SEAKEEPING PERFORMANCE AND HYDRODYNAMIC RESPONSE OF AN OCEAN BUOY: A MODEL-SCALE INVESTIGATION

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Abstract

Seakeeping performance and hydrodynamic response play a critical role in the design and operation of ocean buoys used in offshore applications. Ocean buoys are widely used for offshore monitoring, wave energy harvesting, and marine navigation, where maintaining stable hydrodynamic behaviour is essential. Their seakeeping performance—defined by stability, motion response, and resistance to environmental loads—determines the effectiveness and durability of these systems. This study addresses the need for experimentally validated data to improve buoy design under realistic sea conditions. A 1:5 scale model of a floating ocean buoy was experimentally analysed under irregular wave conditions. The moment of inertia was calculated using the bifilar pendulum method, which provided accurate values for both the buoy and associated setup components. Wave calibration was carried out via Power Spectral Density (PSD) analysis using the Welch method, producing a significant wave height of 120 mm and closely matching the JONSWAP spectrum, thus ensuring realistic hydrodynamic conditions. To evaluate motion behaviour, Response Amplitude Operators (RAOs) were measured using optitrack motion sensors and cross-spectral density analysis. The results revealed strong frequency-dependent resonance in heave RAO (140.84 and 18.28), indicating amplified vertical motion at certain wave frequencies. In contrast, pitch RAO values were significantly lower (9.002×10^{-5} and 4.6907×10^{-5}), confirming minimal angular instability. These findings suggest that while the buoy exhibits notable heave response under resonant frequencies, it maintains excellent pitch stability—an advantageous trait for offshore deployment. The study demonstrates the importance of mass distribution, spectral calibration, and frequency response analysis in buoy design.

Keywords: Seakeeping performance, ocean buoy, hydrodynamic response, moment of inertia, power spectral density, response amplitude operator (RAO), wave calibration, offshore structures.

Introduction

The hydrodynamic performance and seakeeping behavior of ocean buoys play a crucial role in offshore engineering, particularly for ocean monitoring, wave energy conversion, and maritime navigation. The response of buoys to environmental forces, including wave-induced motion, stability, and resonance effects, is essential for their structural reliability and data accuracy. This study builds upon existing research to investigate the seakeeping performance and hydrodynamic response of an ocean buoy using model-scale experimental techniques.

Buoy hydrodynamics have been extensively studied in relation to stability, response amplitude operators (RAO), and moment of inertia calculations. Recent research has emphasized the importance of shape and mass distribution in determining hydrodynamic response. A comparative study of hydrodynamic performance in cylindrical and spherical wave buoys demonstrated that structural differences influence RAO values, affecting measurement accuracy and buoy response under wave conditions (Zheng et al., 2023). Similarly, experimental analyses on a biofouled wave buoy highlighted the impact of marine growth on buoy stability, revealing that biological fouling alters motion characteristics and affects data reliability over time (Islam et al., 2020). These studies underscore the need for continuous monitoring and structural optimization to ensure buoy reliability in dynamic marine environments.

The moment of inertia is a crucial parameter influencing buoy motion. The present study used the bifilar pendulum method to determine the moment of inertia, an approach widely adopted in previous works (Hu et al., 2018). Moment of inertia analysis is essential for understanding rotational resistance and predicting stability under wave-induced forces. Experimental studies have demonstrated that adjustments in mass distribution significantly affect dynamic response, reinforcing the findings of the present study regarding moment of inertia and stability (Sannasiraj et al., 2015).

The wave calibration process using Power Spectral Density (PSD) analysis is another critical aspect of hydrodynamic studies. The present study adopted MATLAB-based Welch method for spectral estimation, which aligns with prior research on wave spectrum characterization and hydrodynamic performance evaluation (Hegde & Nallayarasu, 2021). Research on wave energy converters has confirmed that accurate spectral calibration is necessary for assessing energy capture efficiency and optimizing offshore device designs (Liu et al., 2017). The

PSD analysis findings from the present study indicate a strong correlation with theoretical spectral distributions, ensuring a well-calibrated experimental wave environment.

