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Emulating aerodynamic forces and moments for hybrid testing of floating wind turbine models

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Abstract. The use of devices with multiple propellers to simultaneously emulate several aerodynamic loads during hybrid testing of floating wind turbines is the emerging state of the art. In this study a validation methodology and a metric are defined for the standardization of the calibration process for multiple propeller hybrid actuators. A statistical validation between the numerical simulations and experimental results is applied and Power Spectral Density is used to calculate the validation metrics. In this paper, the proposed validation method is applied to a novel design for an actuator, which consists of a custom designed frame with six aerial drone propellers. The actuator is named Multi-Propeller Device (MPD). As a test case for the proposed validation method, the MPD is used in this study to emulate the aerodynamic loads of the NREL 5 MW reference turbine at 1:37 scale. The numerical input is generated with the aero-hydro-elastic solver FAST. The aerodynamic loads and effects investigated are rotor thrust and torque, and gyroscopic moment. The recommended validation metric is the Fraction of Measurements within a user defined Tolerance (FMT), which is 1 for a flawlessly operating device. The MPD performs well at emulating rotor thrust and torque loads, with FMT = 0.97 and 0.98 respectively. However, the MPD underperforms at emulating more complex wind loads, such as gyroscopic moment with FMT = 0.27. The poor results for gyroscopic moment are attributed to the generation of significant amounts of high-frequency vibration when propeller pairs of the MPD are operating intermittently at high rotational speeds.

1. Introduction

Hybrid testing combines physical and numerical modelling for scale model tests. Some of the environmental loads acting on the physical model are replaced by a numerical model which calculates the resulting forces. These forces are emulated by a mechanical actuator on the physical model. Hybrid testing for floating wind turbine models is used as an alternative to physical generation of either waves, wind or current. It also provides a solution for the scaling mismatch arising from working in two fluid domains; air and water.

The coupled aerodynamics/hydrodynamics of Floating Offshore Wind Turbines (FOWT) present difficulties when attempting scaled physical experiments [1]. Hydrodynamic loading on the floating platform is dominated by gravity-driven surface waves. To correctly scale the gravity and inertial forces acting on the platform Froude scaling is applied. Aerodynamic loading on the turbine is dominated by viscous forces, i.e. the flow of wind around the structure. Correct scaling of the aerofoils of the turbine depends on the Reynolds number. A geometrically scaled rotor using Froude scaling will have a lower Reynolds number at model scale compared to the rotor at prototype scale. As a result, the model scale



rotor will have a lower lift coefficient and higher drag coefficient, which will affect the aerodynamic performance of the scale model turbine. This in turn, will cause a misrepresentation of the structural response of the FOWT to wind loading.

During hybrid testing in laboratory basins, waves are modelled physically, and the wind field is introduced numerically. One or more actuators emulate the Froude scaled aerodynamic loads at hub height of the model. Air fans can be used as actuator for hybrid FOWT modelling. Wright et al [2] used a single ducted fan on a 1:50 and a 1:30 scale model of a hexagonal braced TLP platform. Only steady thrust force was emulated in their experiments. Andersen [3] fitted a non-ducted 2-bladed fan on a model of a generic semi-submersible FOWT. The aerodynamic thrust loading was modelled using a turbulent wind time series of the OC4 semi-submersible FOWT, a comparable platform to the platform used in the experiments. Azcona et al [4] installed a single ducted fan at hub height of a 1:40 scale model of the OO Concrete Star Wind Floater semisubmersible FOWT. In their experiments, motion tracking data of the physical model was used for real-time feedback as input for the numerical simulation. With the real-time feedback method, thrust force is re-calculated for each timestep and adjusted according to the position of the physical model. They named their hybrid test method Software in the Loop (SIL). Oguz et al [5] used the SIL method to test a 1:36 scale model of the Iberdrola TLP with a single ducted fan.

