Experimental Evaluation of the Dynamic Behavior of an Autonomous Multifunctional Buoy

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ABSTRACT: A multi-functional near-shore autonomous 2m-diameter buoy has been developed with the HORIZON Project SUN-BIO. The buoy incorporates a hybrid wave energy system combining wave, solar and thermal energy generation for versatile ecological monitoring contexts. Details of the system are provided in the referenced publication. The hydrodynamic performance of the system was experimentally evaluated via model tests. A 1/4 scaled model of the buoy was manufactured and tested in regular and random waves at the towing tank of Ship and Marine Hydrodynamics Laboratory (LSMH) at the National Technical University of Athens (NTUA). The dynamic performance of the model was evaluated at the design drafts, in regular waves in the range of periods 2 to 6 sec and a realistic sea state with significant wave height HS = 1 m and modal periods of TP = 3 & 5 sec, corresponding to moderate to heavy weather conditions at the physical size of the buoy. The mooring system of the buoy has been precisely simulated in the model tests. Its efficiency is estimated. The results encompass the heave and pitch motions, as well as the vertical and lateral accelerations of the model in waves.

1 INTRODUCTION

Modern research confirms that over 80% of marine pollutants originate from land-based sources, reaching the sea through rivers, urban runoff, and atmospheric deposition. Sea pollution is now a cornerstone of international sustainability, notably through UN Sustainable Development Goal 14, which targets the reduction of all marine pollution by 2030 (UN). Sequentially, accurate monitoring of the oceanographic and meteorological conditions, water temperature and local seabed topography is becoming a necessity.

However, the harsh sea environment increases dramatically the cost and the complexity of data harvesting (Woodall et al., 2018). Therefore, many researchers are trying to develop standalone platforms with integrated sensors capable of long-term habitat monitoring (Aguzzi et al., 2019, 2020; Masmitja et al., 2025).

In our case, an Offshore Hybrid Renewable Energy System (OHRES) which incorporates a Wave Energy Converter (WEC) alongside solar and thermoelectric harvesting subsystems is introduced. The proposed platform will be deployed in a near shore sea area near Barcelona in Spain and during its operation as a floating and moored structure it will be used as a prime station arrangement embodying Sustainable and Nature Inclusive Offshore Energy for monitoring and protecting the flourishing Biodiversity in that area. The station should be amenable to the relatively adverse weather and wave sea environment pertaining in the specific area.

The scope of this work was to experimentally investigate the dynamic behavior of the proposed design in the pre-described sea environment that the prototype is going to encounter during its life span.

For this purpose, a 1:4 scaled model of the system has been manufactured, installed in the wave tank along with its mooring arrangement and has been tested in the Towing Tank of the Laboratory for Ship and Marine Hydrodynamics (LSMH) of the National Technical University of Athens (NTUA), under the action of monochromatic and natural long-crested wave trains generated by the wave making apparatuses. The anchoring and mooring system was designed to develop minimal underwater radiated noise during motion to promote habitat evolution. Moreover, all the materials selected in the design, has negligible effect in the environment with life-cycle of many years. For the anchoring a corrosion-resistance concrete mix is proposed to ensure durability with minimal environmental impact. Anti-corrosive stainless steel wire ropes with in plastic shell develop minimum noise during motion compared to chains, while withstanding high loads.

2 MODEL DESCRIPTION

A 1/4th scaled buoy model, with diameter of 0.5m, height of 0.212m and actuator hole of 0.15m has been designed and constructed at the LSMH facilities of NTUA (Table. 1). The main dimensions of the buoy are illustrated at Figure 1. The model was designed in the commercial software Rhinoceros5 (Rhinoceros).

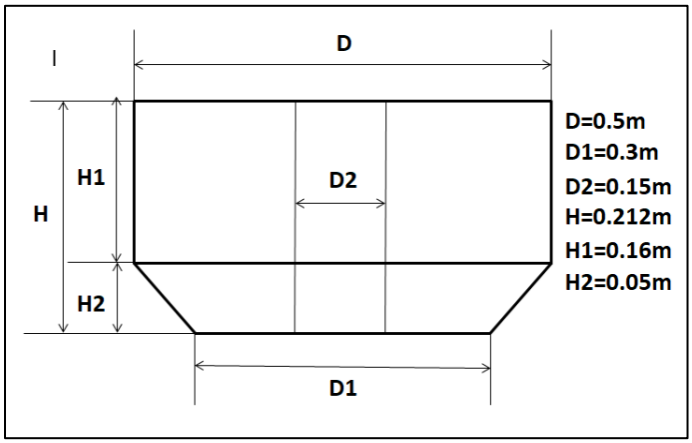


Figure 1. Main dimensions of the Buoy.

Table 1. Main particulars of the buoy model

Scale	Model Scale	Full Scale
Diameter (m)	0.5m	2.0m
Height (m)	0.212m	0.85m
Actuator hole (m)	0.15m	0.60m
Displacement (kg)	14.48kg	950kg
Trim (Deg)	Even keel	Even keel
Draft (m)	0.1m	0.4m



Figure 2. Model construction.

In order to keep the total weight to a minimum, the model's frames and planking was created from plywood (Fig. 2). Complex geometries like the conical shape at the bottom of the buoy were formed by engraved wood shaped by the CNC machine of the laboratory (Fig. 3).



