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Stabilization of Floating Wind Turbines: Experimental Insights into Moonpool Dynamics

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Resumen

Este artículo presenta una serie de investigaciones experimentales realizadas con prototipos a escala reducida de aerogeneradores flotantes desarrollados por la Universidad Complutense de Madrid (UCM) y plataformas tipo barcaza con moonpools diseñadas por la Universidad del País Vasco (UPV/EHU). El objetivo principal es caracterizar e identificar la dinámica natural de un aerogenerador flotante tipo barcaza, fondeado mediante cuatro líneas en disposición catenaria. Se realiza un análisis comparativo para evaluar la respuesta dinámica de la plataforma bajo distintas configuraciones del moonpool: abierto, cerrado y en estados de oscilación controlada de forma pasiva o activa. Además, se evalúa experimentalmente el potencial de un actuador giroscópico para mitigar las oscilaciones de la plataforma y mejorar su estabilidad. Los resultados ofrecen información relevante sobre el papel de los mecanismos internos de amortiguamiento por fluido y de las estrategias de control activo en la mejora del comportamiento dinámico de los sistemas eólicos flotantes en alta mar.

Palabras clave: Aerogenerador flotante, Moonpool oscilante, Estabilidad dinámica

Stabilization of Floating Wind Turbines: Experimental Insights into Moonpool Dynamics

Abstract

This article presents a series of experimental investigations conducted on small-scale floating wind turbine prototypes developed by Universidad Complutense de Madrid (UCM) and barge-type platforms equipped with moonpools designed by the Universidad del País Vasco (UPV/EHU). The primary focus is on characterizing and identifying the natural dynamics of a barge-type floating wind turbine, moored by four catenary lines. A comparative analysis is carried out to evaluate the platform's dynamic response under varying moonpool configurations—namely, open, closed, and passively or actively controlled oscillating states. Furthermore, the potential of a gyroscopic actuator to mitigate platform oscillations and enhance system stability is experimentally assessed. The results provide valuable insights into the role of internal fluid damping mechanisms and active control strategies in improving the dynamic behavior of floating offshore wind systems.

Keywords: Floating wind turbine, Oscillating moonpool, Dynamic stability

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1. Introduction

The global transition toward renewable energy has accelerated the development of offshore wind technologies, with floating offshore wind turbines (FOWTs) emerging as a promising solution for deep-water deployment (Martinez et al., 2023; WindEurope, 2024; Sadraddin and Shao, 2022). Among these, hybrid platforms that combine wind energy generation with oscillating water column (OWC) systems have gained attention due to their potential for passive stabilization and energy co-generation (Aboutalebi et al., 2021).

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However, the complex hydrodynamic and aerodynamic interactions inherent to such multi-physics systems remain insufficiently understood, particularly when real-time control and hardware integration are involved (Galán-Lavado and Santos, 2021; Villoslada et al., 2021; Chuang et al., 2021; Terrero-Gonzalez et al., 2024).

To address this gap, a collaborative research initiative was launched between the Universidad Complutense de Madrid (UCM) and the Universidad del País Vasco (UPV/EHU), combining expertise in floating wind systems and OWC-based barge platforms, respectively. Building on previous prototype developments at UCM and barge designs at UPV/EHU (Aboutalebi et al., 2024), the project aimed to experimentally evaluate the coupled dynamic behavior of hybrid FOWT–OWC systems under controlled laboratory conditions (Universidad Complutense de Madrid, 2025).

The experimental campaign was conducted using scaled prototypes of FOWTs installed on floating barge platforms equipped with OWCs. Tests were performed in the wave tank facilities of UPV/EHU, where a wide range of wave and wind conditions were reproduced. The integration of aerodynamic, hydrodynamic, mechanical, and electrical subsystems—each with distinct dynamic characteristics—posed significant challenges in instrumentation, control, and data acquisition. Real-time monitoring was achieved using custom-built hardware and software solutions (Muñoz-Palomeque et al., 2024; Wang et al., 2024).

Two platform configurations were tested: one with open OWCs and another with closed OWCs. Each platform was moored to the base of the wave tank using a catenary mooring system consisting of four lines (Aboutalebi et al., 2023; Xing et al., 2025). Given the methacrylate floor of the tank, suction cups were used as anchoring points. Different chain lengths were explored to emulate elastic mooring behavior and allow realistic platform motions comparable to full-scale offshore systems. A schematic representation of the mooring setup is shown in Fig. 1.