Rotor thrust is the dominant aerodynamic load on the motion response of the platform of floating wind turbines, the choice to use single ducted fans to emulate thrust force therefore seems reasonable. However, it ignores other aerodynamic loadings such as rotor torque and gyroscopic moment [4]. Bachynski et al [6] conducted a sensitivity study for the NOWITECH semisubmersible FOWT and found that all aerodynamic loads except vertical thrust and gyroscopic moment had significant influence on the response of the platform. Hall et al [7] conducted sensitivity studies for three types of FOWT and found that the influence of aerodynamic loads varies significantly depending on the type of platform. While the actual influence of additional aerodynamic loads depends on the type of floating platform, devices with multiple fans for simultaneous emulation of several loads are the emerging state of the art for hybrid testing with FOWTs in wave basins.

In this study a novel methodology is defined for the validation of multiple degree of freedom aerodynamic actuation devices. This validation methodology is applied to a novel actuator design.

2. Description of the Multi-Propeller Device

The proposed device consists of a custom designed frame with six propellers and is named Multi-Propeller Device (MPD), which is show in Figure 1.

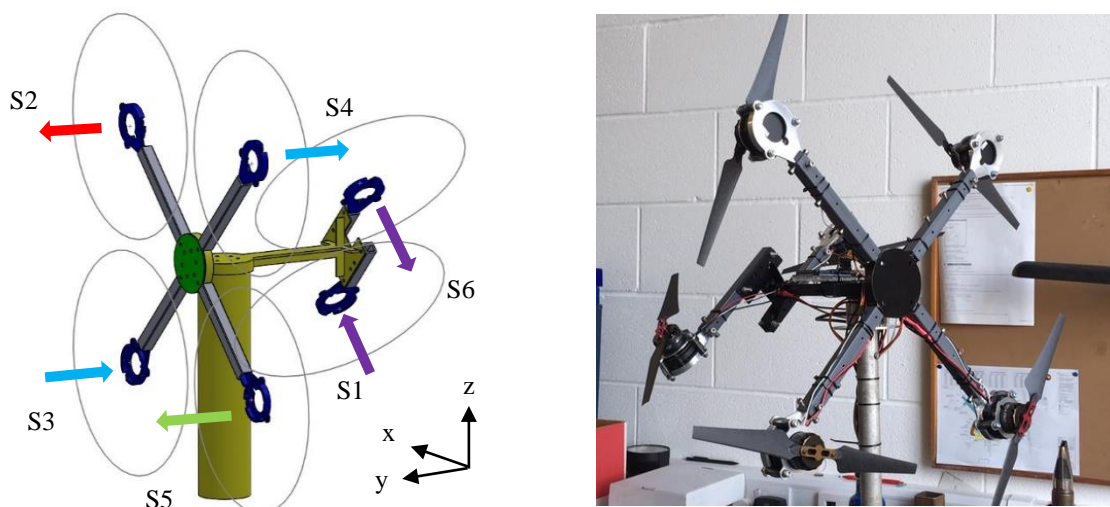


Figure 1. Multi-Propeller Device, the arrows indicate the thrust direction of the propellers

Much of the technology used for the MPD is borrowed from recreational aerial drones. The Electronic Speed Controllers (ESC), electric motors and propeller blades used for the MPD are all the

same parts as used in the DJI S800 aerial drone [8]. The frame of the MPD is made of aluminium and its configuration was chosen to suit the unidirectional thrust of the propellers, while keeping the frame as light as possible. In the configuration shown in Figure 1, propellers S3 & S4 emulate aerodynamic thrust, S1 & S6 emulate rotor torque and S2 & S5 in combination with S3 & S4 can be used to emulate wind shear and gyroscopic moment. The minimum length of each propeller arm is 200 mm from the center of the device. If larger moments are required for pitch, yaw or torque the arms can be extended. The arm extending from the tower to the torque propellers S1 & S6 is 235 mm. The torque propellers are kept away from the other propellers to minimize wake interference while all propellers are in operation. When operating, each propeller will generate its own torque and gyroscopic momentum. To ensure that this effect will not influence the test results, the propellers are installed so that each pair (S3 & S4, S2 & S5 and S1 & S6) has a propeller counter-rotating to the other, cancelling out each other's torque and gyroscopic moment. This technique is also used with aerial drones to ensure torque and gyro effects do not interfere with their flying ability. To control the propellers, the input signal calculated by the numerical simulation is scaled down and sent by the computer to an Arduino Mega 2560 board. The Arduino board translates the input signal into an analog Pulse Width Modulate (PWM) signal and sends it to the ESCs. Each propeller has its own ESC controlling the rotational speed of the DC motor. The motors are powered by a 25V DC power supply, which is connected to an AC power source.