Figure 3. Forming the conical shape with the CNC machine of LSMH.

To reinforce the structure and increase waterproof protection the hull was covered by fiberglass and resins. After the completion of the hull the model was painted with ship paint.

The model was equipped with a metal structure for the anchoring and ballast joining. A ballast of 1 kg was placed at the bottom of the metal structure, lowering the CG and increasing stability.

More extra weights were added to achieve the desired draft. An average displacement of 950 kg at full scaled was selected for the testing. The weights were distributed in such manner to ensure an even keel condition and placed at similar position were the equivalent equipment is going to be placed at the larger prototype model (batteries, electronic devices, etc.)

To calculate the moment of inertia, the model was tested at the towing tank for stability and decay test. The inertial forces were calculated by measuring the natural rolling frequency of the buoy (Fig. 4) and the GM was calculated by conducting the stability test.

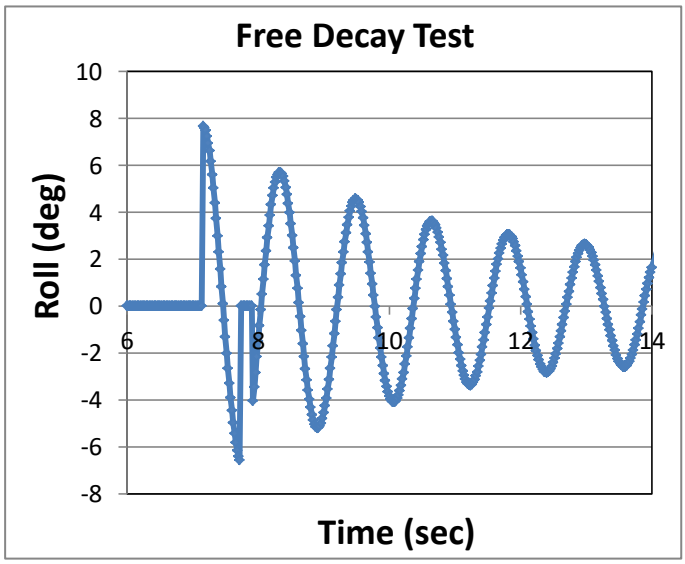


Figure 4. Roll decay test of the buoy.

The total inertial moment was measured 0.846 kg*m^2 and is equal to the moment of inertia of the buoy, I_{XX} and the added mass moment δI_{XX}.

The moment of inertia of the buoy, I_{XX} was experimentally measured by bifilar suspension method. The buoy was suspended in the air by two parallel beams, allowing the horizontal oscillation (Fig. 5).

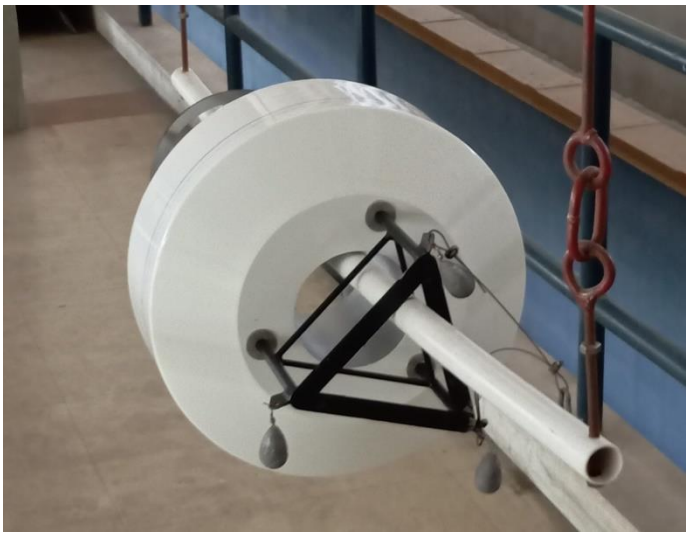


Figure 5. Bifilar suspension method.

Then, by measuring the natural period of oscillation the moment and radius of inertia was calculated as 0.398 and 16.6 cm respectively.

In addition, to experimentally find the vertical center of gravity, the buoy was suspended at several vertical positions from a single line until it balances at a level position (Konispoliatis et al., 2025). The experiments revealed a VCG of 86 mm from the buoy's bottom.

3 MODELING OF THE ANCHORING SYSTEM

SUN-BIO partner, ESI used OrcaFlex software to accomplish the preliminary design and simulation of the buoy mooring system (Fig. 6), adopting a three-point configuration that ensures stability and tension under Mediterranean Sea conditions considering a significant wave height $H_S \approx 1$ m and $H_{Smax} \approx 7$-8 m.

Each mooring line connects an anchoring point on the seabed to a small buoy submerged approximately 2 m below the free surface, following this configuration:

- Mooring line: 19 m of wire rope
- Wire diameter: 3/16 in (5.0 mm)
- Jacket diameter: 0.255 in (6.5 mm)
- Minimum breaking strength: 4,000 lbs (≈ 1,814 kg)
- Weight: 0.077 kg m^{-1}
- End termination: ½ in shackle

The submerged buoy at the upper end of each line is necessary to maintain the line nearly vertically and provide the appropriate tension.

The wire line under the buoy (Fig. 6) serves only for supplying electricity (not as anchoring line) to the bottom base and wasn't simulated at the experiment.

