Aero- and hydrodynamic responses of floating offshore wind turbines

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SUMMARY
Offshore wind turbines benefit from high-capacity wind resources but are subjected to concurrent wind, waves, and current loads. This study experimentally addresses the dynamic performance of a Tension Leg Platform (TLP) system using a scaled model. Experiments conducted for concurrent wind, waves and currents loads provided insight into the aero- and hydrodynamic performance of a floating offshore wind turbine with particular emphasis on the structural response of a TLP. The findings are based on experimental results of integral loads and structural dynamics.

Keywords: Floating offshore wind turbine, concurrent wind, waves, and current loads, dynamic response, JONSWAP waves

1. INTRODUCTION

Offshore wind turbines (OWTs) are a crucial type of renewable energy structure. Compared to their onshore counterparts, OWTs benefit from a significantly more robust and consistent wind resource, allowing for relatively large energy yield and the deployment of larger rotors. Areas far from shore tend to provide stable wind resources due to larger mean wind velocities, reduced turbulence intensity and small wind shear when compared to common onshore sites. These areas, however, are usually in deeper waters where fixed-bottom foundations are no longer feasible or viable. In such cases, the floating concepts are required, with tension leg platforms (TLPs) emerging as promising concepts due to their high stiffness and favorable dynamic characteristics (Bachynski and Moan, 2012).

Deep-water environments are characterized by complex aero- and hydrodynamic loads on OWTs, Buljac et al. (2022). TLPs are subjected to the combined effects of aerodynamic loads from the wind, hydrodynamic loads from the waves, and forces due to ocean currents. These load components are inherently stochastic and interact in a nonlinear manner; thus, they influence the global motion of the platform and the local structural response of its key components. While each load component is well understood when acting alone, its combined effect on the TLP dynamic response presents significant challenges for structural integrity and serviceability. In this work, the combined action of wind, waves and current on a TLP OWT has been experimentally assessed on a scaled model.

2. EXPERIMENTAL SETUP

Experiments were conducted in the Wind-Wave-Current Tank (WWCT) at Newcastle University, UK. The test section is 1.8 m wide and 2.0 m high, equally split into 1.0 m high wind and water sections. The facility allows for precise control of concurrent flows with wind velocities u_w up to 20 m/s, current velocities u_c up to 1.0 m/s, and waves ranging from 0.25 Hz to 1.25 Hz. A wave probe was used to capture the free-surface height. The TLP model is based on a modified Siemens Sapiens FFA W3 OWT (Figure 1). The model was anchored with four mooring lines connected to the high-frequency force balance (HFFB). A buoyancy tank ensured that all four mooring lines were always in tension. This prevented slack and snapping under stochastic loading, Hsu et al. (2017). A potentiometer was installed in the rotor to control the angular velocity for proper adjustment of the tip speed ratio.

Figure 1. Model of the TLP OWT used for scaled experiments

Integral loads were assessed using a DHI 6-Component force transducer (Type 206/6C) fixed to the tank floor. The HFFB enabled concurrent measurement of three forces (surge, sway, heave) and three moments (pitch, roll, yaw) at high frequency. Data were sampled at the sampling rate of 200 Hz with 60 s time record length to account for the transient effects of the wave impact and aerodynamic fluctuations. A high-speed camera was used to track a reflective marker on the TLP OWT model to provide 6-DOF motion data. The experiments were performed using a systematic test matrix, including isolated load cases and fully concurrent loading. The experimental program was categorized into three stages, i.e., single-load cases (wind, wave, or current only), dual-load cases (e.g., wind-wave or wave-current), and fully concurrent triple-load cases. Wave conditions were further altered to encompass regular waves and JONSWAP spectra to simulate natural wave states. The HFFB was used in all test cases, whereas the optical motion-tracking system was utilized only during trials without wind load. This was a necessary constraint of the open-section wind-tunnel configuration. Consequently, the HFFB serves as the primary instrument for characterizing the TLP OWT model for the entire spectrum of wind, waves and current loads.

3. RESULTS

Three load cases were analyzed, i.e., wave load only (JONSWAP wave spectrum), combined wave and current loads, and concurrent action of waves, current and wind. The wave height normalized by water depth H_s/h was 3.25, whereas the wave peak period was set to 0.93 s. Time history of surge force is shown in Figure 2 along with its probability density function (PDF) in Figure 3. The signals are dominated by the wave-induced periodic behavior, with the mean force increasing as additional loads (wind and current) are introduced. At the same time, the variability around the mean decreases due to the longitudinal displacement of the OWT model, which increases mooring line tension. This effect, known as the mean drift stiffness, leads to a reduced standard deviation of the surge force and a more pronounced peak in the probability density function.

