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The Impact of Unsteadiness on the Aerodynamic Loads of a Floating Offshore Wind Turbine

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Abstract. The role of unsteadiness in the aerodynamics of Floating Offshore Wind Turbines (FOWT) remains a subject of discussion among the research community. Therefore, it must be investigated whether and to what extent transient aerodynamic phenomena impact the loads of a wind turbine rotor undergoing motions in unsteady winds. The study of transient aerodynamic phenomena is closely linked to the question of whether the modern Blade Element Momentum Theory (BEMT) methods can be considered reliable for the simulation of FOWTs. In this work, investigations are carried out to identify the relevant transient aerodynamic phenomena and quantify their effects on the torque and thrust of the Floatgen wind turbine. A free-wake panel method is utilised to identify and quantify transient parts of the load response to a set of simplified unsteady scenarios: a wind gust, a harmonic surge motion and a rotor speed oscillation. Transient contributions to the load behaviour of the wind turbine can be identified in all scenarios under consideration. In addition, the ability of a state-of-the-art BEMT method to model the identified transient contributions is evaluated. While an agreement of the qualitative impact of the transient aerodynamic phenomena at moderate motion frequencies is found, a contradicting behaviour of the simulation models becomes apparent at high motion frequencies. This indicates the presence of a transient, three-dimensional wake effect that cannot be reproduced by the common unsteady corrections for BEMT methods.

1. Introduction

The ability to perform precise aerodynamic load simulations is a prerequisite for a successful design of innovative wind turbine concepts. The blade element momentum theory (BEMT) method has been validated extensively and is widely used for this purpose. However, there is no consensus in the research community whether BEMT methods are suitable to accurately predict the aerodynamic loads acting on a floating offshore wind turbine (FOWT) undergoing fast motions. It has been shown in recent literature that the aerodynamic response of wind turbine rotors under slow and moderate motion conditions can be modelled in a quasi-steady way [1][2]. This implies that BEMT methods are suitable to model a FOWT rotor in such conditions. In the case of fast motions, it is still unclear whether transient aerodynamic phenomena noticeably influence the aerodynamic loads on the rotor and if such phenomena can be modelled by modern BEMT methods.

As a part of the VAMOS project, a simulation study on the transient aerodynamic phenomena related to the Floatgen FOWT prototype equipped with a 2 MW Vestas V80 wind turbine has been carried out and is presented in this work. A comparison of the simulation results of the state-of-the-art BEMT method AeroDyn [3] and the free-wake panel method *pan*MARE [4] is performed. In the analysis, transient aerodynamic phenomena in the load response of the Vestas V80 turbine subjected to a number of typical unsteady scenarios are identified. In this context, the free-wake panel method serves as a reference for the BEMT method with two different unsteady corrections. The unsteady scenarios are defined in a way that the quasi-steady part of the torque and thrust response to the rotor inflow remains constant while the characteristic frequency is varied. This allows for the isolated comparison of the transient parts of the load response predicted by the different simulation methods. Three typical unsteady scenarios are analysed: a gust, a harmonic rotor speed variation and a harmonic surge motion. The investigations show that, in all three cases, the torque and thrust response can be divided into a quasi-steady and a transient part. The transient part is negligible for slow motions or slow changes of the inflow velocity. It rises with the characteristic frequency of the unsteady scenario. The unsteady corrections of the BEMT method are only capable of modelling the influence of the dynamic wake and the unsteady airfoil effect. In contrast to this, the panel method is able to capture the influence of unsteady changes in the three-dimensional wake structure on the rotor loads which leads to a contradicting trend of the simulation results in some cases.

The present study is structured as follows: First, the well-known transient aerodynamic phenomena in the context of wind turbine modelling are briefly described (section 2). Next, related research works are summarised (section 3) and the modelling approaches applied and setups are described (section 4). The simulation scenarios are presented and transient aerodynamic effects in the results are analysed and discussed in sections 5 and 6. In the last section, a summary is given and the main conclusions are drawn regarding the occurrence of transient aerodynamic phenomena and the suitability of BEMT methods for their modelling.

2. Transient aerodynamic phenomena related to wind turbine modelling

In a comprehensive review on the unsteady modelling of wind turbines, Leishman [5] describes three aerodynamic phenomena to be most significant to understand the transient loads acting on a wind turbine rotor. Namely, the unsteady airfoil effect (attached flow), the dynamic wake (or dynamic inflow) effect and dynamic stall. This is in-line with Schepers' selection of relevant transient aerodynamic phenomena [6]. In the present case, it was found that stall is of minor importance for the investigated turbine under typical operation conditions. Therefore, only the first two effects will be described in the following.

The unsteady airfoil effect for attached flow, also sometimes referred to as Theodorsen effect, describes the phenomenon that the lift force acting on an airfoil does not immediately react to a change of the inflow conditions. This is due to the shedding of vorticity and added mass effects caused by a change of the flow field and the circulation around the airfoil. Considering a sinusoidal change of the angle of attack, this leads to a phase shift and a reduction of the lift force response compared to a quasi-steady case [7]. This can also be described as a hysteresis of the lift force. However, for very high frequencies, an increase of the lift force also is possible which is related to an added mass effect of the fluid around the airfoil. As a consequence, the unsteady airfoil effect directly impacts the lift force at the blade sections. A reduced frequency k was described by Sebastian and Lackner [8] to characterise the influence of the unsteady airfoil effect on a wind turbine blade section:

$$k = \frac{\pi f c(r)}{\sqrt{v_0^2 + (r\Omega)^2}}. \tag{1}$$

Here, v_0 and Ω describe the wind velocity and the angular speed of the rotor while r and c are the radius and chord length of the radial section under investigation. f denotes the frequency with which the inflow conditions vary (i.e. surge motion frequency). k is referred to as the *airfoil reduced frequency* in this work.