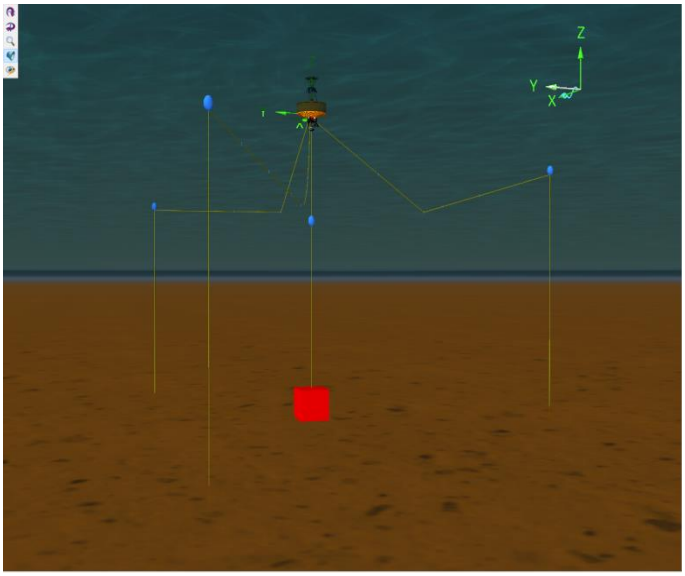


Figure 6. The mooring system of the prototype OHRES system.

From each submerged buoy, an 18 m wire rope connects to the main buoy. This section includes distributed weights (3.5 kg every two meters) to improve vertical alignment and damping of motion.

For the experiments an exact scaled mooring was not feasible due the size constrains of the towing tank of the Laboratory for Ship and Marine Hydrodynamics (LSMH) of the National Technical University of Athens, which has a length of 91 m, a width of 4.55 m and a water depth of 3.00 m.

Thus an equivalent mooring with two anchoring points was designed and implemented in the towing tank (Figs. 7-8).

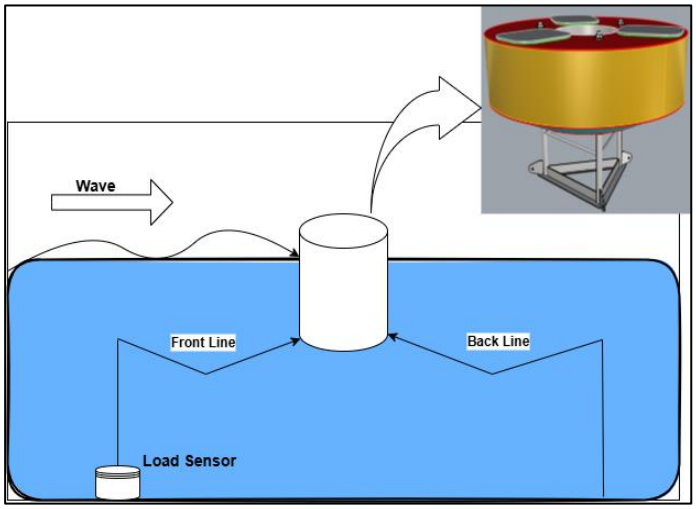


Figure 7. Two line Scaled mooring at towing tank of LSMH, encountering head waves.

All the lines dimensions were designed with the same scale (1/4). The same applies with the mooring supporting buoy's. The tension of the two lines instead of three provides equivalent mooring force.

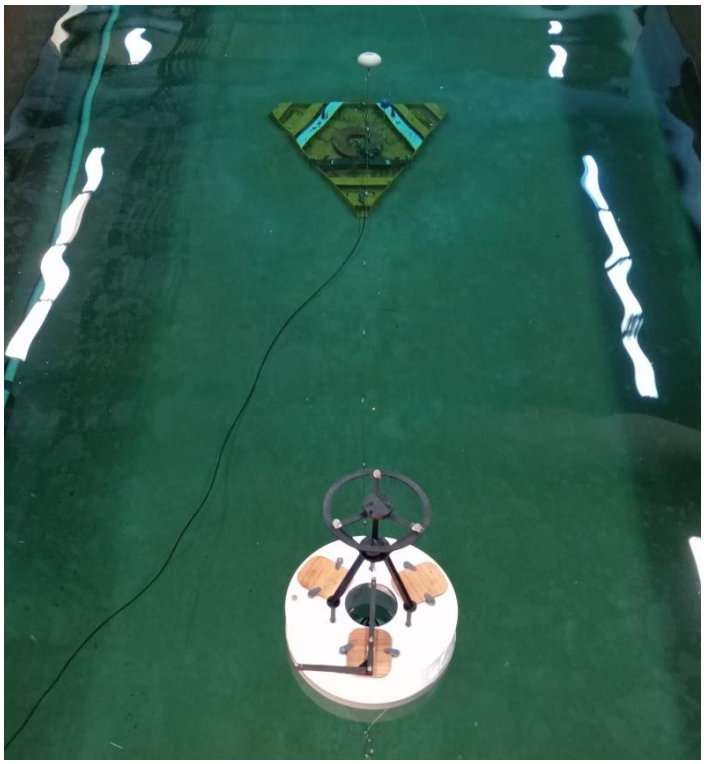


Figure 8. Scaled Mooring at towing tank of LSMH.

For the anchoring, a suitable base was created at the laboratory, loaded with sufficient weights and placed at the bottom of the towing tank (Fig. 9).

