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Behavioural Analysis of Barge-Type Floating Wind Turbines in Wind and Wave-Excited Environments

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Abstract. This article presents the results of various experimental tests conducted on small-scale floating wind turbine prototypes at the Universidad Complutense de Madrid (UCM) in the Universidad del Pais Vasco (UPV/EHU) wave tank. The study focuses on the forced dynamics of a barge-type Floating Wind Turbine (FWT) anchored to the seabed, analysing its behaviour under both wave and wind conditions, with the final goal of being able to identify the influence of the external perturbation on the system dynamics. The experiments are conducted with aggressive wave conditions as well as scaled waves corresponding to the prototype size. The research highlights issues encountered with the monitoring system, particularly difficulties in accurately recording signals at the small scale, both for the prototype and wave measurements. The experimental results provide valuable insights into the turbine's dynamic behaviour when subjected to combined wind and wave excitation.

Key words. Floating offshore wind turbine, towing tank, experimental tests, wind and waves excitation.

1. Introduction

Experimentation with real-life prototypes in all fields [1], and specifically within wind energy with small-scale models of wind turbines, is essential to fully understand their behaviour under the complex interaction of waves and wind, as simulations alone cannot capture all the nuances of real-life conditions. While computational models provide valuable insights and predictions, they are often based on simplifications and assumptions that may not account for unpredictable environmental factors, such as turbulent wind patterns, wave dynamics, and structural fatigue over time. Testing under real-life conditions allows us to observe how wind turbines respond to these dynamic forces, identify unforeseen challenges, and validate the accuracy of simulations. Furthermore, physical prototypes reveal practical issues related to performance, maintenance, and materials durability that simulations might otherwise miss [2]. By combining simulation data with empirical results from real-world models, researchers can refine designs, improve efficiency, and ensure the reliability of wind turbines in harsh offshore environments, thereby driving the development of sustainable energy solutions.

As part of the joint research project [3], which involves the development of various wind turbine prototypes at the UCM and the design of barge prototypes with oscillating water columns (WEC) at the UPV/EHU, the need to conduct integrated experimental tests emerged. The goal is to perform experiments with FWT prototypes, scaled to represent floating wind turbines, in the wave channel at UPV/EHU water tank.

This integration is highly complex, requiring the coordination of aerodynamic, hydrodynamic, electrical, and mechanical systems [4]. Beside, these floating wind systems are excited by both, wind and wave disturbances, which influence the dynamics and have to be taken into account [5].

However, before beginning a serious analysis of the complex effects of external disturbances on floating turbines, it is necessary to carry out pre-experimental work to define the design process of the low-scale WT model, as well as to find the appropriate scaling criteria, and devices and methods for measuring and monitoring the variables [6].

The ultimate goal of these experiments is to use experimental data to identify the dynamics of the floating turbine when disturbed by wind and waves. To this end, this paper describes the system designed for experimentation and monitoring the behaviour of the floating turbine with oscillating columns under various conditions.

This is necessary to design strategies aimed at reducing platform oscillations and achieving more efficient and stable energy production, while reducing structural wear and tear on the system [7-8].

Two scenarios related to wind disturbance have been tested, with and without wind. The results show that the effect of wind on the average inclination of the turbine platform is visible and identifiable. Experiments have also been carried out with various wave conditions, of different heights and periods. However, in this case, it has been shown that the experimental system does not accurately capture small waves, as it introduces peaks and low-frequency components. This prevents the identification of perturbed models from the signals recorded in the experiments.

This analysis of the experimental results suggests a redesign of some parts of the experimental system.

The structure of the article is as follows. Section 2 shows the experimental setup, consisting of a wind turbine, platform, and the instrumentation needed to monitor its behaviour. Section 3 presents a simple mathematical model that allows us to visualize the effects of disturbances on the platform's dynamics. Section 4 graphs and analyses the data obtained in various experiments under different conditions. The paper concludes with conclusions and future work.

2. Experimental setup

At the UCM, several wind turbine prototypes and their corresponding monitoring systems have been developed [9], with some being adapted for installation on floating barges for these experiments.

The UPV/EHU wave tank operates at a scale comparable to that of the UCM prototypes (see Fig. 1). It is equipped with a wave generator at one end and a beach at the other, designed to absorb part of the wave energy and reduce the effects of wave rebound.

