THE SEAWORTHINESS OF A TRAINING SHIP "NAŠE MORE" IN HEAVY SEAS

Srđan Vujičić[1], Tamara Petranović[2], Marko Katalinić[3], Joško Parunov[2]

[1] *University of Dubrovnik, Maritime Department, Dubrovnik, Croatia*

[2] *Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia*

[3] *Faculty of Maritime Studies, University of Split, Split, Croatia*

[*] *Corresponding author: srdjan.vujicic@unidu.hr; Tel.:* +385-98-948-2589.

Abstract: Safe navigation depends on many factors, such as the maneuverability and stability of the ship, the nature of the waterway, the sea state and other external factors and, above all, the seamanship of the mariner. Therefore, it is necessary to analyze the movement of the ship in different conditions. The seakeeping analysis is usually done by model tests and/or calculations during the design stage, while full-scale measurements in real conditions are very rare. This paper presents the full-scale measurement of a training ship motion in heavy seas as part of a research project entitled "Modelling Uncertainty of Ship Wave-Induced Response in the Adriatic Sea (MODUS)", fully supported by the Croatian Science Foundation. The experiment was performed on the training ship "Naše more" in the port of Dubrovnik. The wave height ranged from 4ft to 6ft with SE wind. The waves came from the direction of 180 ° to 183°. The wave buoy SPOTTER was used to collect the data on the movement and height of the waves. The ELLIPSE2-N-G4A2-B1 sensor recorded the ship's behavior and was placed on the bridge.

Keywords: ship motion experiment; six motion components; Spotter buoy; Ellipse2

---

1. Introduction

Safe navigation through channels, straits, the open sea, and oceans and the avoidance of dangerous situations at sea depend on many factors, such as the maneuverability and stability of the ship, the nature of the waterway, the sea state, and other external factors and, above all, the seamanship of the mariner. The collision risk assessment and the decision-making process to prevent collisions at sea are based on the criteria of maritime rules and the experience and knowledge of the officers (Vujičić et al. 2018, Vujičić et al. 2017). The technological advances made the forecast charts and data quite reliable, but some elements important for the safety of navigation may deviate, though. Such elements are the current height of the wave in foul weather and the ship's motion, which even the most experienced officer cannot predict. The interaction between currents and waves must be taken into consideration as it leads to change in wave height and period. Analysis and prediction of environmental conditions should be performed to calculate the environmental loads acting on ships to increase the ship's operability (DNV GL 2017). It is, therefore, necessary to collect all the information available on-board the ship and analyze it for future modelling. Various data collected and stored on board ships could be used for scientific purposes (Vujičić et al. 2020). The simulation of a ship's motion is a fundamental task for ship simulators used as training or studying tools (Varela 2011). The conditions in the simulator should be as real as possible as compared to those at sea. Thus, this is an excellent tool that can improve the simulator software. For all these reasons, it is crucial to know the actual ship motion in each sea area and weather condition. For a more reliable knowledge of the ship's motion at certain wave heights and in a specific area, it is necessary to collect all relevant data and information in real time. Ships must be able to withstand the loads at sea. Thus, it is important to analyze the degrees of freedom and a ship's response to rough seas. In general, uncertainties in modelling a ship's response to rough seas and the uncertainties in numerical calculations can be eliminated by processing the data collected from ships and drawing new conclusions. Furthermore, artificial intelligence can increase the operability of the ship, optimize waterways, help decide how to maneuver the ship in adverse weather conditions, be useful in the design for any shipbuilding project based on reliability methods, and contribute to greater safety of navigation. The paper is part of the research project "Modelling Uncertainty of Ship Wave-Induced Response in the Adriatic Sea - MODUS" and is a dimensional measurement of the research ship motion in rough seas. The purpose of this particular test was to see how ships with similar characteristics to the one used in this trial would react to rough seas. This test is especially useful for the ships that operate on the route between Croatia and Italy. The trial showed how the ship would react to heavy weather, particularly applicable to the route between Croatia and Italy and along the Croatian coast. This data facilitates voyage planning, i.e. helps to the captain to decide whether it is possible to reach the destination safely. In addition, the data obtained is useful for ship simulator providers as the direct implementation of these findings improves the simulator software used for training, practice and voyage planning in a virtual reality environment. The main equipment used for this experiment is the solar-powered floating buoy SPOTTER and Inertial Measurement Unit - ELLIPSE2. The Spotter is a solar powered wave buoy used to explore wave-driven dynamics and can be used as a moored or a free drifting configuration (Raghukumar et al. 2019). The correlation analysis performed by Houghton et al. showed that the Spotter buoy provides data with very low errors (Houghton et al. 2021). ELLIPSE2 is a sensor that records the roll, pitch, and heave movements as well as GNSS position. The investigation carried out by Lüer (2020) showed that it is a very accurate system. This study is a follow-up to previous research carried out by Katalinić et al. (2022), and Matić and Katalinić (2020). They focused on measuring the wave-induced motion of a sailboat in small to moderate waves in relation to its size. The present study is motivated by current efforts in industry and the research community to quantify and reduce the uncertainties in modelling the waves and wave-induced responses (Bitner-Gregersen, E.M. (2022)). The intention is to facilitate many risk-based seakeeping applications, such as ship operability analysis and extreme wave load calculation (Petranović, T. et al. (2021)), heavy weather manoeuvring (Papanikolaou, A. et al. (2014) and Bitner-Gregersen, E.M. & Skjong, R. (2008)), and weather routing (Dong, Y., Frangopol, D. M. & Sabatino, S. (2016) and Prpić-Oršić, J. (2016).