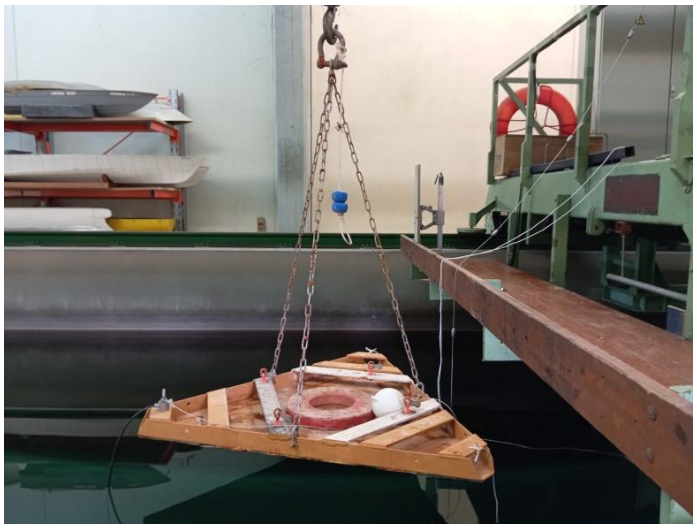


Figure 9. Base for the front mooring line.

The two anchoring point at the base of the tank were accurately positioned parallel to the tank's walls, ensuring that the buoy will encounter waves at the same direction with the front mooring line. Moreover, equivalent weights were distributed at the same manner as the solution provided by ESI.

4 EXERIMENTAL SETUP

The experiments took place at the towing tank of LSMH which operates a wave maker capable of producing both harmonic and random waves between the frequencies of 0.3 to 1.2 Hz and maximum amplitude of 35 cm at the intermediate frequencies.

Two measuring devices were utilized at the experiments. A load sensor at the front base of the anchoring and an optical system that is capable of recording the motions of bodies at a further distance by utilizing marker and high speed cameras.

The load sensor was placed at a vertical position right above the front base at the bottom of the tank. In this manner, the vertical forces created during the motion of the buoy from the waves were recorded.

A configuration of four digital cameras were installed alongside the wave tank (Fig. 10) to record the movement of optical targets placed at various points on the buoy (Grigoropoulos et al., 2011).



Figure 10. Optical system used for recording the motions of the buoy.

The system operates by placing retro-reflective markers at the model's surface that reflect infrared light emitted by the cameras.

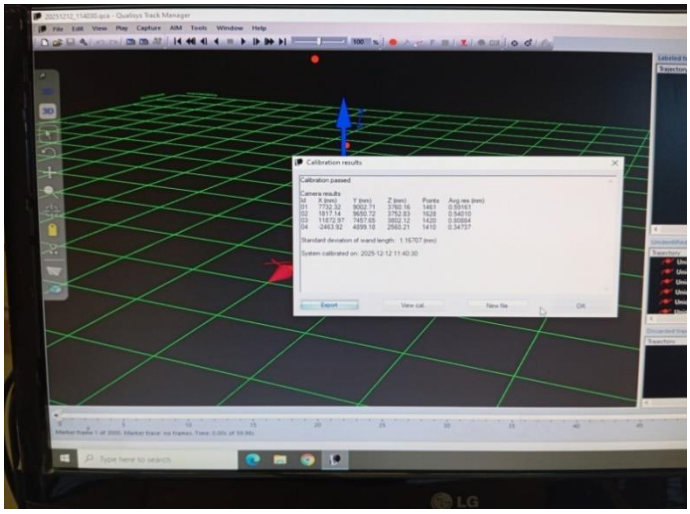


Figure 11. Calibration procedure.

Then by real-time calibration, a 3-D map is created that converts the 2-D position of the markers of each camera to 3-D position data (Fig. 11) (Kouklakis et al., 2025). As a result, the 6-DOF data is calculated.

The software of the system (Qualisys), QTM software provides the surge, heave and sway motions as well as the roll, pitch and yaw rotations of the model and thus the model's real-time motion. Further analysis, provides speed and accelerations of the marker as well as for the buoy. For the specific experiments we adjusted the frame rate at 50 frames per second, a frequency that is well above of the frequencies of the encounter waves. Finally, the wave amplitudes produced by the tank's wave maker were recorded using a non-intrusive acoustic probe positioned close to the wave maker.

5 TEST CONDITIONS

The buoy prototype will be demonstrated at the OBSEA facility within NATURA 2000 area off the coast of Barcelona. Primitive measurements at the area of installation of the prototype model indicated a significant wave height $H_S \approx 1$ m and $H_{Smax} \approx$ 7-8 m, and peak periods from 4 to 8 sec, with the worst case scenario of peak period of 4 sec. Having that in mind, the model was test at nine regular frequencies from 0.3 to 1.1 Hz (Table 2) and three irregular sea states that corresponds to full scale peak period Tp ≈ 4 sec and significant wave height *Hs* of 0.10m and 0.14m (Table. 3).

Table 2. Amplitude and frequencies of the head sine waves encountered.

Frequency (Hz)		Amplitude (cm)	
Model Scale	Full Scale	Model Scale	Full Scale
0.3	0.15	7.5	30
0.3	0.20	7.5	30
0.4	0.25	7.5	30
0.5	0.30	7.5	30
0.6	0.35	7.5	30
0.7	0.40	7.5	30
0.8	0.45	7.5	30
0.9	0.50	6.0	24
1.0	0.55	5.0	20
1.1	0.60	4.0	16

Table 3. Amplitude and frequencies of the random encountered.

