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Executive Summary of the Thesis

Investigation of the Dynamic Models of OpenFAST for the Simulation of Floating Offshore Wind Turbines under Platform Motion

Laurea Magistrale in Energy Engineering - Ingegneria Energetica

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1. Introduction

The issue of climate change is leading to profound transformations in the energy sector, with wind energy set to play a pivotal role in achieving a carbon-neutral future. Particularly, the potential of offshore wind energy in Europe has increased the efforts in the research of floating technologies. However, the inherent unsteadiness of the platforms requires thorough analyses on the loads exerted on the turbine. Given the limited availability of real-life experimentation of turbines subjected to the sea movements, tools capable of effectively simulate these conditions are of great importance. This thesis focuses on the utilization of the blade element momentum code OpenFAST to investigate its reliability and capability in replicating diverse conditions. The initial segment of this work considers pitch platform motion cases associated to the NREL 5MW baseline turbine, while the second part expands the application of OpenFAST by implementing the scaled turbine from the UNAFLOW campaigns in both pitch and surge motion cases.

2. OpenFAST and theoretical aspects

OpenFAST is an open-source simulation tool developed by NREL, which allows for modeling various aspects, including the conditions of a floating offshore wind turbine (FOWT). In particular, in this thesis, version 3.4.1 of OpenFAST was utilized. This tool is composed of modules containing mathematical models for the different aspects that can be analyzed. These modules are interconnected to solve the global, dynamic response of the system. In this work, not all modules were used, thanks to simplified simulation conditions. The aerodynamics was modeled through AeroDyn v15, where a crucial feature was the possibility to switch settings between a blade element momentum theory (BEMT) algorithm and a dynamic BEMT (DBEMT), while also incorporating dynamic stall models [1]. The DBEMT setting activates the dynamic inflow/wake model of Øye, which considers, in the induction velocities, the influence of the delay of the wake response to a loading change. Moreover, dynamic stall models predict the aerodynamic performance of airfoils under unsteady conditions and exceeding the stall limit by correcting the aerodynamic coefficients based on time constants. In this thesis, two Beddoes-Leishman (B-L) type dynamic stall models were examined, both of which assume negligible compressibility effects and do not consider leading edge flow separation as a dominating phenomenon. The two models differ in that one uses four state variables for calculations, while the other introduces a fifth state and bases the function of the trailing edge separation point on different quantities. The third investigated model is that of Øye, a one-state model that linearly combines the two extreme conditions of fully separated and fully inviscid flow. These settings are particularly important when dealing with a FOWT subjected to platform motions. For the structure of the turbine, the ElastoDyn module was employed, InflowWind was used for the wind conditions, ServoDyn managed the control routine, and finally, ExtPtfm was utilized for simulating periodic sinusoidal platform motion. The ExtPtfm module enabled the implementation of large enough force vectors to override the other loads of the system and thus impose a prescribed motion to the machine [3].

3. 5MW turbine

The NREL 5MW baseline turbine serves as a reference machine developed to standardize both onshore and offshore tests. OpenFAST input files for this machine were already available and were subsequently updated to be compatible with the chosen tool version. Consequently, simulations were performed at near-rated conditions of the turbine. Pitch platform motions were calculated by combining amplitudes (Θ) of 1, 2, and 4 deg with frequencies (f) of 0.025, 0.050, and 0.1 Hz, for a total of nine cases [4]. Additionally, an "extreme" case, where Θ=4 deg and f=0.2 Hz, was also analyzed.

3.1. Aerodynamic loads

The first result obtained with the 5MW pertains to the "extreme" pitch platform motion case. The outputs reveal that the Øye model aligns more closely with the values of the other B-L models in comparison to the simulation run using an older version of OpenFAST [5]. Moreover, this model demonstrates the most smooth and symmetrical trend under these conditions.