An Interface 6A40-50N/5Nm six-axis load cell is mounted between the top of the tower and the MPD to measure forces and moments in the X-Y-Z reference frame. The load cell is positioned at the center of mass of the rotor-nacelle assembly of the full-scale turbine.

Aerial drone technology was also adopted for the device developed by Meseguer and Guanche [9]. The six propellers on their device were all in the same X-Z plane. Two propellers were used to emulate torque loads and the remaining four propellers were used to emulate thrust loads and pitch moments. None of the propellers on their device were used to create yaw moments.

Researchers from CENER, Spain, have used an MPD with SIL during a hybrid test campaign of an FOWT as part of [10]. Their device used only four propellers, all positioned in the same X-Z plane. The propellers on their device are bi-directional and are used for the emulation of thrust loads, pitch moments and yaw moments but do not include torque loadings.

3. Methodology

The main objectives were to develop a robust calibration method, and a validation method for use with multi-propeller actuators, such as the MPD, to contribute towards the standardization of the experimental approach used across test facilities. The validation method is based on work done in [11] and applies a statistical comparison between the numerical simulations and experimental results.

The aim of the MPD is to physically emulate the rotor force calculated numerically as accurately as possible, for the NREL 5 MW turbine at 1:37 scale. For simplicity the turbine was modelled on a rigid tower and fixed in the reference frame, i.e. no platform or tower motions were considered. During all physical experiments the MPD was mounted on an aluminium pipe with very high stiffness to replicate the rigid tower.

Two types of propeller blades of different size were used to determine the impact of blade size on the accuracy of the MPD. The first type of blade is the original type used on the S800 drone, and the second type is the blade used on the Mavic drone, with blade lengths of 150 mm and 75 mm respectively.

A test matrix was defined with increasing complexity of the aerodynamic loads. The experiments were designed to test the validation method on the MPD's output and bandwidth, or frequency range. The test matrix is shown in Table 1.

A detailed calibration of the thrust force each propeller can produce was made for both sets of propeller blades. Each propeller was first calibrated individually, then in pairs and finally with the combined propellers operating simultaneously. The difference in the results between individual, paired and combined calibrations gives an estimation of the wake interference between the propellers. The PWM signal range to control the MPD is 320-545 msec. with minimal increments of 5 msec. The propellers were operated for 10 seconds and the measured output was averaged for each PWM step to

produce calibration curves. The first two seconds of each record were discarded to exclude the initial vibrations at start-up.

Table 1. Test matrix of experiments performed with the MPD, (TC = Test Case)

	Wind speed			Blades			Thrust	Torque	Gyro
	12 m/s turbulent	25 m/s steady	8 m/s steady	S800 blades	Mavic blades				
TC 1	√	×	×	√	×	√	√	×	
TC 2	√	×	×	×	√	√	√	×	
TC 3	×	×	√	×	√	√	×	√	

3.1. Experiments.

The aero-hydro-elastic solver FAST v8 [12] was used as the numerical code for all simulations, and MATLAB was used with the Arduino support package to control the MPD. Except for test case 3, all tower and platform Degrees of Freedom (DOF) were disabled in the FAST simulations. To emulate rotor thrust and torque, a time series of turbulent wind with 12 m/s average wind speed and 14% turbulence intensity was used as input for Test Case 1 & 2. To demonstrate more complex aerodynamic loads, attempts were made to emulate gyroscopic moments, which requires propeller pairs S2 & S4 and S3 & S5 to operate intermittently. For the emulation of gyroscopic moments, a 350 second wind-only time series of the OC4 semisubmersible, at 8 m/s steady wind and platform DOFs enabled, was used as input for Test Case 3. The yaw motion of the platform resulting from the gyroscopic moment was used as input from the FAST simulation. The moment required to replicate this yaw motion was calculated and emulated by the MPD. In this case propeller S2, S3, S4 and S5 were actuating in the direction shown in Figure 1, while S2 & S4 and S3 & S5 were actuating as pairs and were operated intermittently to create the oscillations caused by the gyroscopic moment.