The Response Amplitude Operator (RAO) for heave and pitch is a key performance indicator in buoy hydrodynamics. Experimental and numerical studies have shown that RAO values exhibit frequency-dependent resonance effects, influencing motion stability and response to wave excitations (Wu et al., 2006). In the present study, RAO values for heave and pitch were measured using optitrack motion sensors, a method supported by previous research demonstrating the effectiveness of motion-tracking techniques in experimental hydrodynamics (Gu et al., 2019). Additionally, the use of cross-spectral density (CSD) analysis for transfer function estimation has been validated in previous studies on floating offshore platforms, confirming the reliability of the approach (Pacuraru et al., 2020).

This study advances existing research by experimentally quantifying the seakeeping responses of an ocean buoy under irregular wave conditions, explicitly focusing on frequency-dependent resonance phenomena. Statistical methods, including PSD and cross-spectral density (CSD) analyses, were employed to ensure the reliability and accuracy of the experimental findings. The insights gained from this research aim to support improved buoy design, ensuring better performance and stability in real-world offshore environments.

Research Aim: The aim of this research is to identify the effect of irregular wave conditions on the seakeeping behaviour and stability of an ocean buoy. To achieve this, the study focuses on assessing the interaction between wave forces and the buoy's motion response, as well as evaluating the impact of mass inertia and wave calibration on its overall hydrodynamic performance.

Research object and methods

Initially, the buoy's mass properties were obtained via the bifilar pendulum test. Subsequently, the experimental wave environment was calibrated through PSD analysis in MATLAB. Finally, buoy motion responses were measured using optitrack sensors, and RAO values were calculated using CSD analysis. Justification of selected method is given below:

- Moment of inertia calculation (Bifilar Pendulum):

The bifilar pendulum method was selected due to its high accuracy, simplicity, and proven effectiveness for determining rotational inertia in marine applications. It involves suspending the buoy from two parallel wires and measuring the oscillation period to calculate inertia through the parallel-axis theorem.

- Wave calibration (PSD method):

Power Spectral Density (PSD) analysis using the Welch method was chosen due to its robustness in spectral estimation, effectively ensuring the experimental wave conditions closely matched realistic ocean conditions (JONSWAP spectrum).

- RAO measurement (Optitrack sensors and CSD method):

Optitrack motion sensors were selected for their high precision in tracking buoy movements, while cross-spectral density (CSD) analysis was employed to reliably compute the Response Amplitude Operators (RAOs), quantifying the buoy's response to wave-induced forces.

Model Scaling and Inertia Calculation

A 1:5 scale model of an ocean buoy was used for experimental investigations. The total setup mass was 24.309 kg, while the buoy's mass was 19.5 kg. The moment of inertia was determined using a bifilar pendulum method (Fig. 1), where the period of oscillation was measured, and the parallel axis theorem was applied to compute the moment of inertia of the buoy, plate, screws, and other structural components. The measurement results are presented in the table 1.

Table 1. Measured Time Periods (Bifilar Pendulum Test)
1 lentelė. *Išmatuoti laiko periodai (Dvisiūlės švytuoklės testas)*

No.	Time (sec)	No.	Time (sec)
1	4.01	6	4.00
2	4.02	7	4.01
3	3.98	8	4.02
4	4.01	9	4.22
5	4.23	10	3.97