The article is structured as follows: after the introduction, the description of the methodology and equipment used for the experiment are presented in Section 2. The results of the measurements are presented in Section 3 together with the statistical analysis using the STATREL software. Finally, the last section provides conclusions and plans for future research.

2. Methodology

Full-scale measurements of the wave-induced responses of the training ship "Naše more" (LOA 31.35m, beam 7.4m, drafts 2.180m F and 3.485m A) were carried out in the Dubrovnik Pilot station area from 09:30 to 13:28 hours. A free drifting half submerged buoy SPOTTER with a weight of 5.5 kg and a diameter of 38 cm was used to record waves in real-time every 0.4 seconds and reported its GPS location to the user every hour via satellite. The ELLIPSE2 sensor was used to measure the wave-induced ship motion. The Spotter buoy transmitted the real-time data to a laptop and alerted the team to buoy movement. IMU ship sensor provides roll, pitch, heading, heave, and centimetric GNSS position. The experiments were conducted on 05 November 2021. Measurements of ship response were made for 4 different heading angles (with respect to the main wave direction of 180°, 183°) 000°, 180°, 325°, 135° in the area where the Pilot boarding ground is located. The angles of approach 000°, 180°, 35°, and 225° were determined, whereby 35° corresponds to 325° due to the symmetry, while 225° corresponds to 135°. Each measurement trial lasted 30 minutes, and the sailing speed was 5±0.2kn in the first, third, and fourth measurement trials, while it was 4±0.2kn in the second trial. While the ship response measurements were taken, a floating buoy simultaneously measured the waves in the same area where the ship was sailing.

3. Results

The heave and pitch time series were measured at four different heading angles (Euler angle). For illustration and because of the highest ship responses, only the measurements at a heading angle of 180° are shown (Figures 2-3). Simultaneously with the measurement of heave and pitch, a floating buoy was used in the same sea region to record the wave elevation shown in Figure 1, and it can be seen that the largest amplitude of the wave was 1.27 m. Figures 2 and 3 show that at the end of the measurement trial, the highest heave amplitude was 1.72 m, and the largest pitch amplitude was 7.05°.