The dynamic wake effect is related to the influence of the helical wake structure on the induction of the rotor. A change of the inflow situation of the rotor (i.e. due to a blade pitch event) leads to an adaptation of the wake structure and vortex strength, which in turn causes a change of the induction of the rotor. However, the wake originates from the blades and is transported downstream. Therefore, the influence of the 'old' wake, generated before the event, decays over time until a new steady state of the wake and induction is reached. Consequently, the induction of the rotor can only change gradually, which is the main impact of the dynamic wake effect. In the context of a surge motion, the dynamic wake effect can be characterised by the so called wake or rotor reduced frequency f_w (see eg. [9]):

$$f_w = \frac{fD}{v_0}\,, \tag{2}$$

where D denotes the rotor diameter.

3. Previous works on wind turbine rotors in surge motion

The suitability of BEMT methods with unsteady corrections for the simulation of wind turbine rotors in surge motion remains a matter of discussion among the research community. The occurrence of transient aerodynamic phenomena and their impact on the aerodynamic loads is of major importance for this question, because it is commonly known that a wind turbine in a quasi-steady condition near optimal tip speed ratio (TSR) can be modelled with sufficient accuracy using BEMT. Therefore, BEMT methods can be considered as suitable for the simulation of FOWT rotors as long as the motions are slow and the TSR remains near optimal operation. However, the discussion whether this can be assumed for typical motion frequencies of large-scale FOWT is still ongoing.

In order to identify transient aerodynamic phenomena occurring during a surge motion, a number of high fidelity simulation models like free-vortex-wake (FVW) and Reynolds averaged Navier-Stokes (RANS) methods have been utilised. Typically, the oscillation amplitudes of the loads acting on a rotor subjected to surge motions with different frequencies and amplitudes were calculated. Then, the change of the thrust or torque amplitude due to a variation of the motion frequency was investigated. In some studies, a non-linear relation between the amplitude of the thrust response and the maximum velocity of motion is interpreted as evidence for transient aerodynamic behaviour[1] (e.g. [10] and [2]). However, this assumes that the quasi-steady rotor thrust of the wind turbine is linearly dependent on the wind speed, which is only valid when the motion velocity is very low in comparison to the wind speed. Simulation studies by Wen et al. [1], Ribeiro et al. [10] and Mancini et al. [2] showed that the thrust response amplitude increases linearly with the maximum surge motion velocity for moderate ratios of surge velocity to wind speed. For these cases, the thrust amplitudes seem to be determined exclusively by the ratio of maximum surge velocity to inflow velocity, while the motion frequency itself is of minor importance. This indicates that the influence of transient contributions to the load amplitudes is very limited. Otherwise the motion frequency would be a strong influence factor. At higher motion frequencies but also comparably high motion velocities, Ribeiro et al. found a deviation from the linear ratio between rotor thrust amplitude and maximum surge velocity with the motion frequency. However, in this case it is difficult to distinguish whether this is really a

[1] Not all studies use the maximum motion velocity directly as a parameter for the comparisons. In these cases, a the relation between the motion frequency and the thrust force amplitude normalised to the motion amplitude is investigated. However, in terms of linearity this is equivalent to the relation of the thrust force amplitude and the maximum motion velocity.

proof for transient aerodynamic behaviour or a violation of the above mentioned assumption of a small motion velocity in comparison to the wind speed. In addition, hints on a phase shift of the thrust force [11] and a reduction of blade fatigue loads [12] at high surge motion frequencies were found by Bergua et al. and Eliassen. The results of experimental investigations presented by Mancini, Fontanella and others (see e.g. [2], [9], [13]) confirmed the linear trend of thrust amplitude and maximum motion velocity for low to moderate motion frequencies with a minimal motion period corresponding to 13 s for a 10 MW turbine.

Parallel to the investigations focusing on the question if and which transient phenomena occur during a surge motion, other studies directly address the applicability of BEMT methods for the simulation of such scenarios. Sebastian and Lackner [8] state that the momentum equilibrium (assumed by a BEMT method) could break down for a significant portion of time during a simulation of a barge type 5 MW FOWT under realistic environmental conditions. In this case, a higher fidelity simulation method would be required as the momentum balance is a fundamental assumption of BEMT. In another simulation study, Sebastian and Lackner [14] describe the occurrence of a transition between windmill and propeller state at the outboard sections of the blades using a lifting-line FVW method for the same rotor under similar motions. Again, they conclude that higher fidelity models than BEMT may be required to accurately model this phenomenon. Sant et al. [15] argue that a more complex wake structure compared to the steady situation develops and related phenomena like vortex interactions may take place due to the motion of the rotor. BEMT methods would not be able to model such interactions. Despite this theoretical reasoning, Sant also identified deviations between BEMT and FVW simulations. As response to a surge motion of the modelled wind turbine, two BEMT methods predicted a moderately smaller power amplitude in comparison to a FVW method. The FVW simulations also showed a slight dependency of the mean power on the wave-induced motions, which was not the case in the BEMT simulations. In addition, simulations by Mancini et al. [16] showed that the amplitude of power and thrust of a model rotor undergoing an exemplary periodic surge motion calculated by a BEMT method is smaller in comparison to the lifting-line FVW method AWSM [17]. Based on this observation, Mancini et al. presented a new correction model for BEMT methods, which showed better agreement in the presented case.

