. These models are based on potential flow and on the discretization of the fluid domain, requiring high computer processing capacity. A very large number of tides, drafts and waves are simulated offline to define the operational window and/or safe draft for navigation. Another approach that is becoming more usual today is the dynamic underkeel clearance systems, that execute the mathematical model on demand, based on the present ship and measured environmental conditions.

The real-time ship maneuvering simulators are a complementary tool to the vertical design of the nautical access. They are used to test the vessel's maneuverability in restricted areas and to check the maneuvering margin (minimum vertical margin required to guarantee the maneuverability of the vessel). However, they are not adequate tools for a comprehensive verification of the underkeel clearance and safety margins in relation to vertical movements, because the tests are performed in real time and few maneuvers can be done, do not covering all the variability of directions, periods and wave heights that may occur at the study site. Furthermore, the mathematical models must be executed in real time, imposing barriers to the level of sophistication and computational requirements. However, the simulators must have reasonable models of vertical movements, because of the dependence that the underkeel clearance exerts on the maneuverability of the vessel.

This paper presents the mathematical models for vertical motions (squat and wave motions) adopted in the Brazilian simulator SMH (Portuguese acronym for Maritime and Waterways Simulator). The results from the simulator are compared to the benchmark data from (Zwijnsvoorde et al., 2019), comprising model tests conducted with the DTC container carrier. The comparison is used to discuss the validity of the adopted models.

The SMH has been developed by the Numerical Offshore Tank Laboratory of the University of São Paulo (TPN-

USP), Petrobras (Brazilian oil state company), with a technical partnership with the Brazilian Maritime Pilots Association (CONAPRA). The SMH is the core simulation software adopted in the TPN-USP Maneuvering Simulation Center, composed by 6 simulators, being 3 of them classified as full-mission (immersive system with more than 270° angle of projection). All simulators can run together in the same run (multiplayer simulation). Some simulators are shown in Figure 1.

Figure 1. TPN-USP Maneuvering Simulation Center

The SMH has been used for a large number of port analysis in Brazil, as shown in (Tannuri and Martins, 2018). The complete mathematical formulation and physical fundaments of the SMH models are presented in (Queiroz Filho et al., 2014; Tannuri et al., 2014).

2 WAVE FORCES AND MOTIONS

The calculation of the wave forces considers the second order drift components (mean and slow varying drift forces) and the first order high frequency (HF) components separately. The second-order drift coefficients and first-order Hasking Forces are obtained by the potential theory, with the hypothesis of zero advance speed. This approximation is valid for low-speed maneuvering, and its utilization for vessels with advance speed is associated with errors that will be estimated in this paper. The simulator is able to import the hydrodynamic coefficients from different commercial codes, such as Wamit. In the case of shallow waters, the domain of the Wamit model must contains the sea bottom, normally assumed as flat.

The HF motion comes from the application of the wave first order forces to the 6 DOF equations of motions (Pinkster, 1980) (Faltinsen, 1993). The exciting forces are computed by sub-dividing the sea spectrum in hundreds of components with random uneven frequency ranges and random phases. Combining (summing up) these components, we define the irregular incident wave. These components combined with the exciting force RAO in each degree of freedom will define the exciting wave forces. These exciting forces are computed only as a function of the incident wave, so they do not double count with other non-potential effects.

The added mass and damping effects are taken into consideration through the convolution of the IRF (impulse response functions) obtained from the frequency domain hydrodynamic coefficients (added mass or potential damping) and the past motions of the ship. These IRF functions are computed under the assumption of an impulsive velocity applied to the floating bodies. The IRF functions are convolved with the past velocities of the body. Only oscillatory motions will give rise to added mass and damping forces, corresponding to an energy balance between the body motions and the waves radiated due to these ship oscillations. They are function only of the past motions of the ship, and properly include the effect of the waves radiated due to these past oscillations (Oortmerssen, 1976).

The (Aranha and Fernandes, 1995) approximation to the quadratic transfer functions is applied to the calculation of the slow drift wave forces. Wave-drift damping effects (current-wave interaction) are also considered, following the formulation presented by (Aranha, 1994).

