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Impact of the aerodynamic model on the modelling of the behaviour of a Floating Vertical Axis Wind Turbine

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Abstract. Floating Offshore Wind Turbines (FOWTs) can have a very unsteady aerodynamic behaviour at sea. However state-of-the-art aerodynamic models used for FOWTs usually assume a steady and inviscid flow around the rotor. The induction factor is then computed using Froude-Rankine Actuator Disk theory, also called momentum theory. For a Horizontal Axis Wind Turbine (HAWT), the Blade Element Momentum theory (BEM) may miss important unsteady phenomena when the rotor strongly interacts with its wake [1]. For a Vertical Axis Wind Turbine (VAWT), an equivalent momentum method is the Double Multiple Streamtube (DMS) theory [2]. Despite its higher CPU cost, the Free Vortex Wake (FVW) theory is an alternative to momentum theories as it takes into account the vorticity shed in the wake by the blades to compute the induction. The aerodynamics is thus entirely unsteady. This study presents a comparison between the DMS and the FVW theory for a two-straight-bladed Floating VAWT mounted on the *OC3Hywind* SPAR platform [3] for several of the OC3 project load cases [4]. The study shows that the DMS solver is not able to predict important unsteady aerodynamics phenomena when the rotor/wake interaction is strong. The motions of the turbine's platform are significantly impacted and the dynamic loads acting on the rotor blades are very different. It could lead to design issues, especially for blade design.

1. Introduction

A reliable numerical simulation tool for Floating Offshore Wind Turbines is essential in order to reduce their costs. However, their behaviour can be very complex to model and numerous simulations must be run on long durations to verify compliance of the systems with the industry standards. A compromise between CPU cost and accuracy is thus needed.

State-of-the-art aerodynamic models used for FOWTs such as Double Multiple Streamtube [2] theory assume a quasi-static flow, and the induction on the rotor is computed through the momentum theory. However, a floating turbine can have a very unsteady aerodynamic behaviour at sea due to unsteady inflow and turbine motions for example. At high Tip Speed Ratios (TSRs), a turbine's rotor strongly interacts with its wake which can lead to errors in the computation of the induction factor by momentum methods. Some of those induced phenomena can be inherently accounted for with the Free Vortex Wake (FVW) theory. Even though it has a higher CPU cost, the FVW theory can thus be of interest for floating turbines.

An integrated simulation tool [1] has been developed coupling a seakeeping solver to an aerodynamic solver. Implementations of both the FVW theory and the DMS theory are available for the aerodynamic solver. A quasi-static mooring model has been added for computation of the mooring



loads and a control module is available for estimation of the generator torque with complex control laws. The impact of the aerodynamic model is thus studied, comparing the platform motions and aerodynamic loads obtained with either the steady DMS solver or the unsteady FVW code results.

2. Numerical model

2.1. Aerodynamic models for floating VAWTs

Among the various numerical models suitable for the simulation of VAWTs, it is chosen to compare a state-of-the-art DMS method with a FVW theory-based solver. This choice was motivated by the need to assess numerical models which offer the best compromise between accuracy and CPU time consumption.

On the one hand, several momentum models inspired by the Blade Element Momentum model used for horizontal axis rotors have been for instance proposed by Merz [5] or Paraschivoiu [2]. The former derives from the Multiple Streamtube approach defined by Strickland [6] with additional dynamic inflow and stall models. The latter consists in a Double Multiple Streamtube (DMS) model, considering two subsequent actuator disks per streamtube. The downwind part of the rotor is thus impacted by the induction of the upwind half of the rotor. The DMS theory however ignores the effects of the downwind half on the upwind half aerodynamics. Those models are quasi-steady, apart from the added dynamic inflow and stall models, and do not explicitly model the wake effect.

On the other hand, the wake dynamics and induction can be computed explicitly in other models. The Actuator Cylinder (AC) has been for instance presented by Madsen [7]. The vertical axis rotor is here considered as an actuator surface representing the surface swept by the blades. The Euler equation is solved in the fluid domain inside the rotor and in the wake. However, this theory is quasi-steady and is difficult to extend to 3D flow and only a 2D flow is usually considered in horizontal slices of the rotor. An AC solver has been compared to a DMS solver in [8] and the two codes show a good agreement on a floating VAWT's dynamics. The Free Vortex Wake (FVW) theory is unsteady and computes the induction of the rotor by considering vorticity generated on the blade and shed into the wake. The vorticity is advected in the wake and induces unsteady velocities on the rotor. Dynamic stall models can also be added.

2.2. Coupled simulation tool

A floating wind turbine simulation tool [1] has been developed coupling *InWave* [9] with two aerodynamic solvers. *InWave* is a seakeeping software developed by INNOSEA and Centrale Nantes. *InWave* uses NEMOH [10] for computing the hydrodynamic database and a multibody solver (articulated body algorithm) for simulating the system dynamics in time domain. The aerodynamic loads are either calculated through a Free Vortex Wake (FVW) theory based or a Double Multiple Streamtube (DMS) theory based solver.

InWave has been coupled to the FVW solver *CACTUS* [11], developed at Sandia National Laboratories (USA). More details about this coupling can be found in [1]. The theory is based on potential flow theory. On the blade, lifting line and blade element theories are used so that tabulated aerodynamic lift and drag coefficients C_L and C_D can be used. This FVW solver has been largely validated on fixed rotors in different operating conditions [11].