However, there is also a number of studies (e.g. [18], [11]) concluding that BEMT methods with unsteady corrections are sufficient to model a typical wind turbine subjected to a surge motion.

In summary, it can be concluded that transient aerodynamic effects are of minor importance for low to moderate surge motion frequencies. In contrast to this, it is not clear whether this is the case at high motion frequencies. Possible reasons for the contradicting conclusions of recent studies could be that some of the studies are either limited to moderate motion frequency ranges and/or miss a clear distinction between quasi-steady and transient components of the load response. Comparisons between BEMT and higher fidelity simulations often are not corrected for the quasi-steady differences between the compared models. As a consequence, it is difficult to distinguish whether the observed matched or mismatched results can be accounted to the modelling of the transient phenomena or not. In order to overcome these shortcomings, this work aims to identify the transient component of the load response independent from the quasi-steady differences between the simulation models in a broad range of motion frequencies.

4. Simulation methods and setup

4.1. First-order panel method panMARE

The first-order panel method *pan*MARE is an in-house development of the Hamburg University of Technology (TUHH) and has been utilised for floating structures and ship propellers [19] before is was extended to the simulation of FOWTs by Netzband et al. [4]. It has been validated with different wind turbine rotors and was verified with the results of the Offshore

Code Comparison Continuation (OC4) campaign. *pan*MARE has also been utilised to develop and simulate the yaw mechanism of the passively yawing FOWT concept CRUSE Offshore SelfAligner [20]. During the VAMOS project a validation and verification of *pan*MARE with full-scale measurement data and simulations of the Floatgen prototype has been performed [21]. The panel method is a boundary element method (BEM) where the blade surface is discretised by source and doublet panels, while the freely transported, three-dimensional wake is represented by doublet panels only. It is based on the potential theory which allows to describe the flow field as a boundary value problem. The drawback of this formulation is that viscosity cannot be inherently considered. Therefore, viscous drag forces are added by a viscous correction, which is based on empirical, two-dimensional drag coefficients of the blade sections. In every section, the inflow speed is calculated from the stagnation pressure while the effective angle of attack is found by a comparison of the sectional lift force with the lift force of inviscid two-dimensional simulations of the airfoil. Based on these quantities and the empirical coefficients, the sectional drag force is calculated and added to the blade loads. In case of very thick airfoils or high angles of attack, a correction of the lift force is also applied. A more detailed description of the panel method in conjunction with wind turbine rotors can be found in [4].

Due to the direct modelling of the blade surface and the freely transported and deforming wake, the above described unsteady airfoil and the dynamic wake effects are inherently included in the simulation model. In addition, further effects related to transient changes in the three-dimensional wake structure and strength can also be captured by this approach.

The Vestas V80 is discretised by 3,900 blade surface panels and 13,650 wake panels representing approximately 10 rotor rotations where the wake deformation is frozen after 2/3 rotor rotations. A time step of 0.1 s is used. As the cylindrical and transition blade sections near the root cannot be modelled in potential theory, the first part of the blade up to a relative radius of 17 % is neglected. As a consequence, approximately 3 % of the rotor area is not modelled, which may yield a slightly higher rotor torque due to the neglection of the drag loads in the root region.

4.2. Blade Element Momentum Theory Method AeroDyn v15

BEMT methods are based on a momentum equilibrium on annular rings. Therefore, no modelling of the wake or the flow field is necessary, the drawback of which, however, being that the transient phenomena cannot be directly modelled. In AeroDyn v15 (OpenFast v3.1.0), two unsteady corrections are implemented to correct for the above mentioned unsteady airfoil and dynamic wake effect. The unsteady airfoil correction is based on the Leishman-Beddoes model [22] with slight modifications. In the present simulations, the 5-state implemantation is applied (UAMod=5). The unsteady airfoil effect in attached flow conditions is modelled utilising an exponential decay function of the lift force. The dynamic inflow correction is based on Øye's work (presented in [23]) and prevents the axial induction on an annular ring from undergoing rapid changes. A detailed description of theory and implementation of AeroDyn and both unsteady corrections can be found in [3], [24] and [25].

In the present models, the Prandtl tip and hub loss correction as well as both unsteady corrections are utilised. For the unsteady airfoil correction, the extraction of model coefficients based on the airfoil polars was performed with AirfoilPrep[2]. The transient coefficients are set to $A_1 = 0.3$, $A_2 = 0.7$, $b_1 = 0.14$ and $b_2 = 0.53$ in accordance with Leishman's recommendation [26] which is equivalent to the default values in AeroDyn. It has to be noted that these coefficients have originally been determined for a NACA0012 airfoil. However, individualised coefficients for the various airfoil shapes at the blade sections have not been discovered in literature. The application of the unsteady airfoil correction is limited from a relative radius of 18 % to 95 %

[2] available at the NREL website: *https://www.nrel.gov/wind/nwtc/airfoil-prep.html*

Table 1. Definition of simulation scenario sets.

Case	**Wind speed** [m s^{-1}]	**Rotor speed** [RPM]	**Motion / gust period** [s]	**Gust / rot. speed / motion amplitude** [m s^{-1}]/[RPM]/[m]	**Max. surge velocity** [m s^{-1}]
Gust	6	10.58	4 and 150	0.6	-
Rotor speed oscillation	7	12.35	3.2 - 300	0.29	-
Surge motion	7	12.35	3.2 - 300	0.32 - 30	0.63

in order to operate within the limitations of the correction method. For the dynamic inflow correction, the time constant τ_1 is set manually according to Øye (see e.g. [25]).