The experimental setup has been implemented by a wind generation system consisting of an industrial fan, as shown in Fig. 2. Two types of barges have been tested, each anchored to the canal floor with four mooring lines, as depicted in Fig. 3. Suction cups served as an anchoring mechanism. In some experiments, the system was damped without waves, and the lengths of the anchoring lines were adjusted to achieve more realistic behaviour. These modifications significantly altered the system dynamics, making the results not directly comparable across experiments. Different chain lengths were tested until a configuration that mimicked real-world systems was found, providing a certain degree of freedom for barge motion.

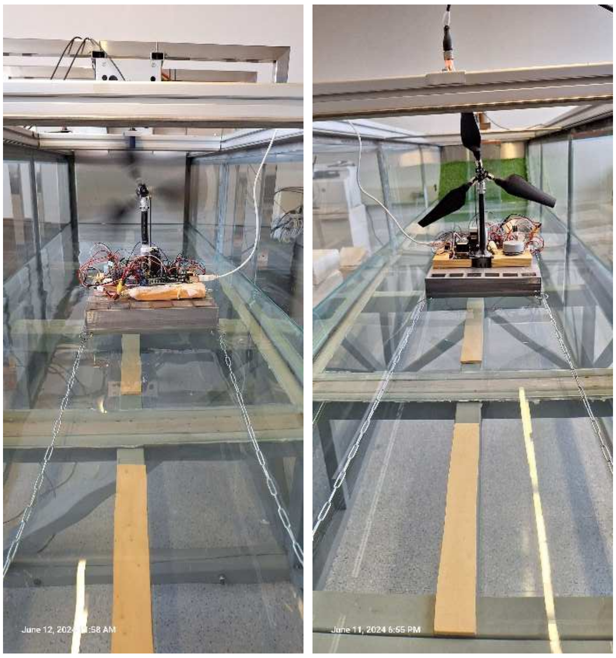

Fig. 1. Wave tank with FWT model, left is the view towards the wave generator, right towards the wave absorber.

The instrumented wind turbine prototypes were mounted on the two types of barges, as shown in Fig. 4. The figure illustrates that the water columns are positioned at the bow and stern of the barge, configured as open columns for these tests. Two FWT configurations have been tested:

- Forced wind turbine and barge with either open or closed OWCs.
- Wind turbine with a gyroscopic stabilizer and barge with controllable OWCs.

A comprehensive range of experiments was conducted:

1. With regular waves at scale:
    - Average swell: T=5s, Hs=2cm
    - Aggressive waves: T=4s, Hs=2cm
    - Aggressive waves: T=5s, Hs=3cm
2. With and without wind.

Fig. 2. In parallel to the wave generator, a fan capable of generating wind was added.

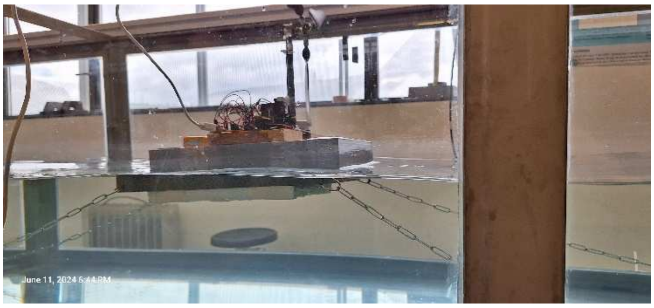

Fig. 3. Barge anchored to the bottom by four mooring lines.

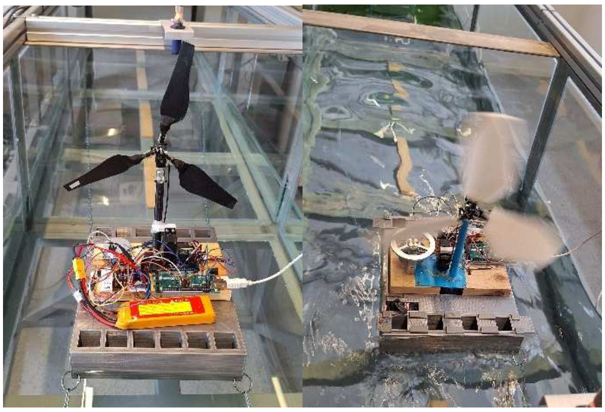

Fig. 4. Instrumented FWT prototypes. The upper image shows a barge-mounted forced wind turbine with open or closed OWCs. The bottom image shows a free-standing wind turbine on a barge with a gyroscopic stabilizer and controllable OWCs.