Next, the nine pitch cases exhibit an overall agreement and similarity among the investigated dynamic stall models. In all cases, there is a general sinusoidal shape observed in the thrust (T) and power (P) outputs. These values reach the maximum when the turbine is moving windward and reach the minimum when moving leeward, in accordance with the variations in wind speed felt by the turbine. When compared with past results [4], most cases are consistent, with the new values being higher and close together, reducing the distance with the old ones as the platform motion becomes more severe. However, an exception is observed in the Θ=4 deg, f=0.1 Hz case, as it is the only instance where the maximum values of thrust and power are exceeded by the older results. Specifically, the B-L 4-states and Øye models display lower P peaks of -0.63% and -1.45%, and T peaks of -0.29% and -0.93%, respectively. This difference is accompanied by a smoother trend in the peak region, which is not observed with the B-L 5-states and the older model. The power of this case is depicted in Figure 1, where the B-L 4-states, 5-states, and Øye models are denoted as "UA4", "UA5", and "UA6", respectively. Moreover, the x-axis labeled as t/T_{rev}, counts the number of rotor revolutions within a platform motion period.

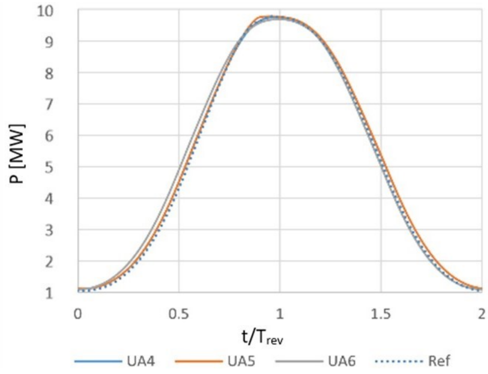

Figure 1: Power of the Θ=4 deg f=0.1 Hz case

Furthermore, a comparison with high-fidelity results from the COSA computational fluid dynamics tool also shows a disagreement with the OpenFAST models, particularly in the peak region. The DBEMT results struggle to capture the highest values achieved by COSA.

To delve deeper into the Θ=4 deg, f=0.1 Hz case, an additional investigation was performed including a steady BEMT case (BEM) and a DBEMT case without dynamic stall models

(DBEM). This allowed for a more comprehensive study of the influences of dynamic phenomena. Overall, it is noticeable that thrust force results present slightly more evidently different values changing the calculation settings. This disparity is likely due to this parameter being more affected by the root part of the blade, where the dynamic stall effects play a more significant role, than the power. The most substantial disagreement is once again found in the maximum, and minimum, values of the period.

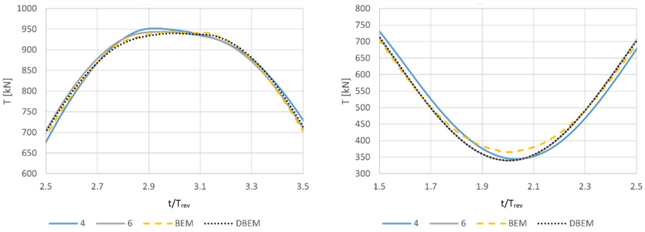

Figure 2: Thrust force at max and min of the Θ=4 deg f=0.1 Hz case

In Figure 2, the differences of the thrust values are visible. This zoom-in is derived from a graph representing two motion cycles. The maximum point, considering the platform, occurs at t/T_{rev}=3, while the minimum corresponds to t/T_{rev}=2.

3.2. Other parameters

Subsequently, these differences were further analyzed by examining parameters of interest at the previously mentioned points in time. These outputs were analyzed for all three blades, as their position at the given time instant can influence the values. In particular, in both the considered points, one blade (blade 1) is in the vertical, upward position.

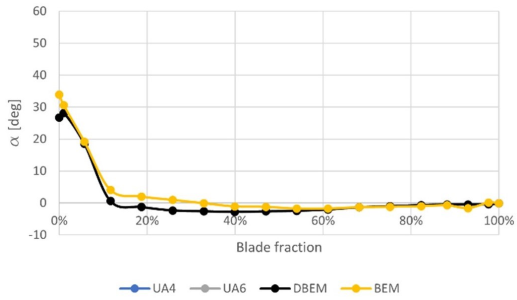

Figure 3: AoA at the minimum point of Θ=4 deg f=0.1 Hz case

The variations observed among the models at the minimum point can be attributed to the AoA. In fact, Figure 3 illustrates the disparities in blade 1 of the BEM simulation compared to the other models, with the other two blades present similar differences. The UA4 and UA6 results are overlapped with the black DBEM line, having the same AoA.