5. Identification of modelling differences

In comparison to bottom-fixed offshore wind turbines, FOWT experience significantly larger tower top motions and rotations in all directions in space. The integral loads on the rotor are most sensitive to the tower top surge motion, as the inflow velocity experienced by the rotor is directly altered by the surge velocity. As a consequence of the tower top surge motion, the rotor torque increases and the rotor rotation is accelerated when the turbine moves against the wind direction and vice versa in below-rated conditions. The response of a wind turbine rotor to a surge motion therefore consists of a part caused by the variation of the inflow speed as well as a part caused by the variation of the rotational speed. Therefore, both, a forced surge motion and a rotor speed variation, are chosen as basic scenarios to investigate differences in the modelling of transient phenomena between the panel method and the BEMT method with corrections. Apart from the floating motion, also a gust can cause a transient response of the rotor loads. From the tower top perspective, a gust and a surge motion have very similar characteristics. Therefore, the transient gust is also chosen to exemplary investigate unsteady aerodynamic phenomena typical for an FOWT. Details on the sets of simulation scenarios are listed in Table 1. No structural flexibility was applied and the influence of all load components other than aerodynamic (i.e. gravity or inertia) has been excluded from the results, in order to allow for a basic comparison of the aerodynamic loads. All unsteady simulations were performed using the quasi-steady BEMT without unsteady correction (BEMT), with dynamic inflow correction (BEMT, dyn. wake) and with dynamic inflow correction and unsteady airfoil correction (BEMT, dyn. wake + UA).

5.1. Quasi-steady and transient response to a gust

In Figures 1 and 2, the torque and thrust responses of the wind turbine to a very slow (150 s length) and very fast (4 s length) gust with a height of 10 % of the mean wind speed is shown. The shape of the gust is derived from the *extreme operating gust* defined in the IEC 61400-1 standard and periods and amplitude were adjusted. Both torque and thrust are normalised to the undisturbed inflow case. The time axis is normalised to the gust period, so that both gusts visually have the same length in the graph. In both cases, the rotational speed is forced to a constant value corresponding to the optimal operation point of the rotor at the initial wind speed, so that the variation of the gust length is the only difference between the two cases.

The torque and thrust response simulated by the BEMT method with and without unsteady corrections is illustrated in Figure 1. Naturally, the response computed by the uncorrected BEMT method does not change with the gust period as the method is inherently quasi-steady. Similarly, dynamic inflow and unsteady airfoil corrections do not contribute to the response to the slow gust. Therefore, the slow gust scenario can be considered quasi-steady, while the fast

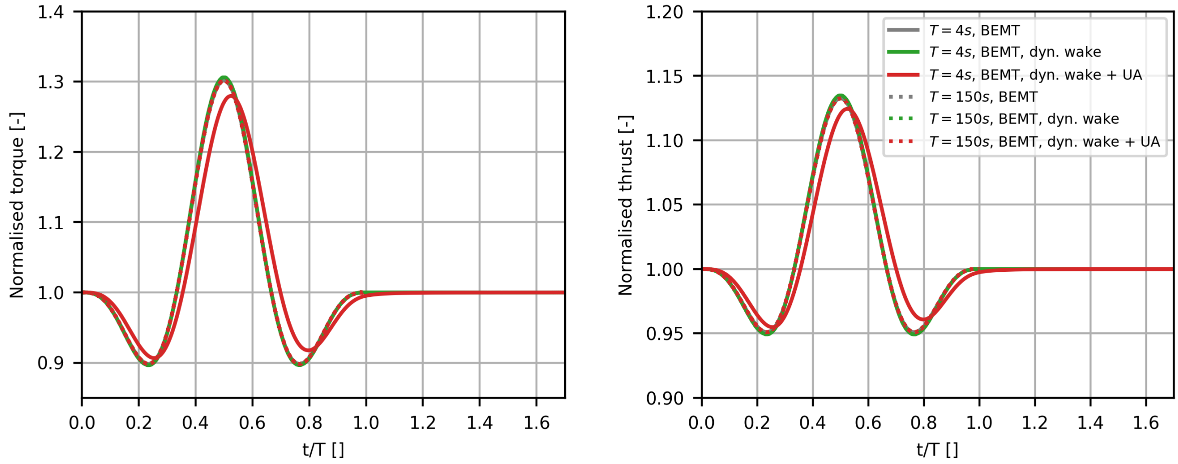

Figure 1. Normalised torque and thrust response of the BEMT simulations to a fast (solid lines) and a slow (dotted lines) wind gust (see 'Gust' in Table 1). Time axis is normalised to the corresponding gust period. Apart from BEMT with dynamic inflow and unsteady airfoil correction, all results are nearly identical.