3.2. Validation.

To minimize uncertainty of hybrid testing of FOWT models with the MPD, high accuracy and repeatability at replicating demanded forces and moments are essential. The initial step in the validation process is a qualitative comparison consisting of two parts. The first part graphically compares the measured outputs with the numerical inputs. For the second part scatter plots are generated to show the correlation between the measured outputs and numerical inputs, and Power Spectral Density (PSD) is plotted to compare the difference in energy of the quantity of interest between experiment and simulation. The final step is a quantitative comparison. The spectral energy of each time series is used to calculate the quantitative validation metrics. The following validation metrics are used [11]:

Relative Error (RE):

$$RE = 1 - \left(\frac{\overline{E}}{S} \right) \quad (1)$$

Fraction of Measurements within a user defined tolerance (FMT):

$$a < \frac{S}{E} \leq b \quad (2)$$

Where E is the experimental PSD, S is the simulation PSD, a is a lower limit and b is an upper limit. Average values are indicated with an overbar. With a perfect performance RE would be zero, and FMT would be 1, with $a = b = 1$.

The direct comparison between simulation and experiment only indicates how well the MPD can replicate the input signal from the FAST simulations and does not give a measure of the ‘accuracy’ of

the system, that is, how close the laboratory experiments are to the expected real world performance. As a performance indicator for the MPD, direct comparison is an interesting metric from an engineering perspective to assist with the set up and calibration of multi degree of freedom actuation devices. However, it does not take the accuracy of the numerical code into account. Work has been done in the Offshore Code Comparison project [13] to assess the accuracy of FAST and other numerical codes, and a methodology to assess uncertainty of FOWT response during wave basin testing has been developed in [14]. However, the work to assign a specific value to the accuracy of numerical and experimental modelling of FOWTs are ongoing. In this work, loads calculated by FAST are assumed to be ‘correct’ and the ability of the MPD to emulate these loads is assessed. A generalized approach is used with RE and FMT for the validation of the MPD. These validation metrics take different sources of error and uncertainty into account and represent bias and scatter of the data.

With FMT, a user defined tolerance can be introduced by setting the limits of a and b . This is a clear benefit of FMT over RE as it allows the user to focus analysis on non-trivial or unknown sources of error in the system.

4. Results

A comparison of the calibration curves for aerodynamic thrust with the S800 and Mavic blades is shown in Figure 2. The plots show the combined thrust measured for propellers S3 & S4 for both sets of blades at each PWM step. Note that the thrust at lower rotational speeds is similar for both sets of blades, which is unexpected considering the difference in size.

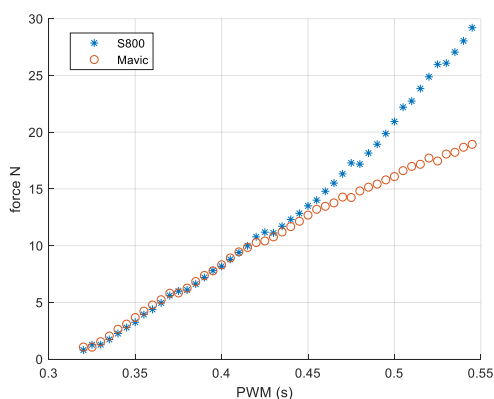


Figure 2. Calibration curves for S3 & S4

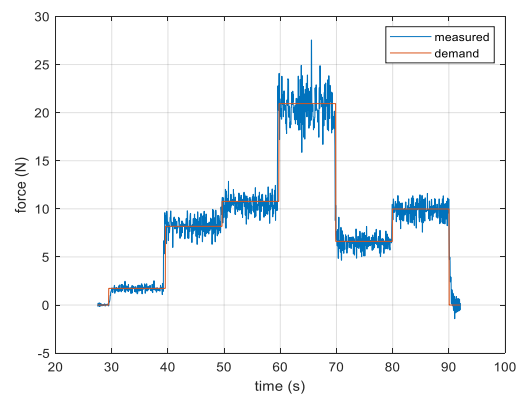


Figure 3. Time series of steady thrust loads by S3 & S4 with S800 blades

Maximum delivered thrust per propeller is 15 N and 9 N with the S800 and Mavic blades respectively. The calibration values were tested with a time series of steady loads, shown in Figure 3, which indicates that the MPD generates a considerable amount of high-frequency vibration noise during operation.