The effect of the advance speed is partially considered in the model adopted in the SMH simulator. The relative velocity between the ship and the wave cause a modification in the wave encounter frequency (ω_e). Therefore, a correction in the incident wave spectrum must be done, in which the wave frequency is replaced by the encounter frequency, while still maintaining the wave total energy.

For the specific case of this paper of a regular wave with frequency ω (rad/s), bow incidence and ship advance U (m/s), the encounter frequency is given by:

$$\omega_e = \omega + k.U \tag{1}$$

Where $k = 2\pi/\lambda$ is the wave number, λ is the wavelength (m) in shallow water obtained from the dispersion relation:

$$\lambda = \frac{2\pi g}{\omega^2}\tanh\left(\frac{2\pi h}{\lambda}\right) \tag{2}$$

being g the gravitational acceleration (m/s^2) and h the depth (m).

3 SQUAT FORCE

The SMH adopts a squat vertical force model based on the ICORELS regression, outlined in the PIANC Working Group 30 Report. Although it is developed only for open or unrestricted channel, we assume as a simplified formulation for all cases. The bow squat S_b (m) is given by:

$$S_b = C_S \frac{\nabla}{L_{pp}^2} \frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}} \tag{3}$$

Being L_{pp} the vessel´s length between perpendiculars (m), ∇ the displacement (ton), the dimensionless $F_{nh} = U/\sqrt{gh}$ and:

$$C_S = \begin{cases} 1.7 & C_B < 0.7 \\ 2.0 & 0.7 \leq C_B < 0.8 \\ 2.4 & C_B \geq 0.8 \end{cases} \tag{4}$$

We have to obtain an equivalent vertical force (F_S) applied on the vessel that will result in a bow squat S_b (m) as given in (3). We assume the hypothesis that the force is applied in the center of gravity of the vessel. Being x_3 the vertical displacement at the center of gravity (positive upwards), x_5 the pitch angle (positive when the bow enters the water) and K_{ij} the terms of the hydrostatic restoring matrix, and disregarding coupling with other displacements, we can write:

$$\begin{pmatrix} F_s \\ 0 \end{pmatrix} = \begin{pmatrix} K_{33} & K_{35} \\ K_{35} & K_{55} \end{pmatrix} \begin{pmatrix} x_3 \\ x_5 \end{pmatrix} \rightarrow$$
$$\begin{pmatrix} x_3 \\ x_5 \end{pmatrix} = \begin{pmatrix} K_{33} & K_{35} \\ K_{35} & K_{55} \end{pmatrix}^{-1} \begin{pmatrix} F_s \\ 0 \end{pmatrix} \tag{5}$$

The bow (b) and stern (s) squat is given by

$$S_b = -x_3 + \frac{L_{pp}}{2} x_5$$
$$S_s = -x_3 - \frac{L_{pp}}{2} x_5 \tag{6}$$

With (5) and (6) we can obtain the equivalent vertical force (F_s) that results, after a transient, into the desired bow squat given by (3).

4 COMPARISONS WITH EXPERIMENTAL TESTS

In this section, the results obtained with the SMH simulator are compared to experimental data from towing tank tests in calm water and in waves presented in (Zwijnsvoorde et al., 2019) . The objective is to verify the reliability of the prediction and the expected deviations.

The tests were executed using a 1:89.11 scale model of the 14,000TEU containership DTC (Table 1), in the Towing Tank for Manoeuvres in Shallow Water (cooperation FHR and UGent).

Table 1. Ship particulars

Particular	Full Scale	Model Scale (1:89.11)
L_{pp} (m)	355	3.984
B (m)	51	0.572
Draft (m)	14.5	0.163
C_B	0.661	0.661
∇	171,800ton	242.8kg

Two sets of captive tests are reproduced in the SMH simulator and compared with the experimental results, including calm water tests (C1, C2, and C3) and tests in waves (CW1 to CW5). During captive tests the ship is fixed in the horizontal plane (surge, sway and yaw), allowing roll, pitch and heave. The hull forces are measured using load cells and the ship's heave, trim and roll are measured by using potentiometers.

All numerical simulations were executed in the free-running mode, because the SMH does not provide the possibility of doing a numerical captive test. In the simulations, a longitudinal external force is applied at the midship and adjusted to deliver the final speed equal to the experimental captive test. After speed stabilizations, the squat, wave motions and resistance forces were compared.