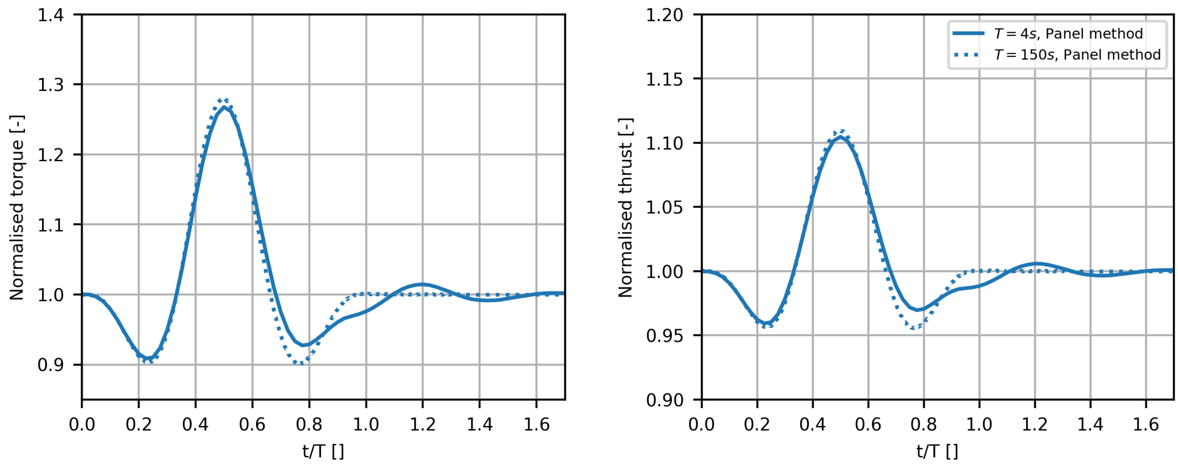

Figure 2. Normalised torque and thrust response of the panel method simulations to a fast (solid lines) and a slow (dotted lines) wind gust. Time axis is normalised to the corresponding gust period.

gust is considered as a transient case. As a consequence, all curves relating to the slow gust are on top of each other. In the case of the fast gust, the contribution of the unsteady airfoil correction causes a notable drop of the maximum and minimum values in torque and thrust as well as a phase shift. The unsteady airfoil correction introduces a hysteresis of the airfoils' lift force with a certain time constant for every blade section. In the lower part of the blade, the variation of the angle of attack is in the magnitude of this time constant. As a consequence, the lift force of lower blade sections cannot follow the change of the angle of attack immediately, so that the maximum lift force cannot be reached before the wind speed decreases again and a time shift is introduced. In contrast to this, nearly no contribution of the dynamic inflow correction to the overall rotor loads can be found. Due to the dynamic inflow correction, a low pass filter acts on the axial induced velocity. Therefore, the adaptation of the induced velocity to a new momentum equilibrium is slightly suppressed. However, this has a very limited influence on the results, as the induced velocity does not change much due to a variation of the inflow wind speed. This leads to nearly no difference of the results with dynamic inflow correction compared to the quasi-steady case and the curves related to the fast gust. Snel and Schepers also observed this insensitivity of the dynamic wake effect to wind speed variations in measurements and simulations [23]. Nevertheless, as the inner blade parts have a minor contribution to the overall rotor loads, the dynamic inflow correction may still impact these regions.

The results of the panel method in Figure 2 show a slightly lower peak response to the slow gust in comparison to the BEMT method. As the slow gust corresponds to a quasi-steady operation, these differences can be attributed to small deviations of the quasi-steady sensitivity of both simulation models to the tip speed ratio (TSR). These differences may be caused by different treatments of tip loss modelling and viscous effects. When comparing the transient to the quasi-steady case, a reduction of the peak values as well as an additional oscillation of torque and thrust after the decay of the gust can be noted. The decrease of the peak values is most likely due to the unsteady airfoil effect. The oscillation of torque and thrust appearing approximately from a normalised time of 0.9 cannot be directly caused by the wind inflow variation as the wind speed nearly reached the steady-state value. This effect is connected to the shedding of vorticity from the blades. The rapidly increasing inflow wind speed causes a fast change of the blade circulation which leads to an increase of the lift force. In consequence, a notable amount of vorticity is shed into the wake (see section 2). On the one hand, this vorticity affects the angle of attack at the blade it was shed from (unsteady airfoil effect). On the other hand, this vorticity approaches the following blade after 1/3 of a rotor rotation. Consequently, the resultant angle of attack of the following blade is perturbed during the approaching and departing of the shed vorticity.

Comparing the results of the BEMT method with unsteady airfoil correction and the panel method it becomes obvious that the drop of the peak loads of the fast gust is strongly overpredicted by the unsteady airfoil correction. The same is true for the phase shift. In addition, neither the pure BEMT nor the unsteady corrections are able to model the load oscillations caused by the shed vorticity, because such three-dimensional effects are not part of these models.

5.2. Quasi-steady and transient response to a forced rotor speed variation

In order to investigate the isolated influence of a variation of the rotational speed caused by a surge motion, rotor speed oscillations with typical periods for the Floatgen platform are applied with a constant amplitude (see Table 1). Due to the constant amplitude, minimum and maximum tip speed ratios are equal for all load cases of the series *Rotor speed oscillation*, while the periods vary. This ensures the same quasi-steady response in all load cases and allows for the identification of transient phenomena when comparing the faster scenarios against the slowest one. The typical range of motion periods was slightly extended. Especially the load cases with the highest and lowest motion frequencies represent academic cases. The simulated torque and thrust amplitudes due to the rotor speed variations are shown in Figure 3. All amplitudes are normalised to the quasi-steady amplitude, which corresponds to the load amplitude of the simulation scenario with a period of 300 s. As a consequence, all amplitudes are 1 at a period of 300 s. Naturally, the BEMT results without any unsteady correction do not change with increasing frequency due to the inherently quasi-steady basis of this method. In contrast to this, a significant influence of the unsteady corrections in BEMT can be observed. The panel method shows significant deviations of about 40 % from the quasi-steady value due to transient phenomena. Interestingly, the transient phenomena lead to a monotonically increase of the