3. Mathematical modelling

Although more detailed mathematical models of turbines exist [10], to identify the effect of different subsystems, the dynamics of the pitch degree of freedom, □, are modelled using a second-order linear differential equation (1). This approach allows for the extraction of the main parameters that govern the system's behaviour.

$$I \cdot \ddot{\phi}(t) + D \cdot \dot{\phi} + K \cdot \phi = T_{waves} + T_{wind} \qquad (1)$$

where I ($kg \cdot m^2$) is the principal moment of inertia with respect to the pitching degree of freedom. This depends on the system's mass distribution and the center of rotation, which in turn is influenced by the center of flotation of the system. D (N·m·s/deg) is the damping factor, primarily determined by the hydrodynamics of the barge and the aerodynamic behavior of the wind turbine. K (N·m/deg) is the restoration factor, mainly dependent on the barge's hydrodynamics and the characteristics of the anchor lines. T_{wave} (N·m) and T_{wind} (N·m) represent the disturbing torques generated by waves and wind, respectively. The differential equation can be normalized by dividing by the moment of inertia, so that this value does not need to be identified. In this way, one works with normalized perturbation torques relative to the system's inertia.

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Prior damping experiments were conducted to identify the system's dynamics. The following section presents experiments on the system perturbed by waves and wind.

4. Experimental data

Several experiments have been conducted using various wave conditions, both with and without wind, to test the system with different sea states [11].

During the initial trials on the first day, highly aggressive waves were tested. Subsequently, wave heights and periods were scaled according to the model scale, working with significant wave heights of 2 and 3 cm, which are comparable to the barge's height. Wave periods of 0.4 and 0.5 seconds were also tested, enabling analysis of behaviours under different resonant conditions.

In Fig. 5, it is evident that when the wave length matches the barge's length, the barge rides the wave smoothly. Conversely, when the wave length exceeds the barge's length, greater resonance is generated.

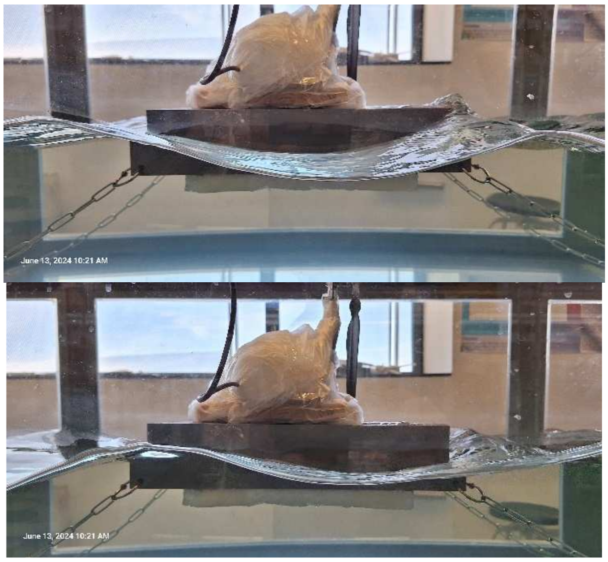

Fig. 5. Coupling between wave and barge.

Figures 6, 7, and 8 illustrate experiments conducted with wave heights of 1, 2, and 3 cm, respectively.

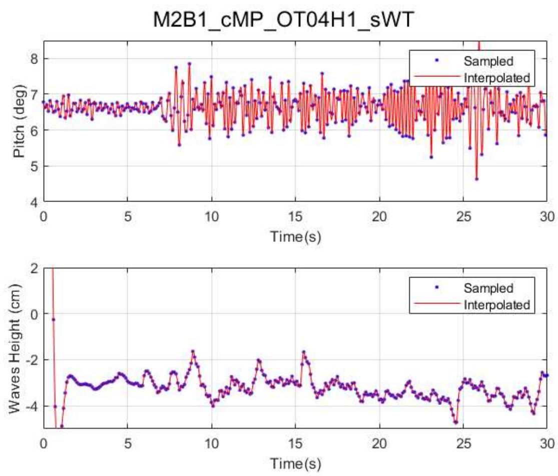

Fig. 6. Experiments with wind and waves of T=0.4s and H=1cm.