This paper presents the methodology and results of these experimental tests, with a focus on dynamic modeling, system identification, and the effectiveness of passive and active stabilization mechanisms (López-Queija et al., 2022; Gao et al., 2024; Li et al., 2024; Yang et al., 2019). The goal is to support the development of more accurate models for hybrid FOWT–OWC systems and to inform the design of future control strategies for platform stabilization.

Figure 1: Barge anchored to the bottom by four mooring lines.

Instrumented FOWT prototypes were mounted on both barge types, as shown in Fig. 2. The OWCs were located at the bow and stern of each barge.

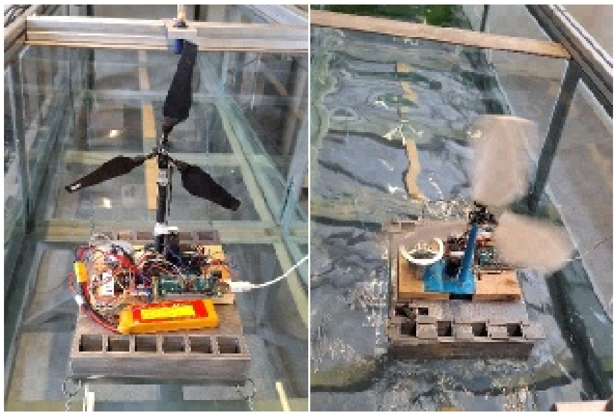

Figure 2: Two key experimental configurations: the left image features a forced wind turbine on a barge with OWCs (open or closed), while the right image shows a freely responding turbine with an active gyroscopic stabilizer and controllable OWCs.

In the configuration shown, the columns are in an open state, allowing free water surface oscillations. Two main experimental configurations were investigated:

1. A forced wind turbine mounted on a barge with OWCs in either open or closed states.
2. A free-response wind turbine equipped with an active gyroscopic stabilizer, mounted on a barge with controllable OWCs.

A broad range of tests was conducted to evaluate the influence of internal damping and active stabilization on the system's dynamic response:

- Free decay tests with OWCs in open, closed, and actively controlled conditions.
- Experiments with and without wind excitation.
- Tests with and without the use of active gyroscopic stabilizers.

2. Mathematical Modeling

Although more detailed turbine models exist, the dynamic behavior of the system is simplified to isolate the influence of each subsystem. The pitch degree of freedom, denoted by ϕ, is modeled using a second-order linear differential equation as follows:

$$I\ddot{\phi}(t) + D\dot{\phi}(t) + K\phi(t) = T_{\text{actuator}} \tag{1}$$

Where:

- I is the moment of inertia about the pitch axis, which depends on the mass distribution and the rotational center, itself related to the center of buoyancy.
- D is the damping coefficient, influenced by the barge's hydrodynamics and the wind turbine's aerodynamics.
- K is the restoring stiffness, mainly governed by the hydrodynamics and the mooring line characteristics.

- T_{actuator} represents control torques from different actuators: oscillating water columns (OWCs), gyroscopic devices, and blade pitch control.

For simplification, the equation may be normalized by I to remove the need for identifying the precise inertia value:

$$\ddot{\phi}(t) + \frac{D}{I}\dot{\phi}(t) + \frac{K}{I}\phi(t) = \frac{T_{\text{actuator}}}{I} \tag{2}$$

3. Dynamics with Oscillating Water Columns (OWCs)

3.1. Passive OWCs

Damping experiments were performed without wave or wind excitation. The barge was initially displaced by submerging its bow or stern to create an initial pitch. Fig. 3 shows the system's response with open, closed, and actively controlled moonpools.