The rates of change for thrust and moment by the propellers were also derived from the calibration data. High rates of change are achieved with both S800 blades and Mavic blades. Thrust changes at a rate of 65 N/s and 50 N/s with the S800 and Mavic blades respectively, and moment changes at a rate of 7.5 Nm/s and 5 Nm/s respectively.

Rotor thrust and torque curves of the NREL 5 MW turbine were replicated by emulating thrust and torque at steady wind speeds found with FAST simulations. The propellers were operated for 15 seconds at each wind speed and measured forces and moments were averaged. The results are shown in figure 4 & 5, where the error bars indicate the standard deviation of the measurements.

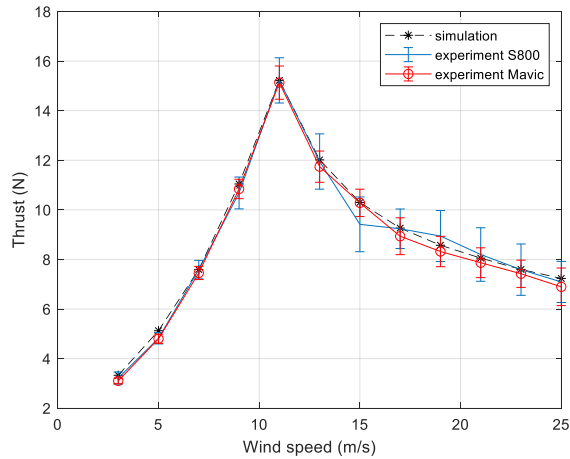


Figure 4. Thrust curve, NREL 5 MW turbine. Thrust values are shown at model scale with corresponding wind speeds at full-scale

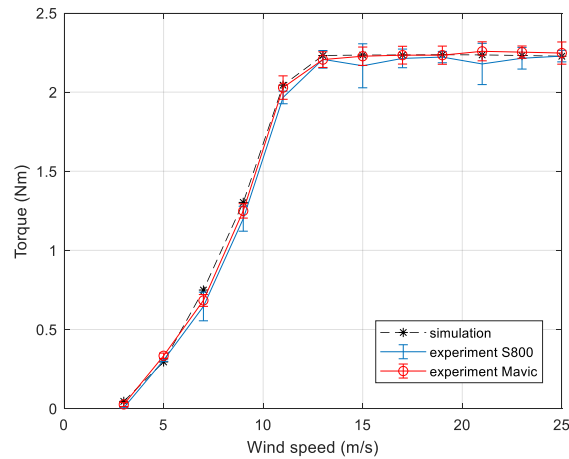


Figure 5. Torque curve, NREL 5 MW turbine. Torque values are shown at model scale with corresponding wind speeds at full-scale

Figure 6 & 7 show Test Case 2 as an example of results for emulating rotor thrust and torque of the NREL 5 MW at 12 m/s turbulent wind with the Mavic blades. All values are shown at scale.