4.1 CALM-WATER TESTS

The results of the tests C1, C2 and C3 in calm water are presented in Table 2. The maximum difference for the bow squat (Z VF) is -6%, what is quite acceptable. However, due to the simplifications of the squat model adopted in the simulator, the stern squat (Z VA) differences are larger (up to 38%). We must remember that the ICORELS regression only provides the value of the bow squat, and the stern squat results from the hypotheses adopted in the model of the simulator. The resistance force is well represented in the simulator, with differences smaller than 4%.

Table 2. Tests in calm water – comparison between experimental and simulation results

C1 V=6kn (0.327m/s model scale), UKC 100%

	Exper.	Simul.	Dif. (%)
Z VF mm	0.88	0.91	3%
Z VA mm	0.58	0.44	-24%
Z MidShip mm	0.73	0.67	-8%
Resistance N	0.80	0.82	2%

C2 V=16kn (0.872m/s model scale), UKC 100%

	Exper.	Simul.	Dif. (%)
Z VF mm	8.34	7.81	-6%
Z VA mm	5.01	3.64	-27%
Z MidShip mm	6.68	5.72	-14%
Resistance N	5.82	6.08	4%

C3 V=6kn (0.327m/s model scale), UKC 20%

	Exper.	Simul.	Dif. (%)
Z VF mm	1.56	1.58	1%
Z VA mm	1.26	0.78	-38%
Z Midship mm	1.41	1.18	-16%
Resistance N	1.09	1.09	0%

4.2 TESTS IN WAVES

4.2 (a) 100% UKC

The Case CW1 represents a stationkeeping test, with no advance speed and 100% UKC. The Table 3 shows that the vertical motion amplitude is slightly overestimated by the simulator model, mainly for the aft point. The comparisons are based on the period in which the captive model test could be considered in a stationary oscillation (from 50s to 100s). Since the average ZVF and ZVA is close to zero, the difference in terms of percentage would be a meaningless high value, which is not calculated. Figure 2 shows the time series of the vertical motion.

The longitudinal force due to wave action (generically refereed as Resistance) is also well estimated by the simulator, as indicated in Table 3 and in Figure 3.

Table 3 .Test CW1 (in waves, no advance speed) – comparison between experimental and simulation results

CW1 UKC 100%, model scale: V=0m/s, Wave H=54.49mm 1.38s full scale: V=0kn, Wave H=4.85m 13.03s			
	Exper.	Simul.	Dif (%)
ZVF amp. mm	20.91	22.27	6.5%
ZVF aver. mm	0.20	-0.07	-
ZVA amp. mm	10.77	13.34	23.9%
ZVA aver. mm	-0.05	0.04	-
Resistance X amp. N	23.46	21.56	-8.1%
Resistance X aver. N	-0.77	-0.81	4.7%

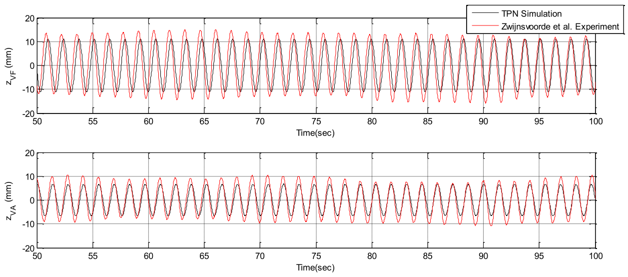

Figure 2. Vertical motion at the forward and aft points – CW1 test

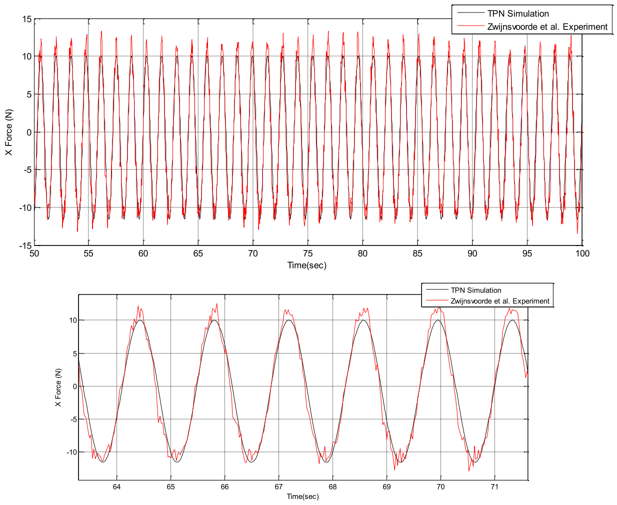

Figure 3. Longitudinal force – CW1 test (up): complete time series – 50s ; (down) detail – 8s

In the case CW3, the carriage is moving with 0,872m/s (16 knots in real scale) and the vessel is subjected to a bow incident wave with the same period of the previous test, and a height slightly larger. The results are presented in the Table 4.