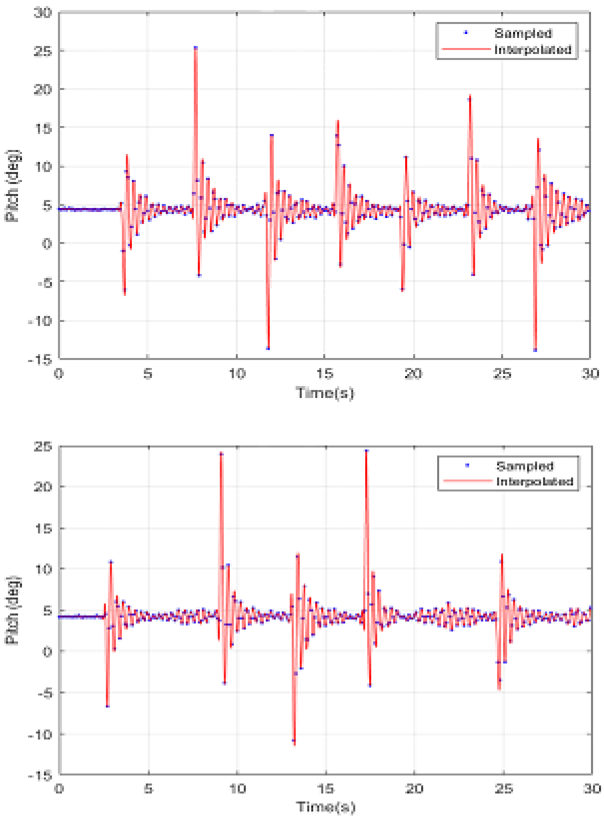

Figure 3: Damping experiments without wave/wind excitation for open, closed, and controlled OWCs.

Measurements were originally sampled at 0.1 s intervals but interpolated to 0.01 s to better capture the fast dynamics. From this dataset, one representative case was used to fit a second-order linear model.

Figure 4 shows the time-domain validation, where the natural frequency is well captured, but damping is underestimated due to its nonlinear behavior—more pronounced under larger pitch displacements, likely due to the added water mass. Table 1 shows the identified poles.

Table 1: Identified system poles for static OWCs

Configuration	Damping	Frequency (rad/s)	Time Constant (s)
Open OWCs	0.197	17.7	0.288
Closed OWCs	0.188	17.5	0.304

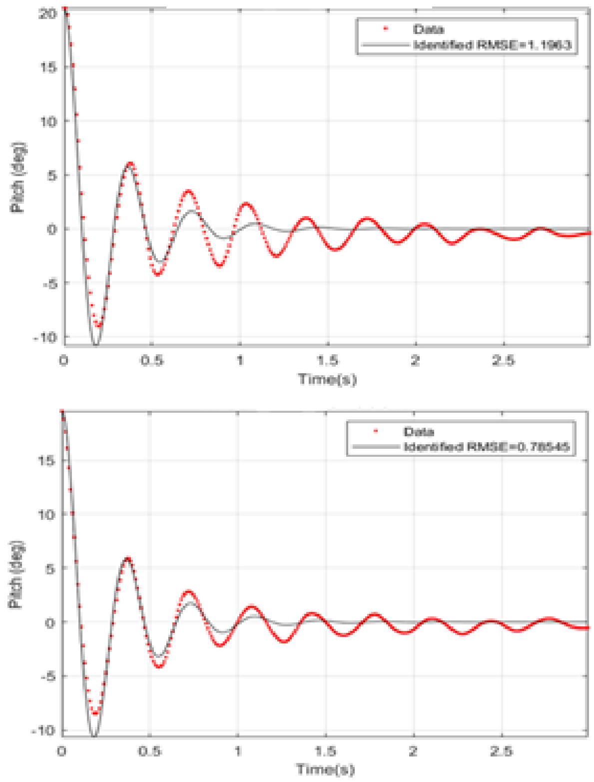

Figure 4: Model identification for open and closed OWC configurations.

3.2. Active OWCs

Experiments were conducted, shown in Fig. 6, Controlled OWCs were tested using a logic based on the sign of pitch angular velocity. Figure 5 shows the results. This configuration stores and releases water mass, effectively increasing system inertia. This results in lower oscillation frequencies and decreased damping, as shown in Table 2.

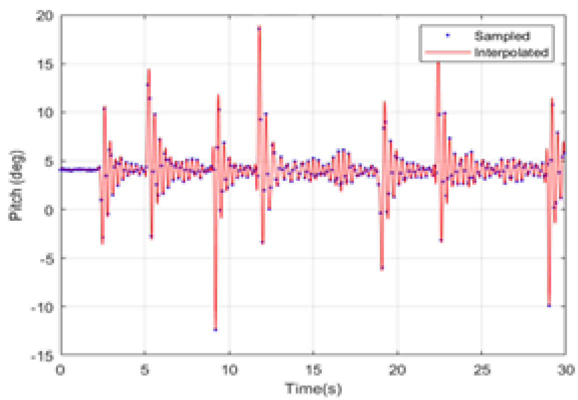

Figure 5: System damping: with controlled OWCs.