At the maximum point, instead, the AoA does not provide significant insights. However, the C_l, as shown in Figure 4 for blade 1, exhibits differences not only from the BEM simulation but also among the dynamic stall models. Notably, these divergences are most pronounced at the root, with differences of approximately 3% in value.

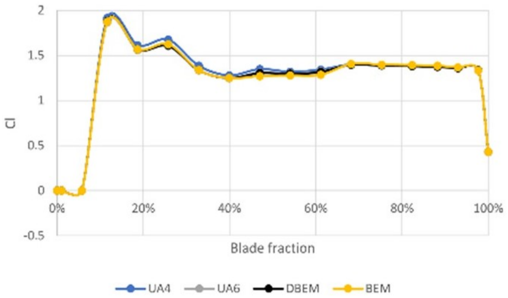

Figure 4: C_l at the maximum point of Θ=4 deg f=0.1 Hz case

Similar trends are observed in the other blades, with these distinctions becoming more pronounced as the AoA increases. The C_d values also confirm the differences seen in the C_l, although they are less pronounced in this parameter.

4. OC6 turbine

The turbine employed for the UNAFLOW experiments is a 1:75 scaled model of the DTU 10MW Reference Wind Turbine. This small machine was tested in the wind tunnel at Politecnico di Milano, and the obtained data served as reference for the OC6 project, which methodology was followed in this work [2]. Since this scaled turbine was originally developed for the aforementioned projects, it was necessary to implement its characteristics into new OpenFAST files. Moreover, a few meaningful tests were selected among pitch and surge cases and reproduced in OpenFAST, in order to verify its capability in simulating this newly implemented turbine.

4.1. Implementation

The input files for the scaled turbine were generated based on those of the 5MW turbine. The environmental conditions, airfoil characteristics, turbine geometry, and control strategies were implemented as described in the OC6 documents. The main characteristics of this turbine include its compact size, featuring a rotor diameter of 2.38 m, rigidity of both the blades and tower, and the use airfoils designed for low Reynolds numbers. The selected tests comprised the following: two steady wind cases (1.1 and 1.2), a surge test (2.5) and its corresponding pitch case (3.5), a verification case with more pronounced platform loads (2.12), and, lastly, a blade pitch control case (2.17) derived from the previous one. For all the unsteady tests, platform motions were implemented in accordance with the explanations detailed in Section 2.

4.2. Aerodynamic loads

The first case 1.1, simulates a steady scenario at rated conditions, with the turbine rotating at 240 rpm and the wind blowing at 4.19 m/s. The BEM calculations return T=34.93 N and P=75.62 W, corresponding to a torque (Q) of 3.01 Nm. These results differ from the corresponding experimental data of the UNAFLOW campaign but align with the OC6 results, making them satisfactory.

In the second steady case 1.2, which simulates an above-rated operation at 265 rpm, wind speed of 6.03 m/s, and collective blade pitch of 12.5 deg, unusual results are obtained. The thrust and power, at T=16.31 N and P=58.59 W, are lower than those of case 1.1, seemingly underestimating the performance in the above-rated conditions.

The unsteady cases 2.5 and 3.5 (Θ=0.035 m, f=1 Hz for the former, Θ=1.4 deg, f=1 Hz for the latter) yield consistent results, as anticipated, with the dynamic stall models and DBEM simulations values being similar. For instance, in case 2.5, the power oscillates by approximately ±17% around the mean, which is similar to the value of case 1.1. The only model that deviates is the B-L 5-states, exhibiting a roughly -0.7% variation compared to the 4-states one. This outcome, combined with the unevenness identified in Section 3, makes this model less interesting. Figure 5 illustrates the thrust trend for case 3.5. For improved visual representation, the x-axis reports the motion phase of the platform, with a complete period corresponding to 360 deg.