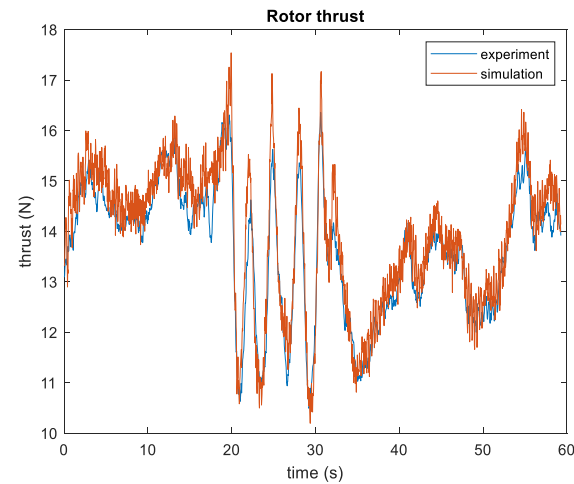


Figure 6. Emulated rotor thrust with Mavic blades

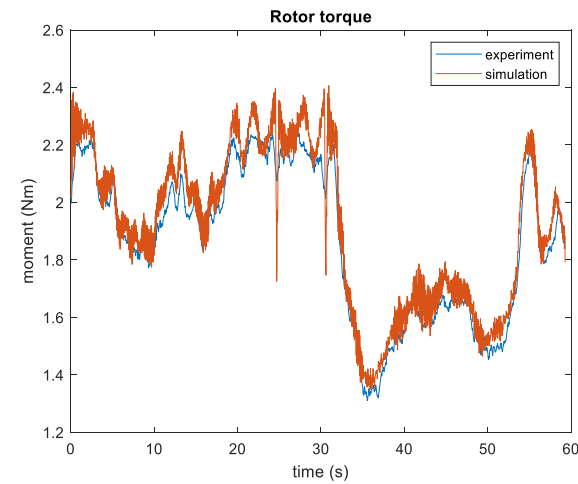


Figure 7. Emulated rotor torque with Mavic blades

This first qualitative comparison indicates that the MPD has the capacity to closely emulate rotor thrust and torque of the turbine. A low-pass filter was applied to the measured data to filter out the high frequency noise.

The next qualitative comparison is shown in Figure 8 & 9.

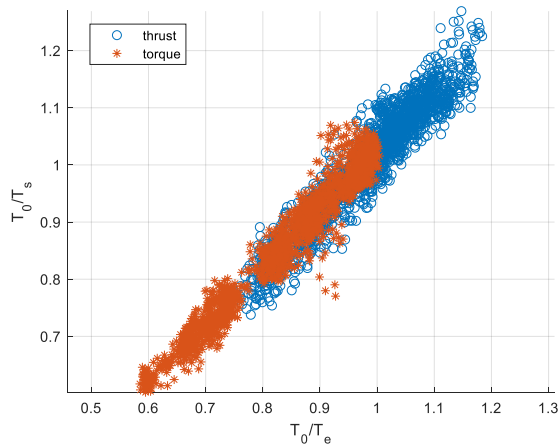


Figure 8. Scatter plot for Test Case 2

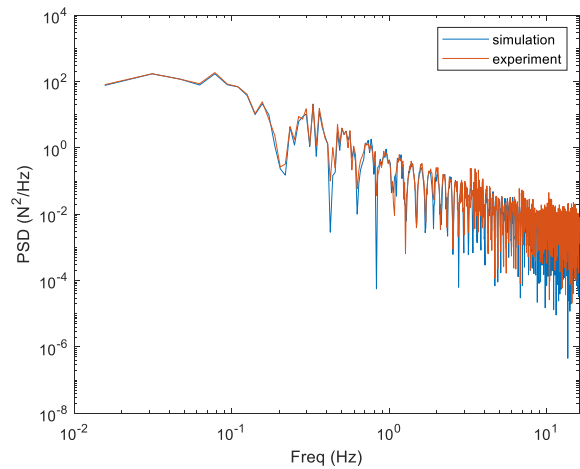


Figure 9. PSD of rotor thrust for Test Case 2

Figure 8 shows a scatter plot for Test case 2 of the normalized noise signal for simulation and experiments, where T_0 is the value at 12 m/s steady wind for the NREL 5 MW turbine, T_s are the values of the turbulent time series from the simulation and T_e are the values of the time series from the experiment. Figure 9 shows a comparison of the PSD of the rotor thrust between simulation and experiment. It shows there is higher energy for the experimental PSD at the high frequencies, attributed to the vibrations measured during the experiments.

While the results shown in Figure 6 through 9 appear encouraging, a non-subjective measure is required. Therefore, the final step in the validation process, the quantitative comparison, is used to calculate a validation metric.