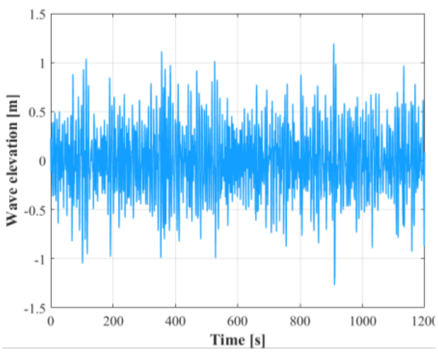

Figure 1. Wave elevation

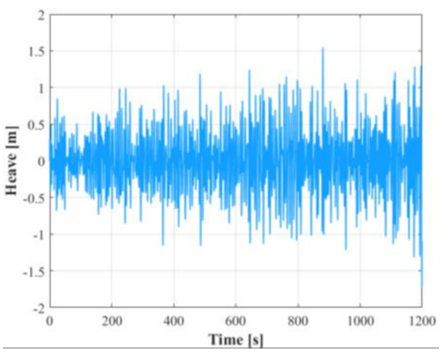

Figure 2. Heave measurements at heading angle of 180°

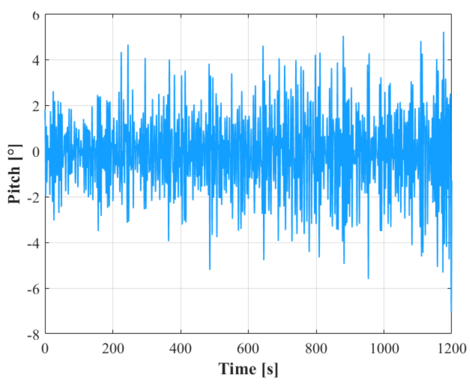

Figure 3. Pitch measurements at heading angle of 180°

The statistical analysis of the heave, pitch, and wave time series is performed using the STATREL software, an auxiliary program in the STRUREL system (STRUREL 2007). STATREL is a tool that allows basic analyses of statistical data and their graphical representation. The time series analysis application in STATREL includes several tools for data manipulation and a set of estimation methods. In addition, STATREL allows some basic transformations of the original time series to perform the relevant spectrum analysis.

Basic statistical descriptors of three time-domain signals are provided in Table 1.

Table 1. Basic statistical descriptors of the measured time series

Statistical property	Wave el., m	Heave, m	Pitch, °
St. deviation	0.342	0.391	1.463
Min.	-1.270	-1.723	-7.051
Max.	1.240	1.546	5.212
Skewness	0.041	0.066	0.022
Kurtosis	3.184	2.996	3.256

From Table 1 it can be seen that the pitch and heave motions, as well as the wave surface elevation, are nearly Gaussian processes since the skewness is approximately zero and the kurtosis is around 3, which corresponds to the values of the normal probability distribution.

In STATREL, the Husid function can be used to determine whether a random process is stationary (Katalinić 2021). The Husid Function is defined as the integral over the square of the process, which represents the energy development of the fluctuating process X(t) with a mean value of zero:

$$Husid(t) = \int_0^t X^2(\tau)d\tau, 0 \leq t \leq T_d \quad (1)$$

where Td is the duration of the observation (STRUREL 2007).

For a stationary process, the Husid function is a curve that slightly oscillates around a straight line. Figures 4 and 5 show the Husid function of wave amplitudes and heave. The Husid function of wave amplitudes tends more toward a straight line than the Husid function of pitch. The reason for this lies in the fact that the waves were measured by a free-floating buoy, and the pitch was measured on-board ship advancing at a forward speed. Consequently, the process of the wave elevation satisfies a condition of the statistical stationarity better than the ship's motion.