The amplitude of the motions is smaller than that of the no advance speed test (CW1), what can be partially explained by the higher encounter frequency (apparent period in model scale 0.89s, real scale 8.4s). The average sinkage is also in agreement with the results from C2 test (same speed, no waves), since the squat effect is the main responsible for it. Figure 4 shows the time series of the vertical motion. The resistance force is reasonably well estimated by the simulator, as can be verified in Figure 5.

Table 4. Test CW3 (in waves, advance speed) – comparison between experimental and simulation results

CW3 UKC 100% model scale: V=0.872m/s, Wave H=62.35mm 1.38s full scale: V=16kn, Wave H=5.56m 13.03s			
	Exper.	Simul.	Dif (%)
ZVF amp. mm	20.94	22.32	7%
ZVF aver. mm	8.10	7.99	-1%
ZVA amp. mm	17.33	17.93	3%
ZVA aver. mm	5.40	3.92	-27%
Resistance X amp. N	-18.60	-20.00	8%
Resistance X aver. N	-7.31	-7.43	2%

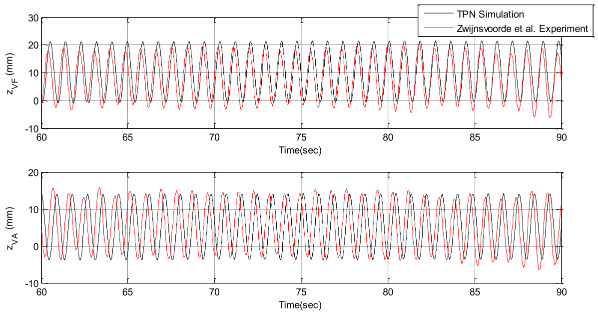

Figure 4. Vertical motion at the forward and aft points – CW3 test

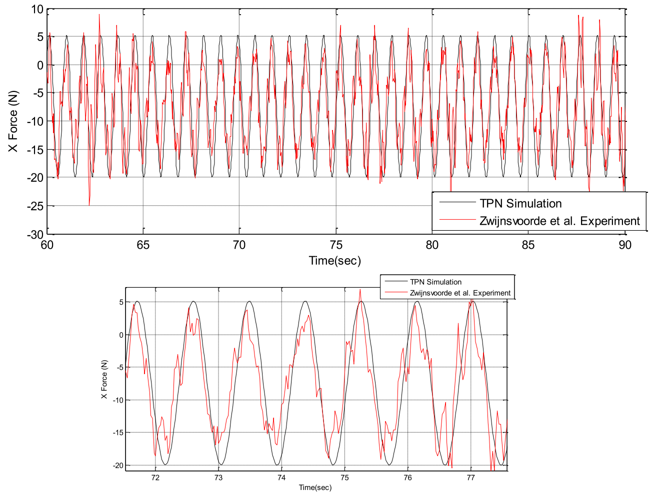

Figure 5. Longitudinal force – CW3 test (up): complete time series – 30s ; (down) detail – 6s

The case CW2 is a blind test, with no experimental ship motions presented by Van Zwijnsvoorde et at. (2019). The results obtained by the simulator model are presented in

Table 5, Figure 6 (vertical motion) and Figure 7 (resistance force).