Tp (sec)		Hs (cm)	
Model Scale	Full Scale	Model Scale	Full Scale
2.5	5	10	40
2.5	5	15	60
1.66	3.33	14	56

Furthermore, one draft was chosen according to the weight estimation of the buoy with all the necessary equipment loaded. The model was tested at even keel condition at fresh water.

6 MEASUREMENTS AND ANALYSIS

6.1 *Regular Waves*

Indicative results concerning of the surge, heave motions as well are the pitch rotation, the wave height and the full scale vertical tension at the frequency of 0.4 Hz are presented below (Figs.12-16).

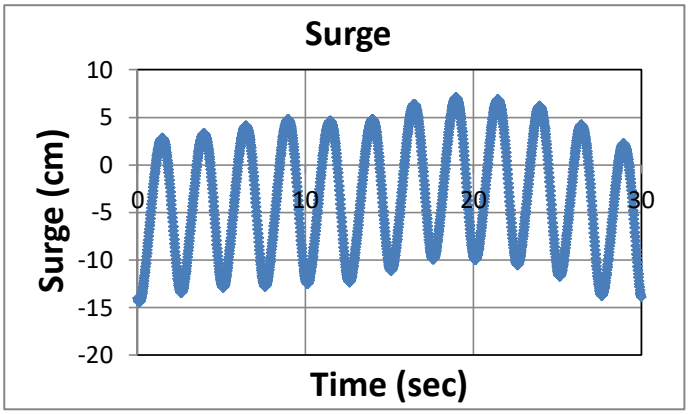


Figure 12. Surge motion versus time at 0.4Hz and 7.5cm amplitude.

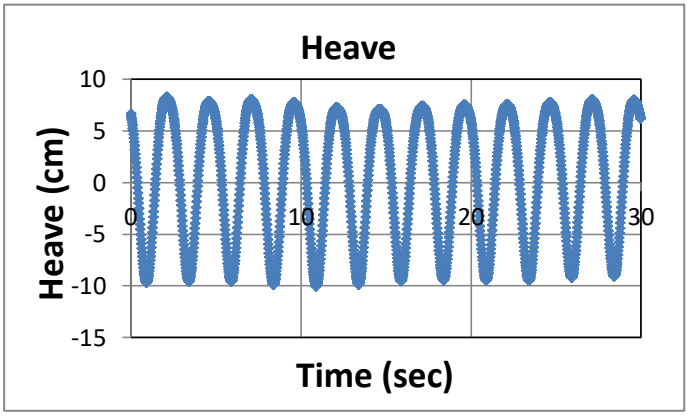


Figure 13. Heave motion versus time at 0.4Hz and 7.5cm amplitude.

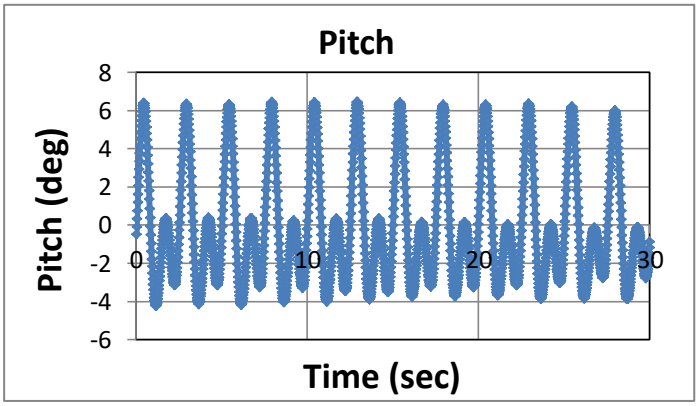


Figure 14. Pitch motion versus time at 0.4Hz and 7.5cm amplitude.

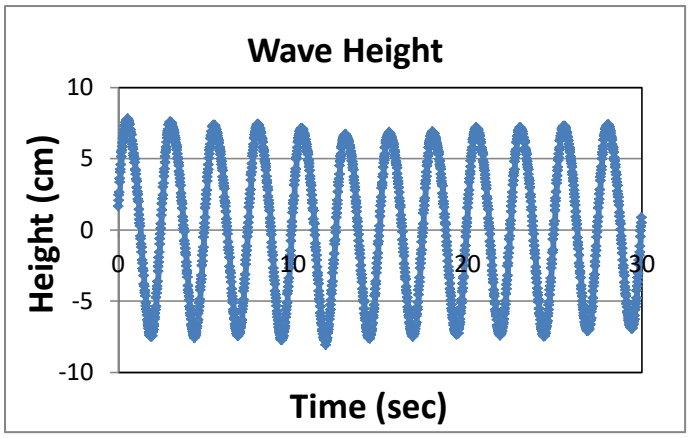


Figure 15. Wave elevation versus time at 0.4Hz and 7.5cm amplitude.