Each Test Case was repeated at least five times and the results of each test have been used for the quantitative comparison. For Test Case 2 RE is -0.03 & -0.04 for thrust and torque respectively. With $a = 0.9$ and $b = 1.05$, for thrust FMT is 0.97 and for torque is 0.98. The quantitative validation metrics for all test cases are shown in table 2.

Table 2. Quantitative validation metrics of the MPD for each Test Case (TC)

	RE	FMT
Thrust S800 (TC1)	0.06	0.61 ; $a=0.9, b=1.05$
Thrust Mavic (TC2)	-0.03	0.97 ; $a=0.9, b=1.05$
Torque S800 (TC1)	0.06	0.74 ; $a=0.9, b=1.05$
Torque Mavic (TC2)	-0.04	0.98 ; $a=0.9, b=1.05$
Yaw moment (TC3)	0.55	0.27 ; $a=0.5, b=2$

The validation process has shown that the MPD is capable of accurately emulating rotor thrust and torque loads with the smaller set of blades, the Mavic blades. However, poor results were achieved for Test Case 3. The emulated yaw moment is shown in Figure 10. A clear time lag is visible, and the experimental curve is far from the smooth curve like that of the simulation. The PSD is shown in Figure 11. The difference in spectral energy is 55% and FMT is 0.27. The propeller pairs S2 & S4 and S3 & S5 acting intermittently at high rotational speeds were exciting a natural frequency of the MPD, with significant vibrations as a result and causing a noticeable displacement of the propeller arms. A slight delay in the start-up of the propellers from zero rpm to the initial spin could explain the time lag.

As the validation metrics clearly show, the emulation of complex aerodynamic loads is very challenging with the MPD in its current configuration.

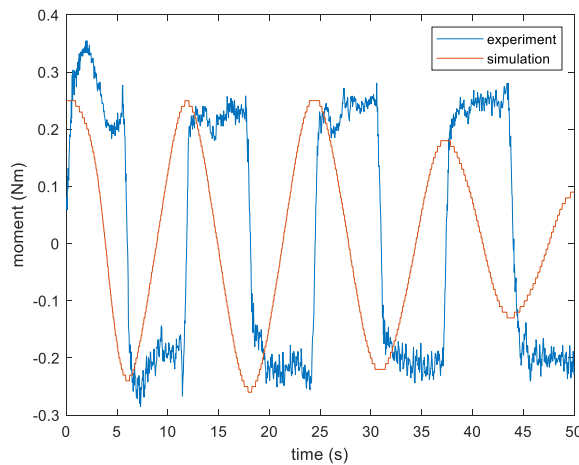


Figure 10. Emulated yaw moment, Test Case 5

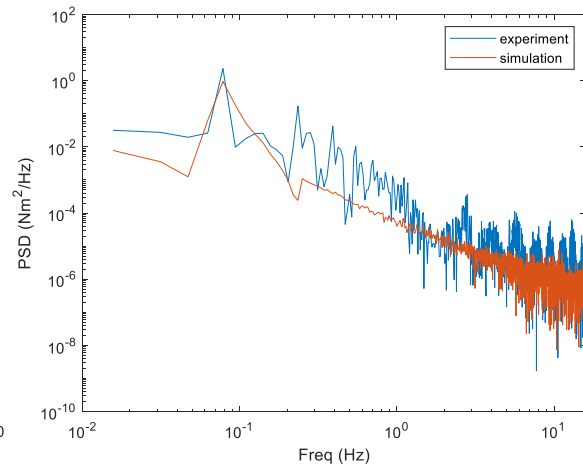


Figure 11. PSD of yaw moment, Test Case 5

5. Discussion

For the quantitative comparison of the validation process, two validation metrics have been proposed. Of these two metrics, FMT is the preferred metric. Setting the tolerance between limits a and b allows the user to ignore known sources of uncertainty and error such as load cell accuracy and data processing methods. Although still somewhat subjective, as the tolerance is an estimate, it gives the user control over the level of tolerance. This is not possible with RE; however, it does give a straightforward comparison between simulation and experiment and is therefore useful from an engineering perspective.