Table 5. Test CW2 (in waves, advance speed) –simulation results

CW2 UKC 100%
model scale: V=0.327m/s, Wave H=62.31mm 1.38s
full scale: V=6kn, Wave H=5.55m 13.02s

	Simul.
ZVF amp. mm	28.76
ZVF aver. mm	1.35
ZVA amp. mm	23.61
ZVA aver. mm	0.62
Resistance X amp. N	26.10
Resistance X aver. N	-1.73
Apparent Period s	10.79s (real scale) 1.14s (mode scale)

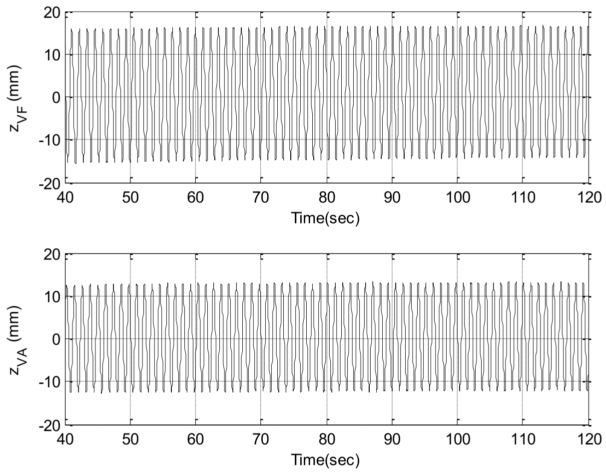

Figure 6. Vertical motion at the forward and aft points – CW2 test

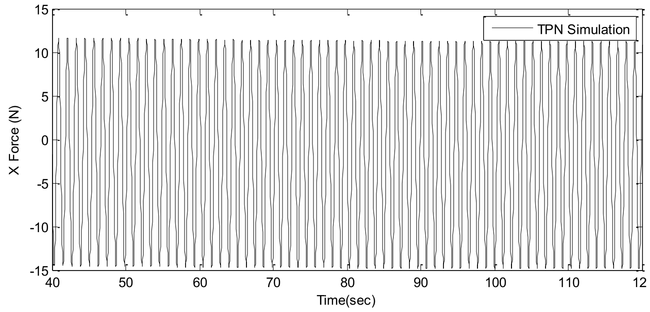

Figure 7. Longitudinal force – CW2 test

4.2 (b) 20% UKC

The Case CW4 represents a stationkeeping test, with no advance speed and 20% UKC. Table 6 shows the comparison between experimental and numerical results. Figure 8 shows the time series of the vertical motion. The longitudinal force due to wave action is shown in Table 6 and in Figure 9. In this case, the simulator underestimated the bow amplitude by 18%.

Table 6. Test CW4 (in waves, no advance speed) – comparison between experimental and simulation results

CW4 UKC 20%,
model scale: V=0m/s, Wave H=54.49mm 1.38s
full scale: V=0kn, Wave H=4.85m 13.03s

CW4 V=0kn, UKC 20%	Exper.	Simul.	Dif (%)
ZVF amp. mm	9.19	7.53	-18%
ZVF aver. mm	0.04	-0.01	-
ZVA amp. mm	6.55	8.11	24%
ZVA aver. mm	-0.06	0.01	-
Resistance X amp. N	10.17	10.57	4%
Resistance X aver. N	-0.07	-0.18	-