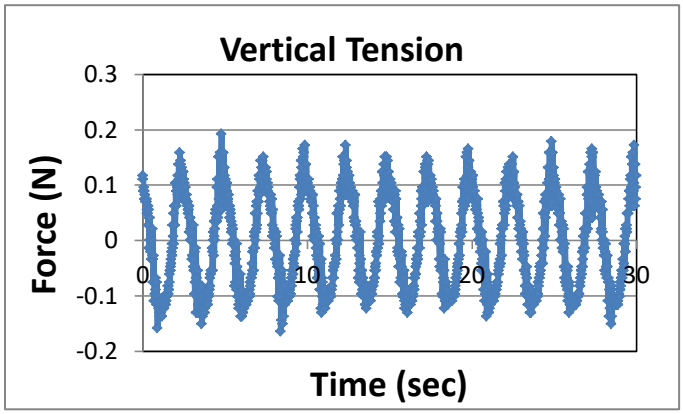


Figure 16. Wave elevation versus time at 0.4Hz and 7.5cm amplitude.

6.2 *Response Amplitude Operator*

Response amplitude operator refers to the degree of movement induced in a floating structure due to a passing hydrodynamic wave. It uses the experimental results to calculate the transfer function that indicates the dynamic behavior of floating structures and ship vessels.

By measuring the response of a model in regular waves, a set of response amplitude operators can be used to predict the performance in actual sea conditions (Liarokapis 2015).

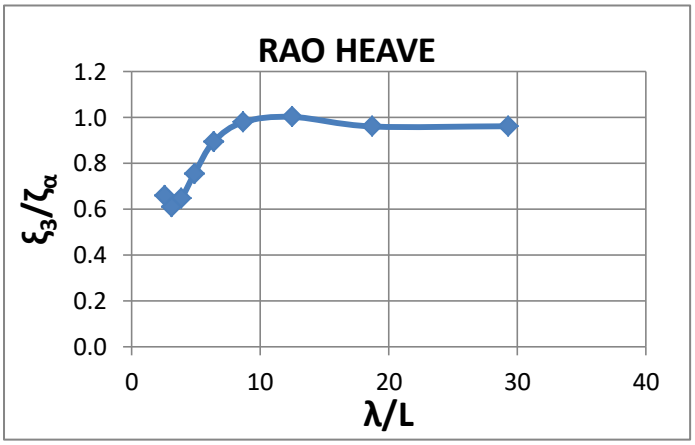


Figure 17. RAO heave versus λ/L.

In our experiments, the center of motion is measured at the center of the buoy on the top surface. The results presented concerns the RAO for the heave, pitch, surge and vertical tension. The RAO's are plotted against the non-dimensional ratio λ/L (Figs.17-19).

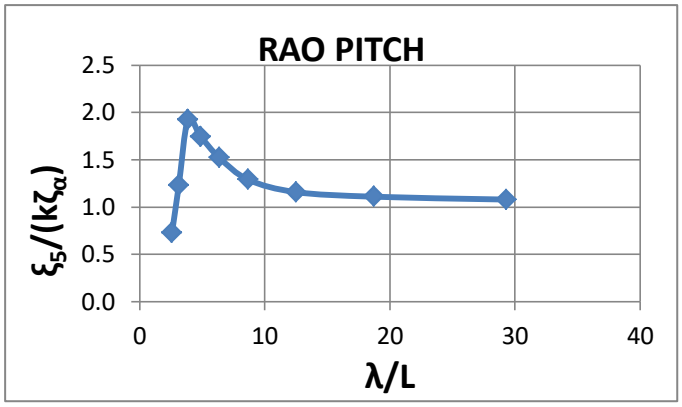


Figure 17. RAO pitch versus λ/L.

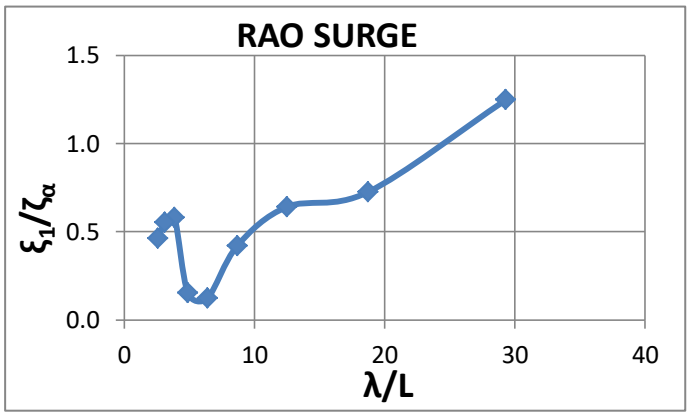


Figure 19. RAO surge versus λ/L.

The results reveal that the RAO for surge reaches its highest value (resonance) of about 3 (1Hz) which is unlikely to encounter at open sea. The same applies for the RAO of pitch while at higher λ/L it matches the waves steepness. The higher value of the RAO of heave is observed at λ/L around 10, where the buoy is heaving 1.2 higher than the induced wave.

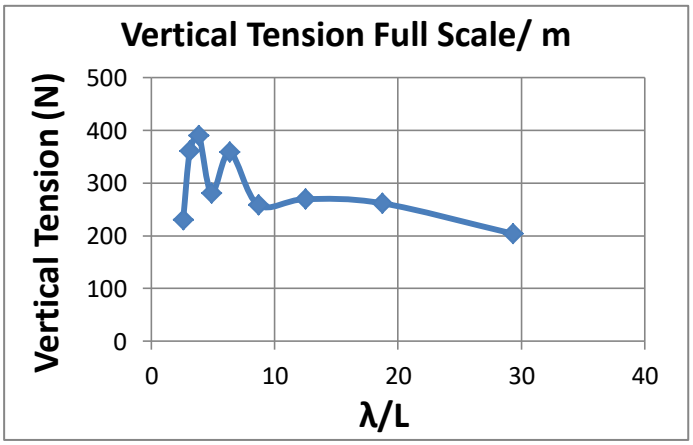


Figure 20. Vertical tension / m versus λ/L.