Sources of uncertainty and error during this study were: the accuracy of FAST, the accuracy of the 6-axis load cell, the accuracy of the calibration of the propellers, repeatability of actuation, the data processing method and the level of vibrations generated during operation of the MPD. Clearly, a detailed and careful calibration is important to minimize the level of uncertainty. It is also clear that the vibrations of the device have a significant impact on the levels of uncertainty. As the test results showed, the amount of vibrations depend on how the propellers are used. For this reason, the tolerance level has been assessed for each Test Case separately. With the tolerance level set, it is then up to the user to decide what FMT is acceptable for a suitable actuator. For this study, $0.9 \leq \text{FMT} \leq 1$, was considered acceptable.

To calculate the validation metrics PSD was chosen, rather than using the measured and numerical values directly for equations (1) and (2). The high frequency vibrations generated by the MPD are likely to have limited effect on the motion response of the platform of the FOWT model it will be used on. The high frequencies form only a small part of the total spectral energy of the actuator outputs. Therefore, using PSD will give a better representation of how the platform reacts to the MPD and is considered more appropriate to calculate the validation metrics.

The validation process showed that the MPD is a suitable actuator to emulate aerodynamic thrust and torque loads. The rates of change of the propellers are high enough for the MPD to emulate the aerodynamic loads within the required frequency range at model scale.

However, the device underperforms with emulating yaw moments. These poor results are attributed to excessive high-frequency vibrations when the propellers operate at high rotational speeds, made worse when the propeller pairs are operated intermittently to change the direction of the moment acting in the yaw DOF. Structural stiffness of the device and vibration damping will have to be improved to reduce the vibrations, and these issues will need to be addressed in a potential follow-up study. However, the stiffness will be a trade-off between weight and strength; increasing the stiffness will increase the weight of the device, meaning the mass envelope could be exceeded on models with small scales.

Another potential improvement of the device would be the use of bi-directional propellers. Although it would increase the complexity of controlling the MPD, it will also give it more flexibility of actuating in several degrees of freedom.

The number of aerodynamic loads to be emulated simultaneously will depend on the type of FOWT model and its sensitivity to each load. The aim of the design of the MPD was to emulate as many loads as possible and so make it suitable for any type of FOWT. However, for hybrid testing of TLP models, with their strong structural coupling between tower and moorings, the MPD in its current configuration is most likely not the best type of actuator. Semisubmersible FOWTs in contrast, are not as sensitive to tower/mooring coupling, nor is it likely that platform response to aerodynamic yaw will be very high. In that case only thrust and torque would need to be emulated and the MPD would be a very suitable actuator. It is important, however, to investigate the sensitivity of the FOWT to aerodynamic loads numerically prior to each testing campaign to decide on the suitability of the actuator.

6. Conclusion

A proposed validation method of actuators for hybrid testing of floating wind turbine models in wave basins has been outlined in this paper. A validation metric, the Fraction of Measurements within a user defined Tolerance, is recommended and is calculated using the spectral energy of the actuator outputs. With a perfect performance of the actuator, FMT is 1.

The validation method has been applied to the Multi-Propeller Device, a novel type of actuator. Its design, operation and validation are described along with a discussion of the test results. For this study aerodynamic loads of the NREL 5 MW turbine at a scale of 1:37 were emulated in the experiments. The aero-hydro-elastic code FAST v8 was used for the numerical simulations.

The MPD is a suitable actuator for emulating rotor thrust and torque loads. The FMT is 0.97 for thrust loads, 0.98 for torque loads, when using the propeller blades with a length of 75 mm. However, poor results were achieved when trying to emulate the moment required for yaw motion of the platform of a semisubmersible FOWT. These results are highly influenced by high-frequency vibration generated when the propellers are operating at high rotational speeds, and when the propellers are operating intermittently.

The maximum output of each propeller is 15 N, and high rates of change of 65 N/s and 7.5 Nm/s were achieved, when the blades of 150 mm length were used. These high rates give the MPD enough bandwidth to emulate thrust and torque loads from turbulent wind.

Proof of concept is shown for the MPD, however, its suitability as an actuator, in its current configuration, depends on the type of platform and the aerodynamic loads of interest.

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