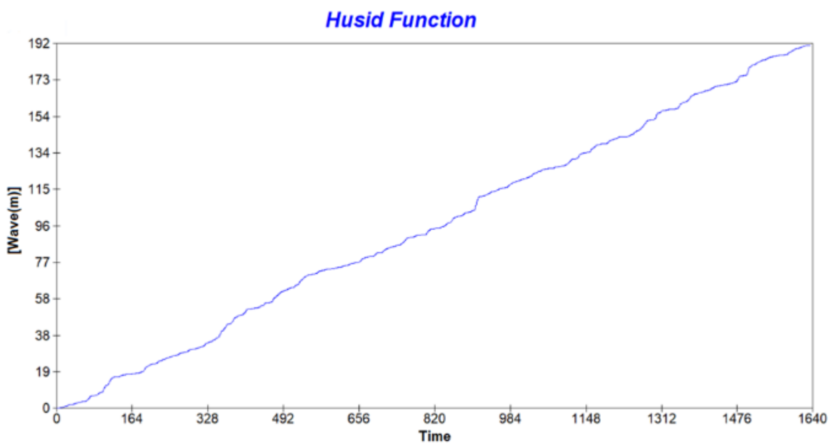

Figure 4. Husid function of wave elevation

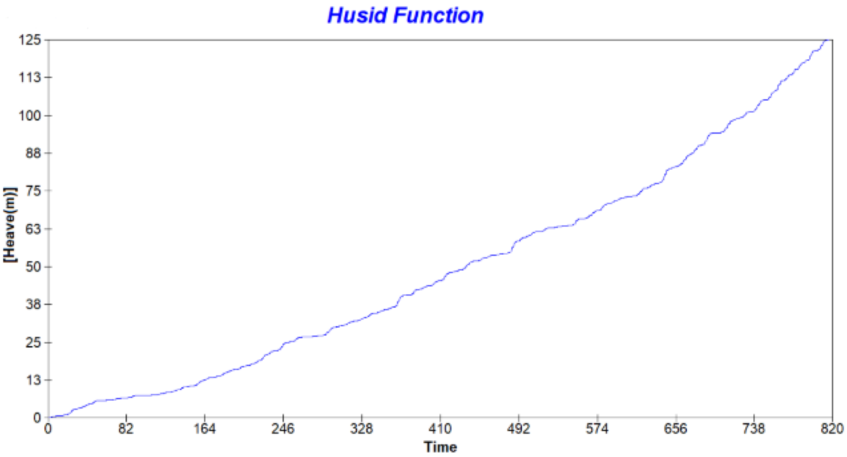

Figure 5. Husid function of heave

The energy spectrum in STATREL is calculated as the Fast Fourier transform (FFT) of the auto-correlation function. The energy spectra obtained for the time series of wave elevation, heave and pitch are shown in Figures 6 - 8. The wave spectrum presented in Figure 6 is measured by the freely floating buoy, and response spectra presented in Figures 7 and 8 were measured on-board ship progressing with forward speed.