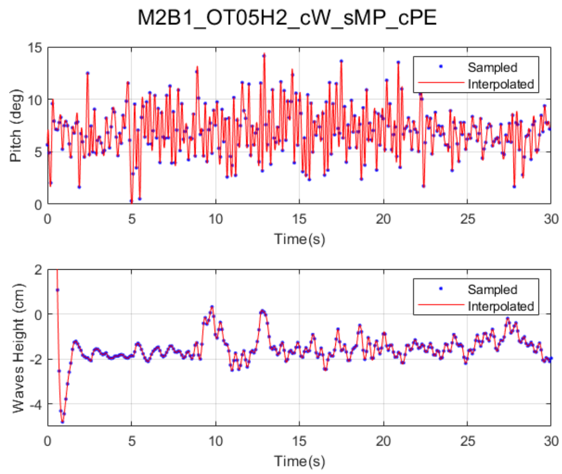

Fig. 7. Experiments with wind and waves of T=0.5s and H=2cm.

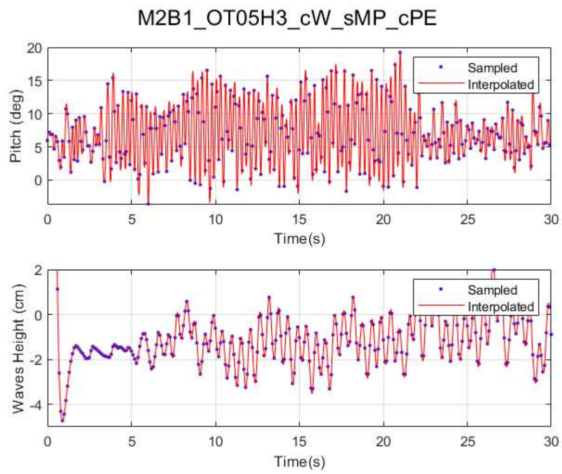

Fig. 8. Experiments with wind and waves of T=0.5s and H=3cm.

The experiments were carried out under constant wind conditions, which introduced an average pitch observed across all trials. This pitch is attributed to the drag imposed by the wind turbine relative to the wind. However, wave recordings were not synchronized with the barge motion recordings, as they were captured using different systems. The wave sensors required a stabilization time of approximately 2 seconds, preventing synchronization. Additionally, the wave sensor's resolution was suboptimal, performing acceptably only for wave amplitudes of 3 cm and becoming increasingly inaccurate for smaller measurements, such as 1 cm and 2 cm. In trials with 1 cm waves, the wave sensor exhibited cyclical measurement errors, occasionally reporting unrealistically high values not observed during the actual experiment.

Due to the wave sensor's initialization, the initial portion of each experiment had to be discarded. Similarly, the final part was excluded due to wave reflections. Synchronization of wave signals with motion signals was necessary since, after a few seconds of initialization, the waves reached the barge and began to influence its movement.

Given the low quality of wave measurements, the focus was placed on waves with a significant height of 3 cm for model identification. However, attempts to identify models from these selected signals yielded unsatisfactory results, as shown in Fig. 9. The pitch signal's biases from wind effects and wave sensor inaccuracies were removed, yet discrepancies remained. The pitch signal produced by the model had a frequency approximately double that recorded by the experimental electronics. This discrepancy arose because the excitation signal, the wave swell, exhibited a lower frequency than the experimental pitch. Consequently, some signals were not sampled at twice the period.

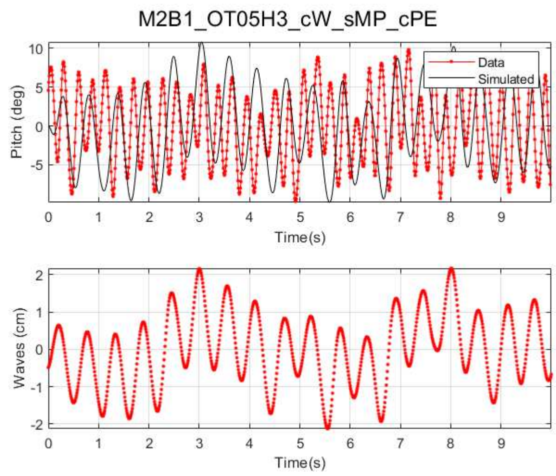

Fig. 9. Identification of the perturbed model with original waves.