Table 2: Identified system poles for controlled OWCs

Configuration	Damping	Frequency (rad/s)	Time Constant (s)
Controlled OWCs	0.153	15.6	0.417

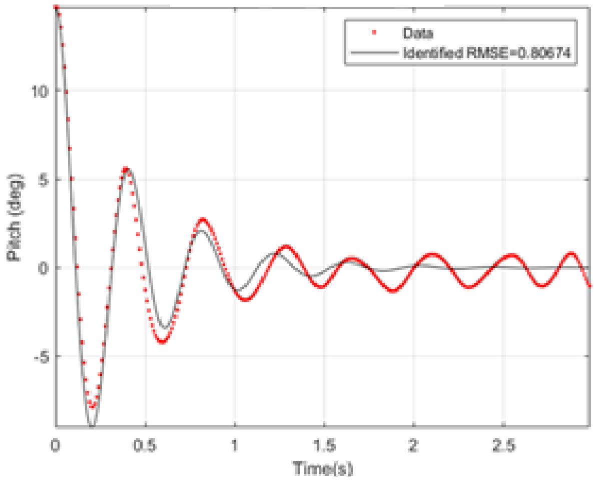

Figure 6: Damping test with actively controlled OWCs without waves or wind.

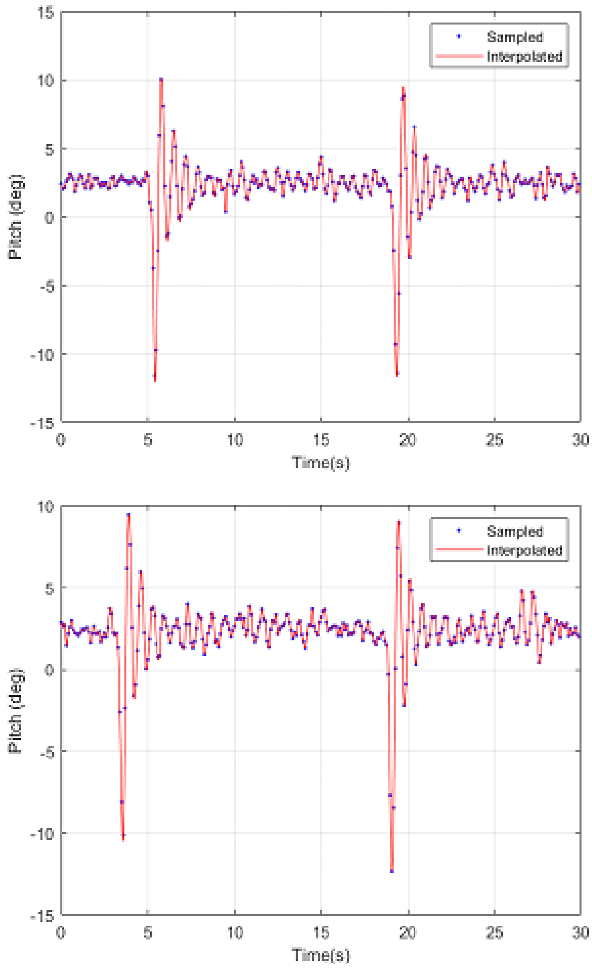

Figure 7: Pitch damping response with and without active gyroscope.

4. Dynamics with Gyroscopic Stabilizers

Experiments were conducted both with and without an active gyroscopic actuator, consisting of a motorized disk aligned along the turbine's mast. When spinning, the actuator generates gyroscopic torques that redistribute energy via precession effects.

Figures 7 and 8 show that although stabilization time increases (due to longer mooring lines and higher buoyancy contributions), the effect of the gyroscopic actuator remains negligible. This is due to the underactuated nature of the system, dominated by mooring and buoyancy forces.