At Figure 20, the full scale vertical tension is plotted against λ/L. It is observed the higher values were recorded for the lower values of λ/L.

6.3 *Random Waves*

Indicative results concerning of the surge, heave motions as well are the pitch rotation, the wave height and the full scale vertical tension at significant wave height *Hs* of 0.10m and peak period Tp = 2.5 sec (Bretschneider spectra) are presented below (Figs.21-25). The Bretschneider spectra is a two parameter spectra, suitable for modeling fully developed seas at not restricted areas like the intended place of installation.

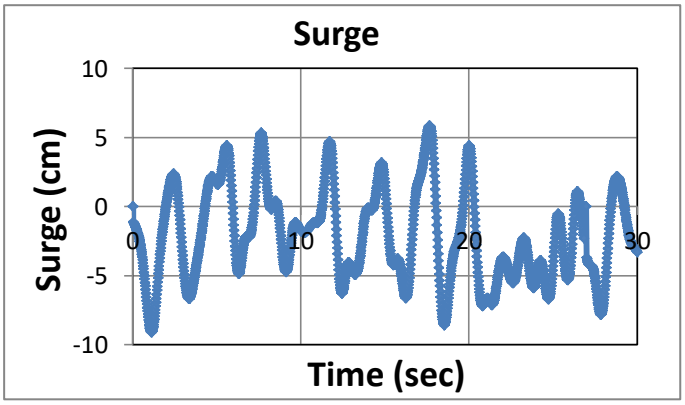


Figure 21. Surge motion versus time for *Hs* of 0.10m and peak period Tp = 2.5 sec.

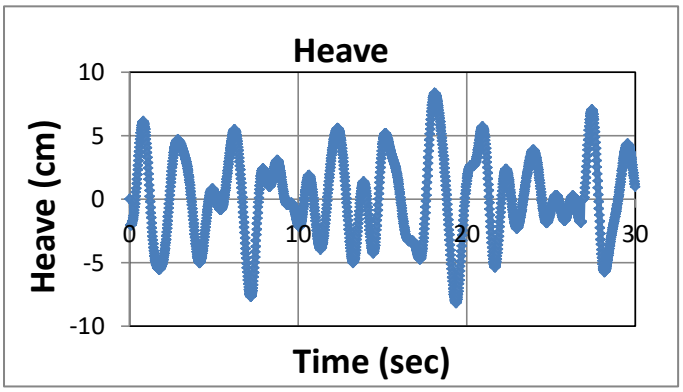


Figure 22. Heave motion versus time for *Hs* of 0.10m and peak period Tp = 2.5 sec.

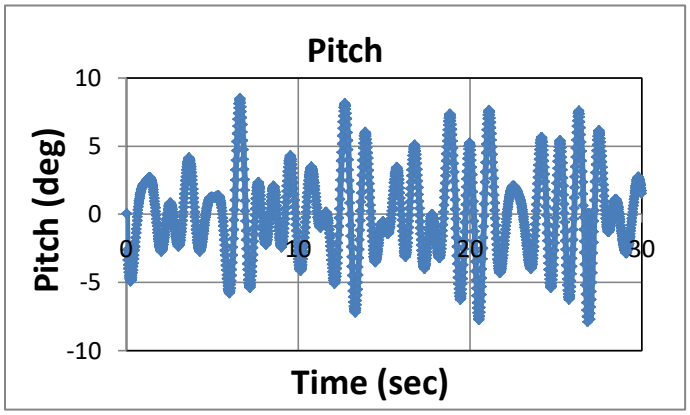


Figure 23. Pitch motion versus time for *Hs* of 0.10m and peak period Tp = 2.5 sec.

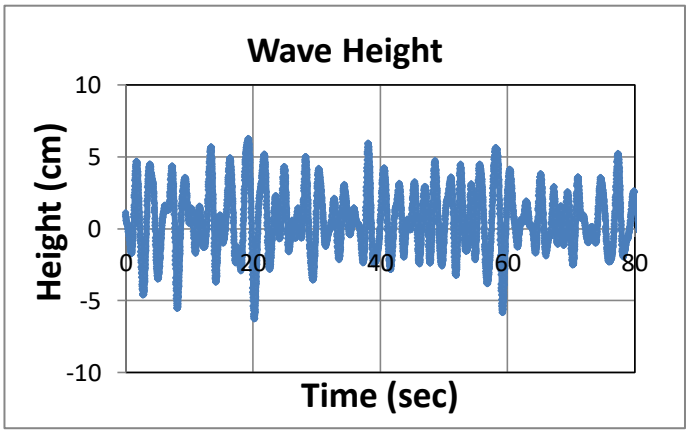


Figure 24. Wave elevation versus time for *Hs* of 0.10m and peak period Tp = 2.5 sec.