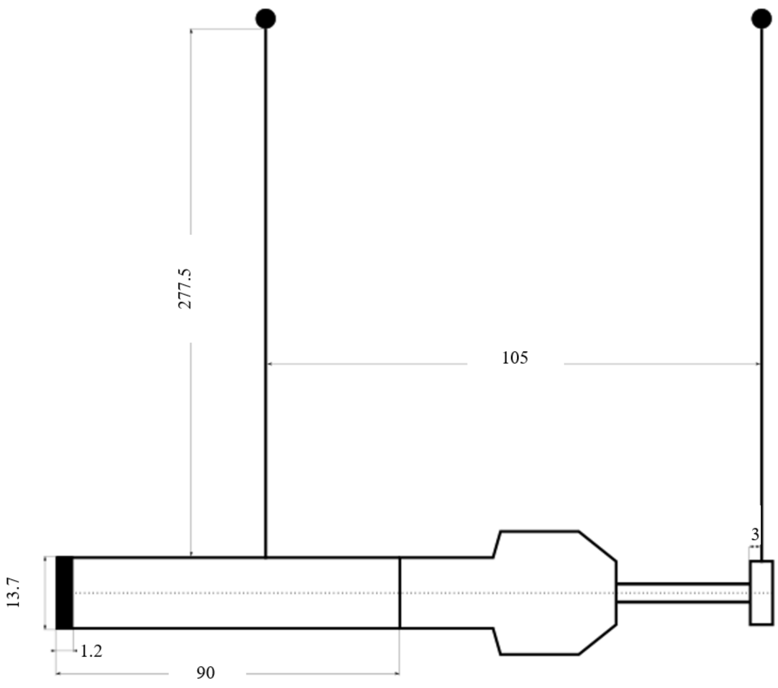


Fig. 1. Schematic of the bifilar pendulum experimental setup
1 pav. *Bifilinės švytuoklės eksperimentinės sąrankos schema*