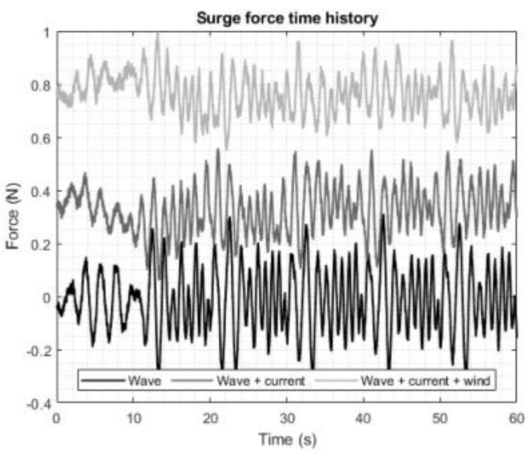

Figure 2. Surge force time history for three load cases

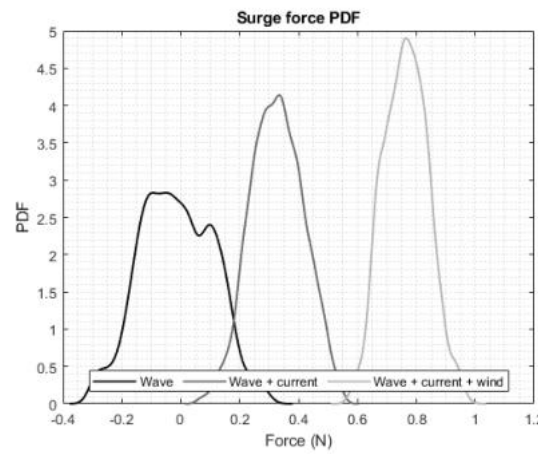

Figure 3. PDF of surge force for three load cases

The response of the TLP OWT model in the frequency domain is characterized by response amplitude operators (RAOs), which define the ratio between the incident wave spectrum and the resulting structural loads. For the integral forces measured by the HFFB, the Force RAO is derived using the spectral density method. The power spectral densities (PSDs) of the wave elevation, $S_{\eta\eta}(\omega)$ and the measured force, $S_{FF}(\omega)$, were estimated using Welch's method to reduce spectral leakage and variance. The magnitude of the Force RAO is calculated as:

$$\mathrm{RAO_{Force}}(\omega) = \frac{\sqrt{S_{FF}(\omega)}}{\sqrt{S_{\eta\eta}(\omega)}}. \quad (1)$$

Figure 4 shows the PSD of the wave elevation, surge force RAO and surge force PSD for two load cases, i.e., JONSWAP waves only and concurrent action of JONSWAP waves, wind and current. The wave PSD remained constant throughout both load cases, since the wave elevation is not substantially affected by the wind and current in such a short section. Therefore, the observed differences in the response are due to the system dynamics, not the input.

Surge force PSD exhibits a strong peak at the same frequency, corresponding to the maximum wave loads. The wave-only load caused a much stronger peak in the force PSD, exhibiting high energy content in oscillations around the peak wave frequency. On the other hand, the surge force RAO exhibits a plateau at that frequency, i.e., the surge response is not resonantly driven, but stiffness-controlled.

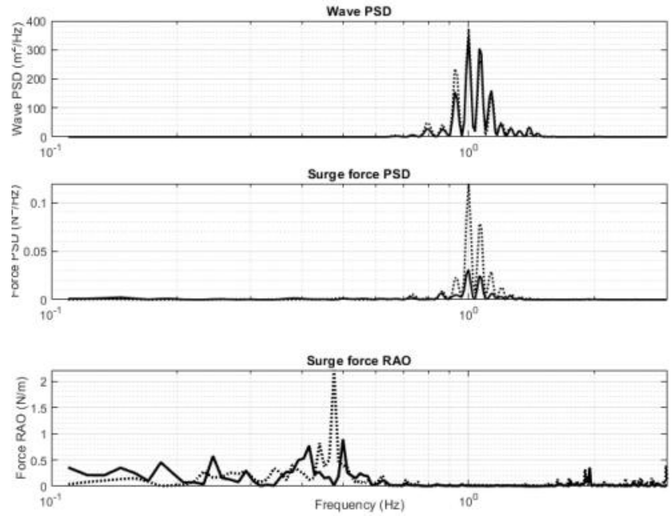

Figure 4. Wave PSD, surge force RAO and surge force PSD for two load cases (waves only and concurrent action of waves, wind and current)

The peak RAO is at ~0.5 Hz, corresponding to the natural frequency of the structure. The peak magnitude at the resonance frequency is pronounced in the waves-only load case compared to the combined load case. This increase in the peak is attributed to the increased aerodynamic and hydrodynamic damping provided by the OWT model rotor and the steady current flow. Furthermore, a shift in the peak frequency was observed in a combined load, likely a result of the geometric stiffening of the mooring lines due to the mean horizontal displacement of the platform, which increases the effective restoring force of the system. It should be noted that the RAO formulation assumes a linear relationship between the wave elevation and structural loads. While nonlinear interactions are known to influence the TLP response, the experimental results show that the integral surge force is dominated by the first order wave response.

4. CONCLUSIONS

The aero- and hydrodynamic loads on the TLP OWT model were experimentally studied. Three separate load cases were studied, i.e., JONSWAP waves only, waves and current flow, and a concurrent action of waves, current and wind. The results indicate a stiffness-controlled dynamic response, where the wave-only case exhibits a higher peak, while combined loads yield additional damping and geometric stiffening, reducing and slightly shifting the resonant response.

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