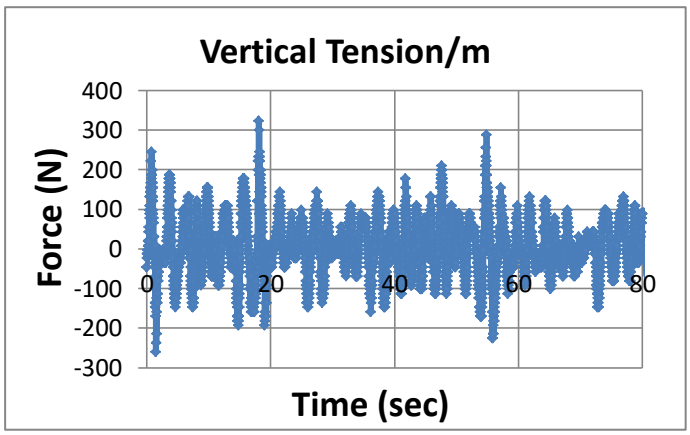


Figure 25. Full scale vertical tension versus time for *Hs* of 0.10m and peak period Tp = 2.5 sec.

Table 4. RMS values for surge, heave, pitch and vertical tension at random waves.

H_s (cm)	10	15	14
T_p (sec)	2.5	2.5	1.66
Heave (cm)	3.17	4.58	3.54
Surge (cm)	5.57	10.76	25.08
Pitch (deg)	3.70	4.72	6.59
Vertical Tension (N)	0.46	0.63	0.61

Finally, the rms values for the surge, heave, pitch and vertical tension are presented at the table (table. 4). The results clearly show that the buoy and the anchoring system operate satisfactory at moderate wave conditions. Relatively low forces are developed at the anchoring base.

7 CONCLUSIONS

The present work presents the experimental evaluation of the dynamic behavior of an autonomous multifunctional buoy at rough seas. A scaled model and an equivalent anchoring system was designed and tested at the towing tank of the Laboratory for Ship and Marine Hydrodynamics of NTUA at regular and random waves at similar conditions that the prototype is going to encounter during its lifetime.

The design consisted of two anchoring lines at a positioned at a straight line with same line length as the initial design. The RAO's of the buoy were calculated for various wave periods and heights, revealing relative low motions at moderate to heavy weather conditions. The mooring and anchoring system operated satisfactory at the same weather and relatively low forces were developed at the anchoring base. Only in extreme conditions (hurricane, typhoon) failure may occur. It is expected to have a minimum life cycle of more than 5.5 years.

8 AKNOWLEGMENTS

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9 REFERENCES

Aguzzi, J., Chatzievangellou, E., Marini, S., & Company. J., 2019. New high-tech interactive and flexible networks for the future monitoring of deep-sea ecosystems. *Env. Sci. Technol*. 53: 6616-6631.

Aguzzi, J., Ivesa, N., Gelli, M., & Danovaro. R., 2020. Ecological video monitoring of Marine Protected Areas by underwater cabled surveillance cameras. *Marine Polution*, 119: 104052.

Grigoropoulos. G., Damala. D., & Liarokapis. D., 2011, "Experimental evaluation of the dynamic responses of ship models moored in scaled ports", in *Proceedings of the 9th International Maritime Association of the Mediterranean*, Genova, 2011

Konispoliatis. D., Chatjigeorgiou. I., Liarokapis. D., Mavrakos. A., & Grigoropoulos. G, 2025. Theoretical and experimental analysis of a dual chamber OWC device, in *Proceedings of the 16th European wave and tidal energy conference*, 7 -11 September 2025, Funchal.

Kouklakis. S., Liarokapis. D., Loghis. C., Thaxanas. G, & Grigoropoulos. G., 2025, Development and evaluation of an autonomous ship model in the towing tank of NTUA, in *Proceedings of the 20th International Maritime Association of the Mediterranean*, 28th Septeber – 2nd October, Chania, Crete.

Liarokapis. D., Tsami. I., Trachanas. J., & Tzabiras. G., 2015, An experimental study on the added resistance of a bulk carrier model, IMAM 2015, in *Proceedings of the 16th International Maritime Association of the Mediterranean*, Pula, 21-24 September 2015.

Masmitja, I., Palomeras, N., Toma, D.M., Bahamon, N., Carandell, M., García del Arco, J.A., Chatzievangelou, D., Real, M., Sánchez-Márquez, A., Batet, G., Vial, P., Bonin-Font, F., Muntaner, C., Hurtós, N., López, J.M., Ripoll, A.R., de Arcas, G., Grinyó, J., Gomariz, S., Katija, K., Aguzzi, J., Carreras, J., del Rio, J., Navarro, J., Company, J.B. 2025. Interconnected robotic platforms inform deep-sea ecological restoration trends. *Marine Pollution Bulletin*, 219:118314. https://doi.org/10.1016/j.marpolbul.2025.118314.

Qualisys, Software, Qualisys Track Manager QTM - Software | Qualisys.

Rhinoceros, https://www.rhino3d.com/

UN Sustainable Development Goals, Goal 14: Conserve and sustainable use of the oceans, seas and marine resources, https://www.un.org/sustainabledevelopment/oceans/

Woodall, L. C., Andradi-Brown, D . A., Brierley, A. S., Clark, M. R., Connelly, D., Hall, R. A., ... & Rogers, A. D. (2018). A multidisciplinary approach for generating globally consistent data on mesophotic, deep-pelagic, and bathyal biological communities. *Oceanography*, 31(3), 76-89