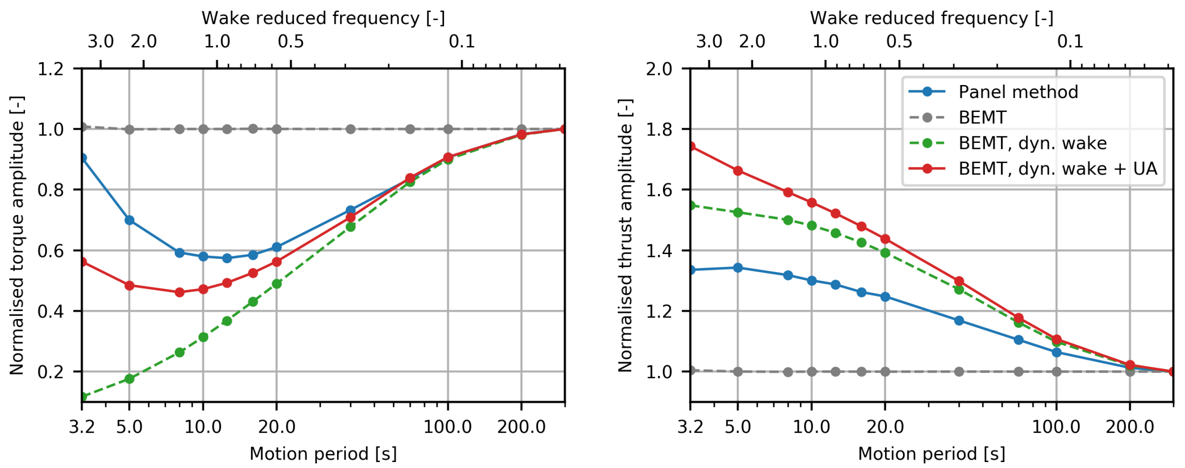

Figure 3. Normalised torque and thrust response amplitude of the BEMT and panel method simulations to harmonic rotor speed oscillations with increasing motion period (y-axis) and a constant amplitude (see 'Rotor speed oscillation' in Table 1). Values differing from 1 indicate a transient contribution in the simulated response.

thrust amplitude in all unsteady models with rising motion frequency while a decrease is visible in the torque response amplitude. For higher periods than 40 s, the unsteady airfoil model has limited influence on the results. Here, the dynamic inflow correction determines the response of the unsteady BEMT results. At least in terms of torque, the dynamic wake effect seems to be captured quite well in this region, as a good agreement with the panel method simulations can be observed. However, with regard to thrust, the dynamic wake effect seems to be overpredicted.

At lower periods i.e. higher frequencies of the rotational speed oscillation, the unsteady airfoil model impacts the BEMT simulations. This can be concluded from the difference between the solid red and the green dashed line in Figure 3. It seems to reproduce the increase of the torque amplitude at higher frequencies simulated by the panel method. In contrast to this, the results with unsteady airfoil correction contradict the trend of the panel method simulations for the thrust amplitude. The panel method predicts only a slight increase and finally a stagnation of the amplitude growth at higher frequencies, however, the results of the BEMT simulation with unsteady airfoil correction show a strongly increasing trend.

The differences in the modelling of the dynamic wake effect between the panel method and the BEMT method with dynamic inflow correction are of a quantitative nature. This can be concluded from the same trends for torque and thrust that can be observed in the results for moderate to high periods where the dynamic wake effect is dominant. In contrast to this, a qualitative difference between the panel method and the BEMT with unsteady airfoil model is present. While good qualitative agreement could be shown for the rotor torque amplitude at higher frequencies, a contradicting trend between the unsteady airfoil correction and the panel method is obvious for the thrust amplitude.

In sum, the normalised load amplitudes of all unsteady methods in Figure 3 differ from the quasi-steady response. This clearly shows that a significant part of the modelled load response to the variation of the rotational speed can be considered as transient. Interestingly, the cases at low motion frequencies are also affected. This is in line with the findings from [11], where the presence of transient effects was identified in a surge motion scenario with rotational speed variation, while no transient contribution was found without the rotational speed variation.

The normalised results were found to be nearly independent from forced amplitude of the rotational speed. It has to be noted that the present analysis aims at a comparison of modelling approaches for transient effects. The differences between the models in Figure 3 therefore only apply to the torque and thrust fluctuation, which is caused by a rotor speed oscillation. An evaluation of how much rotor speed variations impact the overall loads of an FOWT in a realistic environment cannot be determined from the present analysis.

5.3. Quasi-steady and transient response to a forced surge motion

A forced, periodic surge motion with typical periods for the Floatgen platform is applied in the following simulations (see Table 1). In these cases, the rotational speed is kept constant. The amplitudes are chosen in such manner that the magnitudes of the surge velocity variation are the same for every applied motion period. This leads to an increasing motion amplitude with rising motion period. Consequently, the equal peak velocities of the sinusoidal surge motions lead to a constant quasi-steady part of the load response in all load cases. Again, the typical range of motion periods is slightly extended so that the load cases with the highest and lowest motion periods in particular represent academic cases.