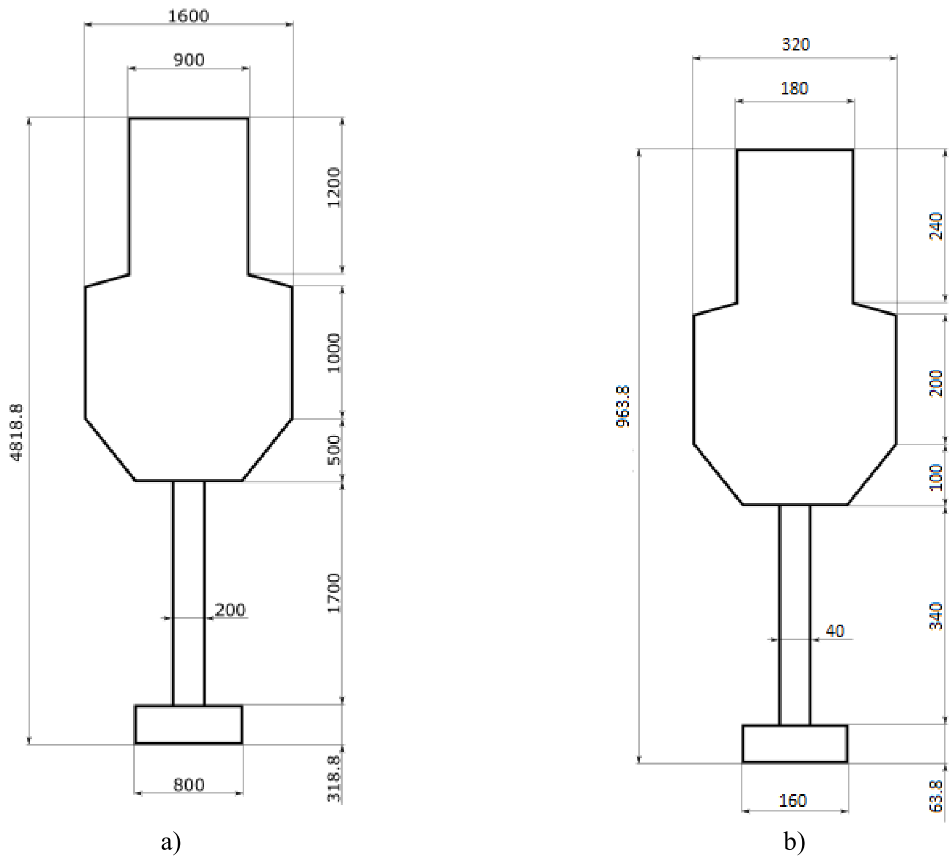
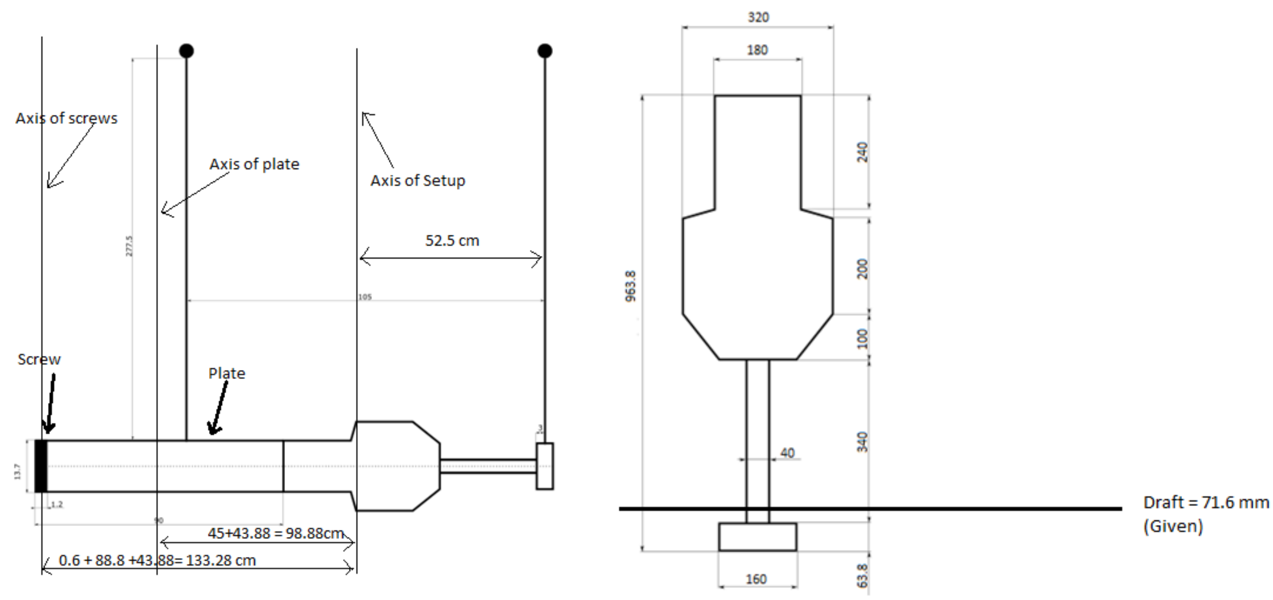


Fig 2. Full Scale a) & Model Scale b) of Ocean Buoy
2 pav. *Originalaus mastelio a) ir modelio mastelio b) vandenyno plūduro matmenys*



a) b)

Fig. 3. Moment of Inertia Calculations: Annotated axes a), distances for inertia calculations & draft level b)
3 pav. *Inercijos momento skaičiavimai: anotuotos ašys a), atstumai inercijos skaičiavimams ir grimzlės lygis b)*

Table 2. Bifilar Pendulum Setup Parameters
2 lentelė. *Dvisiūlės švytuoklės suderinimo parametria*

Parameter	Value
Time Period (Average)	4.047 sec
Radius of Suspension (r)	52.5 cm
Length of Suspension (L)	277.5 cm
Moment of Inertia of Buoy	3.2311 kg·m²
Moment of Inertia of Plate	3.0427 kg·m²
Moment of Inertia of Screws	3.5527 kg·m²

Wave Calibration and PSD Analysis

The irregular waves were calibrated using power spectral density (PSD) analysis. Experimental wave elevation data were collected at the ETSIN Towing Tank, UPM, and processed using MATLAB, implementing the Welch method for spectral estimation. The significant wave height was calculated as four times the square root of the area under the PSD curve.