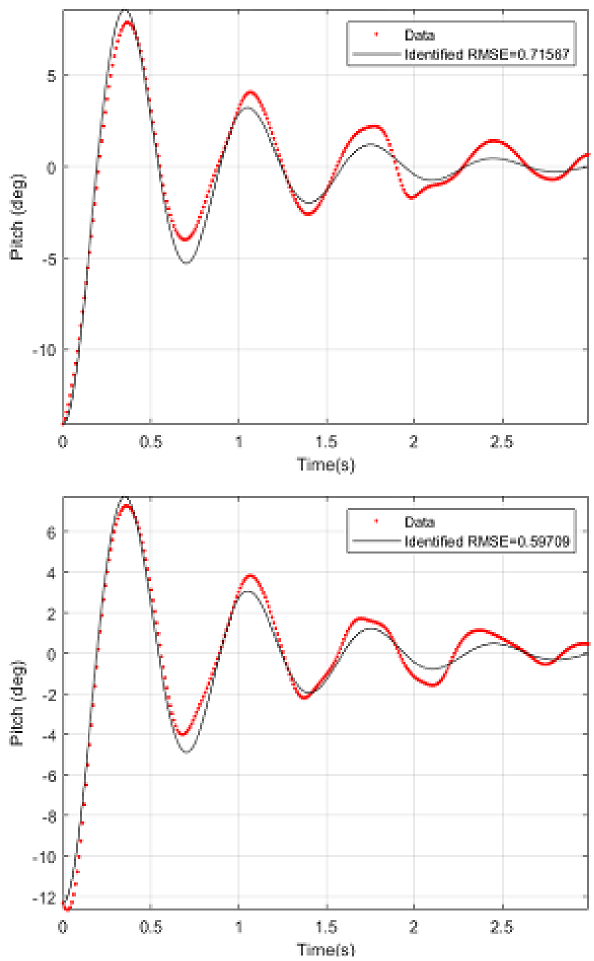

Figure 8: Model identification for the gyroscopic stabilization test.

Table 3: Identified poles with and without gyroscopic actuation

Configuration	Damping	Frequency (rad/s)	Time Constant (s)
Gyro inactive	0.154	9.09	0.714
Gyro active	0.146	9.06	0.759

5. Conclusions and Future Work

The integration of floating wind turbine prototypes developed at the Universidad Complutense de Madrid (UCM) with floating platforms equipped with Oscillating Water Columns (OWC) from the Universidad del País Vasco (UPV/EHU) has been successfully achieved. Preliminary experimental tests have been conducted to evaluate the feasibility of identifying dynamic models that incorporate the effects of various actuators. This foundational step aims to support the future design and implementation of active and passive control strategies for floating offshore wind energy systems.

Several limitations were identified in the measurement system, which was based on an Arduino Mega microcontroller. The sampling process was programmed via MATLAB, which restricted the minimum sampling period to 0.1 seconds. Given the fast dynamics of the floating structure, this resolution is insufficient. A more appropriate sampling frequency, on the order of 0.01 seconds, is necessary. This improvement could be realized by programming the data acquisition firmware directly in C to bypass the limitations imposed by the MATLAB interface.

The relaxation tests revealed significant nonlinear behavior in the system response. While linear models have been identified and provide a reasonable first approximation, more accurate modeling would require either nonlinear system identification techniques or linear models with time-varying parameters. Furthermore, the results highlight the critical role of the mooring system in the overall dynamics of the platform. Therefore, maintaining consistent and realistic mooring configurations is essential for all experimental setups.

The experiments also indicated a minimal dynamic effect from both the oscillating water columns and the gyroscopic actuators. This limited influence is attributed to the excessive static stability of the current OSWT (Oscillating System Wind Turbine) prototypes. The system appears to be heavily underactuated, where the restoring forces provided by buoyancy and mooring lines dominate the system dynamics, overshadowing the contributions of other actuators.

To address this, future prototypes should aim to reduce inherent system stability in order to amplify actuator effectiveness. This could be achieved by elevating the center of gravity of the platform or by employing longer and more flexible mooring lines to reduce restoring stiffness. These changes would create a more representative experimental model of realistic offshore floating systems.

Based on the insights gained from these initial tests, several weaknesses in the current experimental setup have been identified. Addressing these shortcomings will be a priority in future experimental campaigns to enable more accurate system identification and robust control validation under realistic offshore operating conditions.

Acknowledgments

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