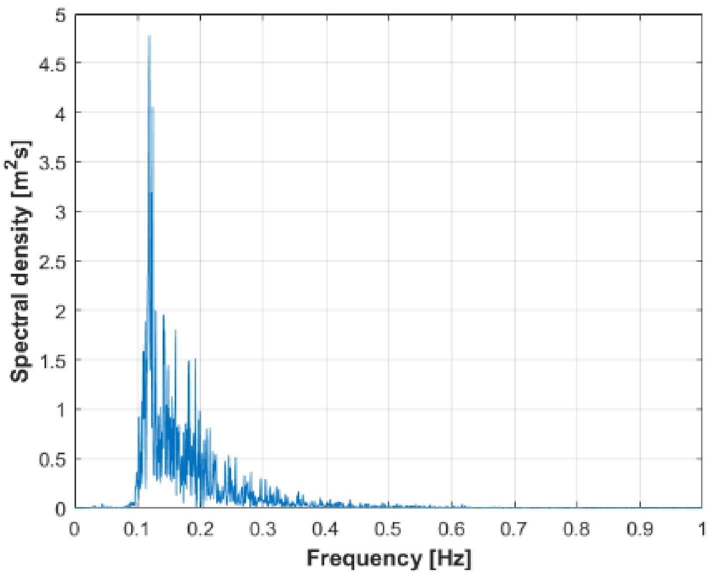

Figure 6. Wave energy spectrum for time series presented in Fig. 1

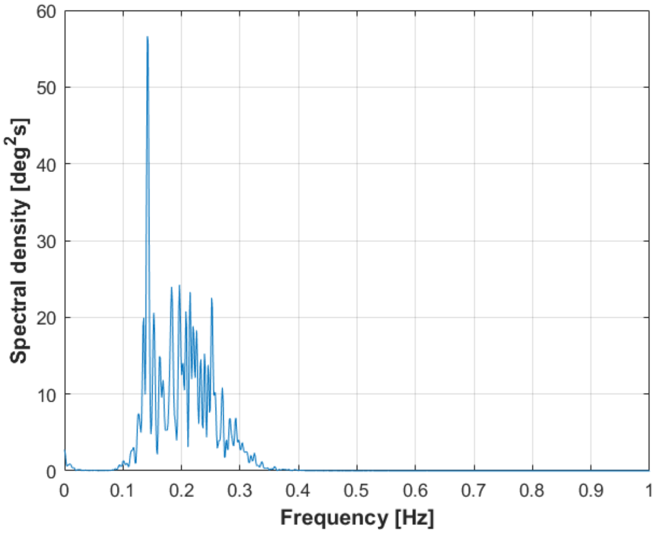

Figure 7. Energy spectrum of pitch for time series presented in Fig. 3

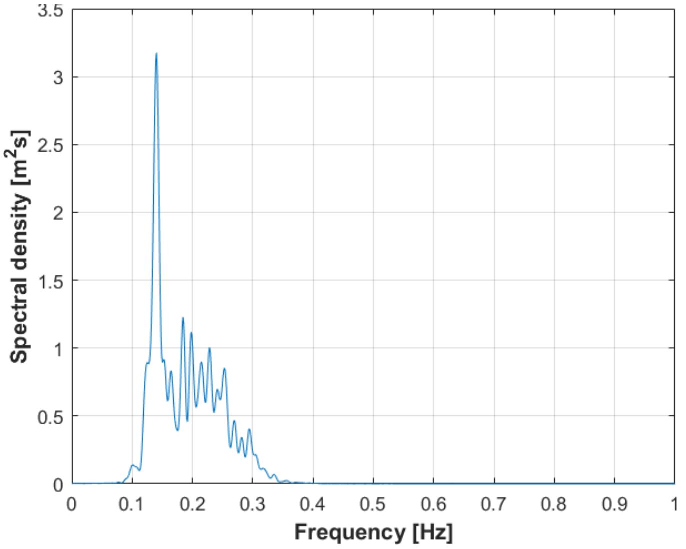

Figure 8. Energy spectrum of heave for time series presented in Fig. 2

The integrals of the energy spectra in Figures 6-8 can be used to derive the spectral characteristics of the random wave process. Table 2 shows a comparison of the standard deviations and mean zero-crossing frequency of three random processes based on measurements and spectral analysis. Table 2 shows that the compatibility of the standard deviations is excellent, despite minor variations in the mean zero up-crossing frequency. These inconsistencies appear as a result of the "smoothing" of the wave energy spectrum and the resulting integration error of the second spectral moment, as explained in the STATREL theoretical manual (STRUREL 2007). These small differences in the mean zero up-crossing frequency have no practical significance.

Table 2. Comparison of statistically and spectrally defined characteristics of random process

Statistical property	Wave elevation		Heave		Pitch	
	measured	spectral	measured	spectral	measured	spectral
Standard deviation, m	0.342	0.342	0.391	0.391	1.463	1.461
Mean zero up-crossing frequency, Hz	0.201	0.207	0.195	0.201	0.203	0.209

4. Conclusion

This paper presents the full-scale measurement of the wave-induced ship response of the training ship “Naše more” in the Adriatic Sea, namely in the port of Dubrovnik approach area. The advantage of this method is that the testing was conducted in real sea waves. It lasted four hours and during this time the ship was on different courses and wave heights. The 4-hour voyage proved that the SPOTTER buoy and the ELLIPSE2 sensor were reliable in rough seas and met the requirements of this experiment. The movements of the ship, i.e. the heave and pitch motions, were observed with the direction and wind speed as well as wave height at four different heading angles. The pitch and heave motions, and the wave surface elevation are almost Gaussian processes as the range of skewness and kurtosis indicate the normal probability distribution. The STATREL software was used for the statistical analysis of the heave, pitch, and wave time series as well as for their energy spectra. Based on this experiment, the wave-induced ship motions in the port-approach channel can be predicted with reasonable accuracy. Standard seakeeping theories assume a linear relation between varying wave spectrum and the respective ship response spectrum. This relation, the square of the transfer function between wave and ship response at different frequencies usually referred to as RAO (response amplitude operator), that is deducted from the presented full-scale experiment can thus be applied also for different sea states that the ship will sail in. Moreover, the measured results can be used to validate the results obtained by standard seakeeping calculations and to estimate their accuracy for the vessel at hand.

Future research should focus on the comparison between the measured wave spectra in sheltered and deep-sea waters. The measurements of coastal waves should be compared with the ship response in deep seas and obtain the results that would help reduce the seakeeping uncertainties.

Acknowledgements

This work has been fully supported by Croatian Science Foundation under the project lP-2019-04-2085.

References

[1] Bitner-Gregersen, E.M. & Skjong, R. 2008. Concept for a risk-based navigation decision assistant. Marine Structures 22: 275-286.