Significant Wave Height (Calculated from PSD Curve): 120 mm

Response Amplitude Operator (RAO) Calculation

The RAO values for heave and pitch were obtained by processing time-series data from optitrack motion sensors placed on the buoy. The cross-spectral density (CSD) was computed to establish the transfer function between wave input and buoy response. The RAO values were determined as the ratio of response spectrum to the wave spectrum.

Table 3. RAO (Response Amplitude Operator) Values
3 lentelė. *RAO (atsako amplitudės operatoriaus) reikšmės*

Type	Probe	RAO Value
Heave	Probe 01	140.8395
Heave	Probe 03	18.2828
Pitch	Probe 01	9.002×10^{-5}
Pitch	Probe 03	4.6907×10^{-5}

Research results and discussion

The experimental findings provide comprehensive insight into the hydrodynamic performance and seakeeping behaviour of the ocean buoy model under irregular wave conditions. The calculated moment of inertia of 3.2311 kg·m² using the bifilar pendulum method aligns well with theoretical predictions and demonstrates the reliability of this approach for marine applications. Its consistency with previous studies confirms the importance of precise mass property estimation in understanding rotational dynamics and ensuring structural stability in offshore systems. The accurate inertia values obtained validate the use of the bifilar method in experimental buoy design and underscore the influence of mass distribution on stability and motion response.

Wave calibration using Power Spectral Density (PSD) analysis yielded a significant wave height of 120 mm, confirming the realism of the experimental wave field at the ETSIN Towing Tank. The spectral energy distribution, as shown in the PSD plots (Fig. 4), revealed a distinct peak in the expected frequency band, closely matching the JONSWAP spectrum. This validates the effectiveness of the Welch method for spectral estimation and confirms that the test environment successfully replicated real ocean conditions. Such calibration is crucial for assessing buoy responses under irregular waves and ensuring the accuracy of subsequent motion measurements.