To address these issues, wave time was scaled to align the excitation frequency with the system response frequency. The processed results, shown in Fig. 10, reveal that the model accurately captures the average pitch generated by the wind and the correct frequency, as small peaks appear matching the experimental data's frequency. However, the wave-induced response still does not align with experimental results. This mismatch arises from a low-frequency component in the recorded wave signal that does not correspond to the observed experiments. The generated waves were confirmed to be regular, but the recorded component, amplified by the model, reflects phantom waves with larger amplitudes that were not actually present. This phantom response constitutes the dominant system response and undermines the accuracy of the results.

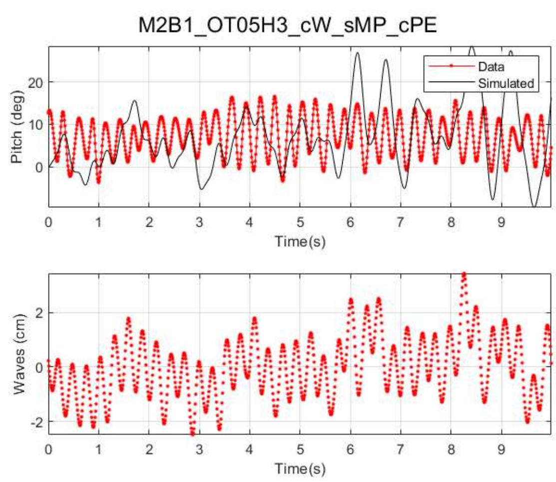

Fig 10. Identification of the perturbed model with processed waves.

5. Conclusions and future works

The UCM wind turbine prototypes have been integrated with the UPV/EHU barges with oscillating water columns. An experimental system has been set up on the UPV/EHU wave channel, adding the functionality of generating wind for the floating wind turbines. Preliminary experiments have been carried out in this environment to evaluate the feasibility of identifying models and assessing the behaviour of control systems.

The effect of the wind on the average pitch of the FOWT can be seen and identified. However, in the experiments with waves, several problems have arisen. The waves must be scaled to the size and time of the model. Therefore, it is necessary to work with significant wave heights of 1, 2 and 3 cm. The current system does not correctly capture such small waves, introducing peaks and lower frequency components. This makes it impossible to identify perturbed models from the signals recorded in the experiments.

Arduino Mega [12] has been used as an instrument to monitor and control the prototypes. This device has been managed from Matlab, which introduces a lot of delay in the capture of the signals. To avoid this problem, it is already being reprogrammed in C, to achieve sampling periods of 0.01 s.

The main conclusion of this work is that an experimental setup has been implemented that will allow validating the attenuations of the pitch of the platform of a floating wind turbine when it is disturbed by waves and wind. It allows to identify some of the effects of these external perturbation on the system.

Besides, according to these first experiments, the weak points of the experimental system have been detected, which will be improved for future experiments.

Another system needs to be developed that allows wave recording in real time with centimetre resolution. One possible alternative is through image processing. Using the photographs and videos captured during the experiments, a real-time image processing can be designed that captures the wave profile and the position of the barge. The barge is easy to recognize, and its upper corners can be determined. From these corners, the pitch, surge and heave of the barge can be determined. Since it has a uniform bottom, it would also be possible to determine the wave profile relative to the barge, which is precisely the signal that excites the model. This would allow the excitation signal (wave profile) and the system output (barge pitch) to be determined in a synchronized manner and with millimetre precision. By opening up the image capture further, it would even be possible to determine the shape of the anchor lines, and their state of tension could be estimated. This monitoring system can be considered as a new task in research projects.

This environment will allow the evaluation experimental of platform pitch control strategies with hybrid devices. These devices can be part of the wind turbine, such as the Blade Pitch Control (BPC), or added to the platform, such as the Tuned Mass Damper (TMD) or the Wave Energy Converters (WEC).

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