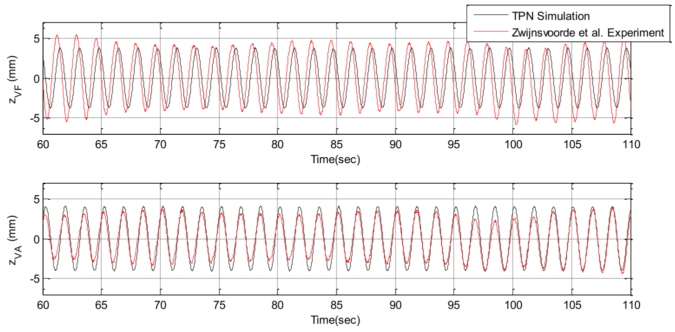

Figure 8. Vertical motion at the forward and aft points – CW4 test

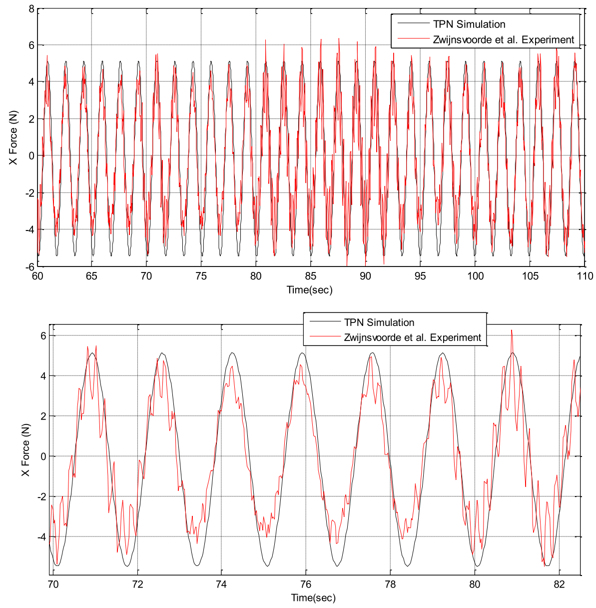

Figure 9. Longitudinal force – CW4 test (up): complete time series – 50s ; (down) detail – 6s

The case CW5 is a blind test. The results obtained by the simulator model are presented in Table 7, Figure 10 (vertical motion) and Figure 11 (resistance force).

Table 7. Test CW2 (in waves, advance speed) –simulation results

CW2 UKC 20% **model scale: V=0.327m/s, Wave H=21.36mm 1.66s** **full scale: V=6kn, Wave H=1.90m 15.67s**	
	Simul.
ZVF amp. mm	9.01
ZVF aver. mm	1.55
ZVA amp. mm	10.48
ZVA aver. mm	0.66
Resistance X amp. N	11.04
Resistance X aver. N	-1.12
Apparent Period s	12.55s (real scale) 1.33s (mode scale)

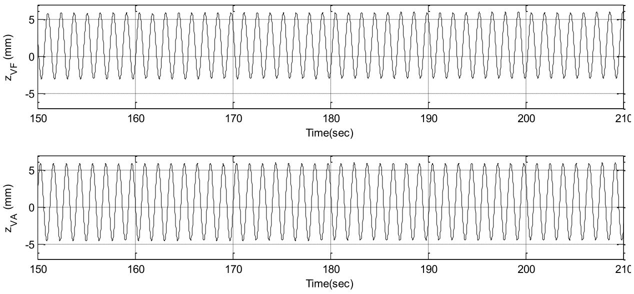

Figure 10. Vertical motion at the forward and aft points – CW5 test

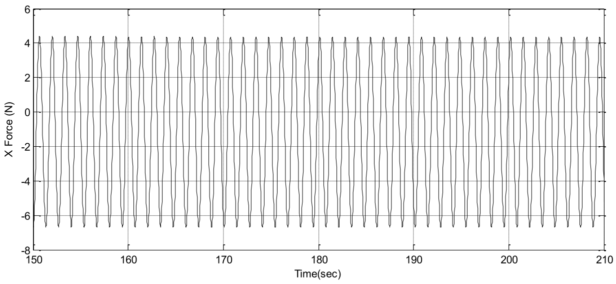

Figure 11. Longitudinal force – CW5 test

5 CONCLUSIONS

The paper carried out the comparison between experimental results and numerical results from the SMH real time maneuvering simulator, regarding the vertical movements of a container vessel. We evaluated cases with or without advance speed (6 and 16 knots) in shallow waters (20% and 100% UKC), subjected to bow waves or in calm waters.

The results showed that the models adopted in the maneuvering simulator are adequate to represent the maximum bow sinkage of the vessel due the squat, with maximum differences of 6%. For the cases with waves, there is an acceptable adhesion among the results, in spite of the simplifications used in the mathematical model implemented in the simulator. The differences between the amplitude of motion in the bow (which shows greater movement) reach 18%.

The stern squat predicted by the model is less accurate, with a difference up to 38% (calm water tests) and 24% (amplitude in wave tests). The squat model adopted in the simulator is based on a vertical force applied in the center of gravity of the ship. The force is adjusted so that the bow squat is equal to the ICORELS regression (base model). The model must be improved to better predict the stern squat. A possible solution, still keeping the necessary simplicity for a real time simulator, is a better definition of point of application of the vertical force. Another approach is the utilization of a more comprehensive base model that predicts both the bow squat and trim, such as the Ankudinov model (Briggs et al., 2013). In this case, a vertical force and pitch moment must be applied in the ship to induce the squat and trim of the Ankudinov model.

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8 AUTHOR BIOGRAPHY

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