In Figure 4, the response amplitude of rotor torque and thrust due to the surge motion with varying period is shown for the set of scenarios *Surge motion*. The occurrence of transient contributions to the load responses predicted by the different modelling approaches can be easily identified when comparing the fast surge motions to the slowest one (quasi-steady). Therefore, torque and thrust amplitudes are normalised to the load amplitude of the quasi-steady case with a very slow motion period of 300 s. Again, no significant change of the amplitudes calculated by the classical BEMT without unsteady corrections over the motion period can be seen. This is due to the quasi-steady nature of the classical BEMT method. Qualitatively, torque and thrust amplitudes show the same behaviour for the different unsteady modelling approaches. While the dynamic inflow correction yields a weak increase of the rotor torque amplitude and a little stronger increase in thrust at periods below 40 s, the unsteady airfoil model causes a significant decrease of both amplitudes for low motion periods. In contrast to this, the amplitudes of the panel method show a monotonically increase with decreasing motion period. For all models, the response of torque and thrust can be considered as quasi-steady for periods above 40 s. For realistic motion periods in a range between 6 s and 20 s, the differences between all models are in a range of +/-10 % of the rated torque and thrust.

As the unsteady airfoil effect leads to a reduced lift force amplitude at fast oscillations of the angle of attack (see section 2), the decrease of the amplitudes with rising motion frequency due to the unsteady airfoil correction is straight forward. The same effect can be seen in the Figures 1 and 2, where the unsteady airfoil effect decreased the maximum torque and thrust response to a gust. In the case of the gust, the BEMT method with unsteady correction and the panel method show a qualitatively similar behaviour. However, as panel methods are able to capture the unsteady airfoil effect, it is remarkable that the panel method results show a contradicting behaviour in case of the oscillatory surge motion.

Comparable to the rotational speed oscillation scenarios, the normalised results were found to be nearly independent from amplitude of the surge velocity.

6. Discussion of identified modelling differences

The response to a fast gust, shown in Figures 1 and 2, indicates that the unsteady airfoil correction is able to qualitatively model the drop of the peak amplitude due to the unsteady airfoil effect, but overpredicts it. The same is true for the phase shift. A more precise tuning of the parameters A_1, A_2, b_1 and b_2 (see section 4) may reduce this overprediction. Analogously, the overprediction of the dynamic wake effect shown in Figure 3 could be corrected by the adaptation of the corresponding time constant. However, this would require a tuning of the

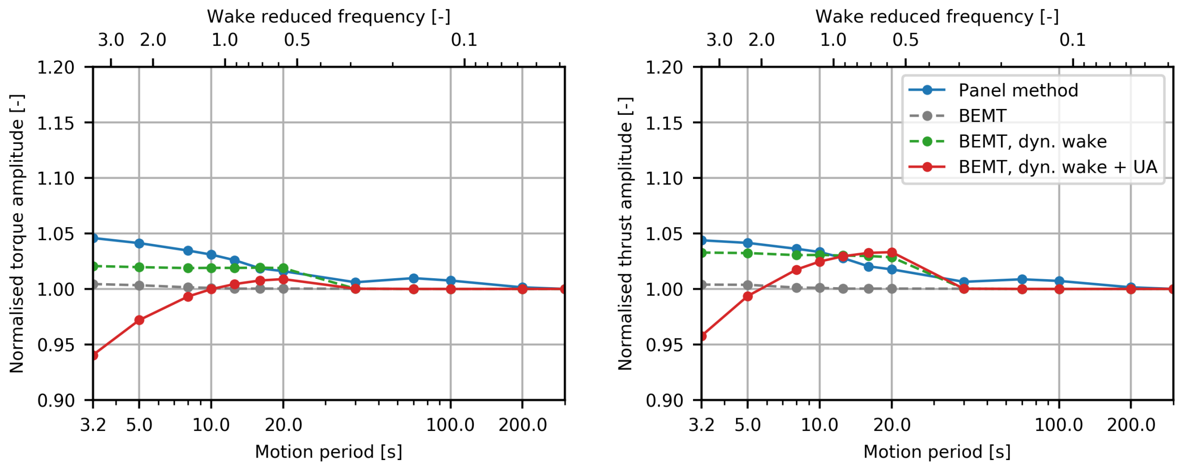

Figure 4. Normalised torque and thrust response amplitude of the BEMT and panel method simulations to harmonic tower top surge oscillations with increasing motion period (y-axis) and a constant velocity amplitude (see *Surge Motion* in Table 1). Values different from 1 indicate a transient contribution in the simulated response.

corrections to this individual turbine which requires extensive investigations with high fidelity simulation methods or experiments.

The differences between the panel method and the BEMT method with unsteady corrections in the surge motion scenario (see Figure 4) cannot be resolved with a tuning of the unsteady corrections. This is due to the fact that the differences at high frequencies are of a qualitative nature. Therefore, a clear contradiction between the models is present. It is likely that a physical phenomenon, which can only be modelled by the panel method, gains influence on the load amplitudes at higher frequencies. The authors assume that there is a three-dimensional wake effect, which is related to the impact of shed vorticity from one blade to the upcoming blade. Most likely, this is the same physical phenomenon causing the oscillation in the load response to the fast gust. A similar assumption was formulated by Eliassen [12], who showed that the wake of the preceeding blade can have a notable influence of the response of the aerodynamic rotor loads to a tower vibration in surge direction.

7. Transfer of findings to larger turbines

In the present investigation, three aerodynamic phenomena causing a transient load response have been identified, namely: the unsteady airfoil effect, the dynamic wake effect and a wake effect not yet fully characterised. The latter effect is most probably a three-dimensional wake effect related to the unsteady vorticity shedding of the preceeding blade. The occurrence of these effects is related to different flow scenarios, which can be evaluated by dimensionless numbers in the first two cases. When transferring the previous findings to larger turbine diameters, it is convenient to estimate the expected change of these dimensionless numbers in order to predict a tendency to what extent the individual transient phenomena will influence the turbine loads.