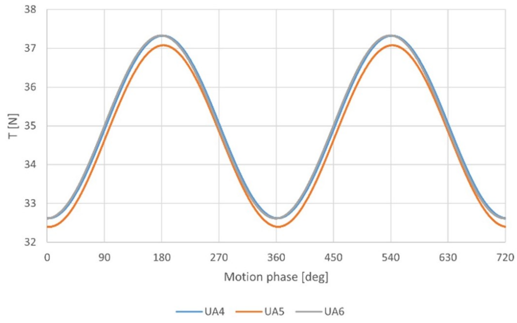

Figure 5: Thrust of case 3.5

Furthermore, case 2.12 simulates a more extreme surge scenario, with Θ=0.08 m and f= 2 Hz. The oscillations are significantly increased, with peak-to-peak amplitudes exceeding by more than three times those of case 2.5. In B-L 4-states, the P amplitude reaches 112.89 W, with all simulations yielding similar values. An analysis on the phase shift was also conducted, expecting a 90 deg shift between the platform motion and the turbine response. The Øye model exhibits the closest values to 90 deg, while the B-L 4-states shows a slight delay. The deviation from the reference value becomes more evident in case 2.12, with values of 91.44 and 96.48 deg. As it is also depicted in the OC6 report, the higher frequency leads to greater shifts of the results from the expected ones.

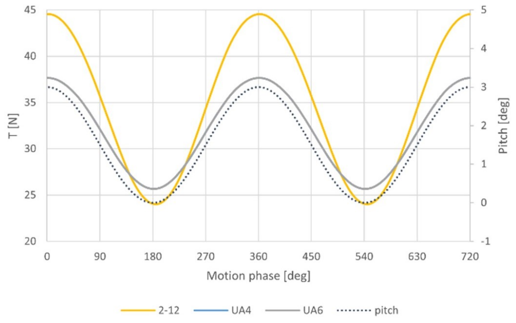

Figure 6: Thrust of case 2.17 and 2.12 UA4 and blade ptich

Finally, in case 2.17, a collective blade pitch control strategy is introduced to the previous scenario. This strategy involves a sinusoidal blade pitch variation of 1.5 ± 1.5 deg, synchronized with the surge motion, resulting in a damping effect in the oscillations. Figure 6 illustrates this difference by comparing the UA4 and UA6 simulations of case 2.17 with the UA4 of case 2.12 (depicted in yellow), along with the blade pitch (represented by the black dotted line). The reduction in peak-to-peak amplitude is particularly effective at the maximum region, with the peak thrust value decreasing by -15.5%. Accordingly, the power oscillation is also reduced to 93.63 W (UA4), with a mean value closer to that of the steady wind, in contrast to case 2.12. This scenario demonstrates an effective and more realistic strategy for mitigating the stresses on the turbine and its electrical components.

5. Conclusions

This thesis aimed at investigating the feasibility and the reliability of utilizing the Open- FAST models for simulating the load response of a FOWT subjected to platform motions.

The first analysis, focusing on the 5MW turbine, has highlighted the advantages of the tool's continuous improvement, as the Øye model had been corrected.

Subsequent 5MW analyses have shown an overall sinusoidal and symmetric response from all the investigated models. However, in the Θ=4 deg f=0.1 Hz case, the trends have exhibited closer results to the reference ones but issues in the maximum and minimum regions of thrust and power. This observation has also been corroborated by comparison with the COSA tool. Discrepancies in the minimum region have been attributed to differences in AoA, especially in the steady BEM simulation. Conversely, differences in the maximum points, across all the models, have been traced back to the C_l of the root part of the blades.

Moving on to the UNAFLOW turbine, the experimental data were successfully replicated, obtaining consistent results with the OC6 report. Overall, all models returned similar values, the most promising being the B-L 4-states and Øye, exhibiting significant oscillations around the mean value of approximately 75 W. Case 2.5 and its corresponding pitch case 3.5 have reported expected consistent values, while case 2.12 has demonstrated an exaggerated peak-to-peak amplitude of 112 W. This last case has also shown a more significant phase shift between motion and response, considerably distant from the reference value due to its higher frequency. The actuation of the blade pitch control in case 2.17 successfully reduced these oscillations.

In future developments, OpenFAST analyses may be extended to include updated or newer models, with the aim of identifying the best solution for FOWT. Furthermore, the simulations in this work leave room to include other modules and inputs to better replicate real-life conditions, such as introducing other control strategies.

References

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