[2] Bitner-Gregersen, E., Waseda, T., Parunov, J., Yim, S., Hirdaris, S., Ma, N. & Guedes Soares, C. (2022) Uncertainties in long-term wave modelling. Marine Structures, 84, 103217, 21 doi:10.1016/j.marstruc.2022.103217.

[3] DNV GL 2017. Recommended practice DNVGL RP C-205: Environmental conditions and environmental loads. Det Norske Veritas Germanischer Lloyd.

[4] Dong, Y., Frangopol, D. M. & Sabatino, S. 2016. A decision support system for mission-based ship routing considering multiple performance criteria. Reliability Engineering & System Safety 150: 190–201.

[5] Houghton, A., Smit, P.B., Clark, D., Dunning, C., Fisher, A., Nidzieko, N.J., Chamberlain, P., Janssen, T.T. (2021) Performance Statistics of a Real-Time Pacific Ocean Weather Sensor Network, Journal of atmospheric and oceanic technology, Volume 38, Issue 5, April, 2021. available at: DOI: 10.1175/JTECH-D-20-0187.1

[6] Katalinić, M., Matić, P. Petranović, T., Parunov, J., (2022) Full-scale measurements of ship motion in rough seas in the Adriatic Sea, accepted for publication in proceedings of MARSTRUCT 2022

[7] Lüer J. Design and Development of a Measurement System to Track the Motion of a Point Absorber [Internet] [Dissertation]. 2020. (ELEKTRO-MFE). Available from: http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-416222

[8] Matić, P. & Katalinić, M. 2020. Artificial neural network boat seakeeping model based on full scale measurements. ICTS 2020 Maritime, transport and logistics science conference proceedings: 226-230, September 17-18, Portorož, Slovenija

[9] Papanikolaou, A., Alfred Mohammed, E. & Hirdaris, S.E. 2014. Stochastic uncertainty modelling for ship design loads and operational guidance. Ocean Engineering 86: 47-57.

[10] Petranović, T., Mikulić, A., Katalinić, M., Ćorak, M. & Parunov, J. 2021. Method for prediction of extreme wave loads based on ship operability analysis using hindcast wave database. Journal of Marine Science and Engineering 9(9): 1002

[11] Prpić-Oršić, J., Faltinsen, O.M. & Parunov, J. 2016. Influence of operability criteria limiting values on ship speed. Brodogradnja 67: 37-58.

[12] Raghukumar, K., Chang, G., Spada, F., Jones, C., Janssen, T., Gans, A. Performance Characteristics of ‘‘Spotter,’’ a Newly Developed Real-Time Wave Measurement Buoy (2019), Journal of atmospheric and oceanic technology, Volume 36, April 2019. available at: 10.1175/JTECH-D-18-0151.1

[13] Raghukumar, K., Chang, G., Spada, F., Jannsen, T., "Directional Spectrum Measurements by the Spotter: a new Developed Wave Buoy" (2019). Ocean Waves Workshop. 1.

[14] STRUREL 2007. STATREL: User's manual, Statistical analysis

[15] Varela. J., Guedes Soares, C., Interactive Simulation of Ship Motions in Random Seas based on Real Wave Spectra. Conference: GRAPP 2011 - Proceedings of the International Conference on Comput Graphics Theory and Applications, Vilamoura, Algarve, Portugal, March 5-7, 2011

[16] Vujičić, S., Mohović, R. i Đurđević Tomaš, I. (2018). Methodology for Controlling the Ship's Path during the Turn in Confined Waterways. Pomorstvo, 32 (1), 28-35. Available at: https://doi.org/10.31217/p.32.1.2

[17] Vujičić, S., Mohović, Đ. i Mohović, R. (2017). A Model of Determining the Closest Point of Approach Between Ships on the Open Sea. Promet - Traffic&Transportation, 29 (2), 225-232. Available at: https://doi.org/10.7307/ptt.v29i2.2197

[18] Vujičić, S., Hasanspahić, N., Car, M. & Čampara, L. (2020) Distributed Ledger Technology as a Tool for Environmental Sustainability in the Shipping Industry. Journal of Marine Science and Engineering, 8 (5), 366, 14 doi:10.3390/jmse8050366