- For the unsteady airfoil effect, the airfoil reduced frequency k (see section 2), is the characteristic dimensionless number. k is linearly dependent on the chord length in the nominator and approximately linearly on the rotor size in denominator. As a consequence, no general trend can be deduced for increasing turbine ratings, since both grow with the rotor diameter.

- The occurrence of the dynamic wake effect can be determined by the wake (or rotor) reduced frequency (see section 2). Here, the rotor diameter is the only factor which changes with an increased turbine rating, so that larger turbines will most probably experience a stronger influence of the dynamic wake phenomenon.
- For the newly observed transient phenomenon, it is difficult to precisely predict its influence for turbines with larger power ratings, since the effect has not been characterised to date.

8. Summary and Conclusion

An aerodynamic simulation study on the 2 MW Vestas V80 subjected to a gust and surge motion has been presented. Simulations were performed with a BEMT method with and without unsteady corrections as well as a first order panel method with viscous correction. The first aim of the investigation was to identify the occurrence of unsteady aerodynamic effects on the loads of a FOWT which cannot be modelled in a quasi-steady manner. To point out this, such effects are referred to as transient effects. The second aim was to evaluate to which extent the influence of these effects on the rotor loads can be predicted by common unsteady corrections for BEMT methods (namely dynamic inflow and unsteady airfoil correction). A gust and a tower top surge oscillation with moderate amplitudes and a broad range of frequencies have been selected as simplified inflow scenarios representing typical conditions for an FOWT operating below rated wind speed. In normal operation conditions, the torque fluctuations originating from the surge velocity oscillation cause an oscillation of the rotor speed. These two oscillations were investigated isolated from each other in this work in order to distinguish between their impact on the aerodynamic response of the rotor loads.

The most relevant findings from the results of the simulation study of the Floatgen rotor can be summarised as follows:

- A clear identification of the transient parts of the aerodynamic load response to unsteady events could be achieved using a specialised set of load cases that maintain a constant quasi-steady contribution to the load response. A comparison of load cases with varying characteristic frequency therefore revealed the transient contributions directly.
- Rotor speed oscillations and surge motions clearly trigger transient aerodynamic phenomena. In reality, surge motion and rotor speed variation occur simultaneously and the transient phenomena superpose.
- Both unsteady corrections for BEMT methods, namely the dynamic inflow correction and unsteady airfoil correction for attached flow conditions, were unable to predict the transient contributions to the torque and thrust response to an unsteady event with sufficient accuracy in most scenarios.
- For high surge motion frequencies, a contradiction between the simulation results of the different methods indicate the presence of an aerodynamic phenomenon related to the unsteady three-dimensional structure of the wake. This cannot be modelled by the unsteady corrections of the BEMT. In the present case, an underprediction of the load amplitude calculated by BEMT with unsteady corrections can be expected in a range of 5-10 % for small wave periods.
- A variation of the surge motion and the rotational speed oscillation amplitudes revealed that the identified transient contributions to the (normalised) load response are insensitive to such variations in a moderate range. Therefore, the motion frequency can be considered as the driving factor for the occurrence of the observed transient aerodynamic phenomena.
- For upcoming wind turbine sizes, the occurrence of transient phenomena during operation may increase due to a significant rise of the wake reduced frequency. Therefore, the modelling deficits of BEMT methods and associated corrections become more and more

relevant and larger discrepancies between free-vortex-wake and BEMT methods may arise from this. On the other hand, larger floating platforms will most likely be less sensitive to wave excitations, which may reduce the relevance of tower top motions for the aerodynamic loads in general.

Finally, the presented investigations revealed that transient aerodynamic phenomena are present for the Floatgen prototype, when it is excited in the upper range of expectable wave frequencies. Their influence is notable at high motion frequencies, however, the quasi-steady contribution dominates the load response. In the case of a rotor speed variation or surge motion, neither the well-known unsteady effects nor the indicated three-dimensional wake effect can be captured with satisfactory accuracy by the BEMT method. As a consequence, the influence of these effects on the loads of turbines with larger sizes should be evaluated carefully before a utilisation of a BEMT method with unsteady corrections can be safely used for load prediction.

Most conclusions in this work are drawn on the basis of a comparison of two numerical methods, where the panel method is assumed to model the physical behaviour of the rotor more accurately. In addition, no tuning of the unsteady corrections for the BEMT was applied. Thus, the above-listed findings must be considered in this context. Future work should therefore aim at reproducing the findings with other simulation methods and experiments. Especially the indication of a three-dimensional wake effect which cannot be modelled by common unsteady corrections for BEMT methods needs to be evaluated in detail. If the presence of such effect can be confirmed, a complete physical explanation and a careful characterisation of this phenomenon is required. In addition, the influence of transient aerodynamic phenomena on the aerodynamic loads in general should be investigated for various larger turbines mounted on a number of representative floating platforms. Such analysis would lead to a clear indication in which cases a higher fidelity modelling, such as a free-vortex-wake method, is required to gain reliable load estimations for future FOWT designs.

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Author contributions

CWS led the development of the load case sets, performed the panel method simulations, overtook major parts of the analysis of numerical results and wrote the manuscript. UÖ performed OpenFAST simulations, strongly contributed to development of the load case sets and the analysis of the simulations and reviewed the manuscript. SN implemented the extension of *pan*MARE for wind turbines, supported the panel method simulations, contributed to the analysis of their results and reviewed the manuscript. PWC contributed to the theoretical discussions, supervised the works of UÖ and acquired funding. MM contributed to the theoretical discussions, supervised all works of CWS and SN, reviewed the manuscript and acquired funding.

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