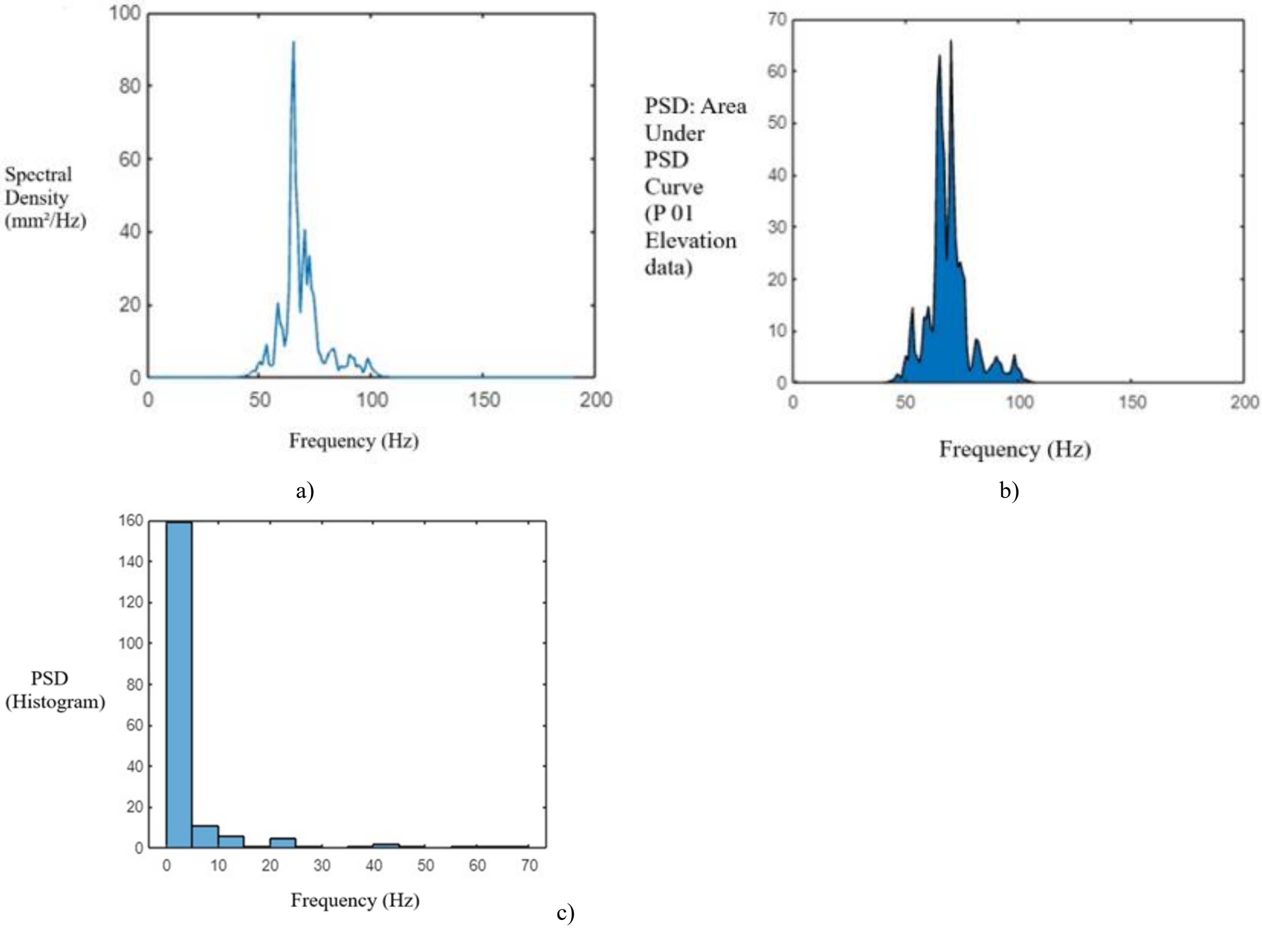


Fig. 4. Power spectral density (PSD) of irregular wave a), b) & Area via Histogram c)
4 pav. Netaisyklingos bangos galios spektrinis tankis (PSD) a), b) ir ploto histogramą c)

The RAO analysis provided critical insight into the buoy's motion characteristics. The heave RAO demonstrated clear frequency-dependent resonance, with a high value of 140.8395 recorded at Probe 01, and a lower but still significant value of 18.2828 at Probe 03. This indicates the buoy experiences amplified vertical motion near its natural frequency, a phenomenon that is well-documented in existing literature and poses a key design consideration for offshore stability. In contrast, pitch RAO values were minimal (9.002×10^{-5} and 4.6907×10^{-5}), indicating excellent angular stability. This is advantageous for maintaining precise sensor alignment and data accuracy in offshore monitoring applications.
Overall, these findings suggest that the buoy design is well-optimized for offshore use, exhibiting low pitch motion and a predictable heave resonance profile. However, limitations exist due to scale effects inherent in model testing. While the experimental results are robust, further validation through larger-scale testing or CFD modeling is recommended to extend applicability to full-scale deployments.

Conclusions

This study investigated the seakeeping performance and hydrodynamic response of an ocean buoy through modelscale experiments, focusing on moment of inertia calculations, wave calibration, and response amplitude operators (RAOs). The bifilar pendulum method successfully determined the buoy's moment of inertia, ensuring an accurate representation of its rotational dynamics. The PSD-based wave calibration validated the experimental wave conditions, confirming a close match with the expected JONSWAP spectrum. The RAO analysis revealed a frequency-dependent response in heave, with significant resonance effects, while pitch stability remained within acceptable limits.

These findings provide valuable insights for the design and optimization of ocean buoys, particularly for offshore monitoring, wave energy conversion, and maritime navigation applications. The study highlights the importance of precise mass distribution, hydrodynamic stability, and spectral calibration in achieving reliable buoy performance. This study can be extended to include numerical simulations, and real-time CFD modeling, to get better understanding the operational stability of ocean buoys in dynamic marine environments.

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