The DMS theory-based solver has been developed by Centrale Nantes and INNOSEA following [2] and [12]. It uses a skew model to account for the tilt angle of the platform. Also, the velocities induced by the platform motions are accounted for. However, the aerodynamics is quasi-static as it assumes a steady flow at each time-step. The induction is computed by using Froude-Rankine theory. The code has been validated on fixed rotors in various conditions (to be published). It has been demonstrated that such an approach is less accurate than the FVW theory at high TSR as more rotor/wake interactions may happen.

As both aerodynamic solvers assume an inviscid flow, dynamic stall can only be accounted for by using semi-empirical models, such as Leishman-Beddoes (as described in [11]).

The simulation tool integrates the quasi-static mooring solver *MAP++* [13] developed at the National Renewable Energy Laboratory (USA). It also includes a control module to compute the generator torque as designed by [14]. It has been adapted to the considered turbines following [15]. This control module allows filtering the $n * p$ frequency from the measured torque at the generator, n being the number of blades and p the rotational frequency of the rotor.

A schematic view of the modular framework is presented in Figure 1. A screenshot from a typical *InWave-CACTUS* simulation of a floating VAWT in one of the OC3 load cases is presented in Figure 2.

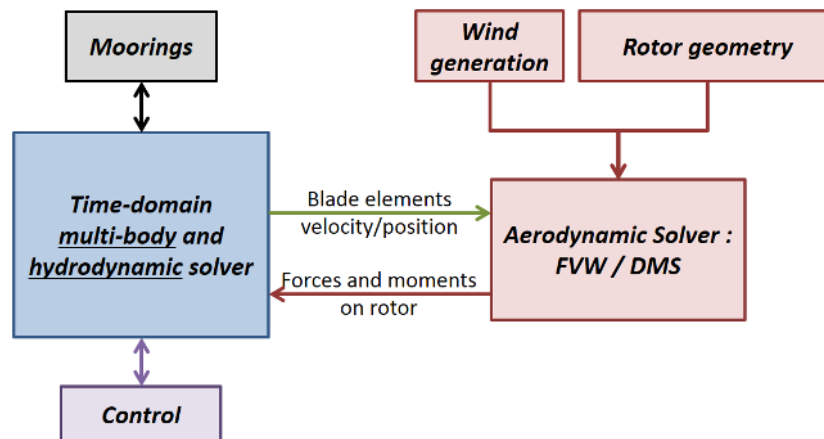


Figure 1. Schematic view of the modular framework

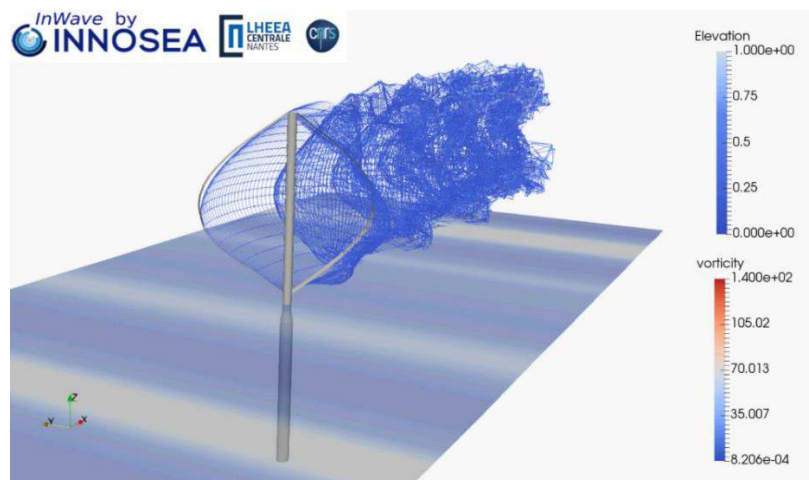
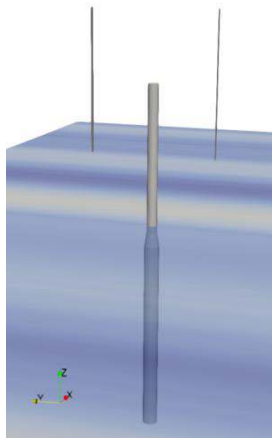
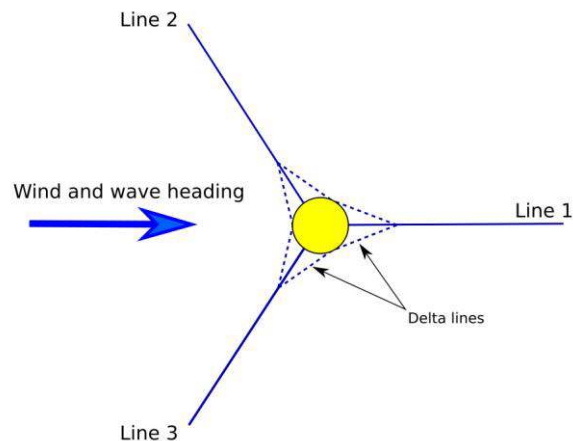


Figure 2. Screenshot of a typical *InWave-CACTUS* simulation of the *DeepWind* [16] VAWT

3. Floating VAWT design and load cases

A two-straight-bladed VAWT (called H2) based on the *OC3Hywind* SPAR [3] is considered. The design follows [15]. It is presented in Figure 3. The blade length is 80m, the rotor is 39m radius and the blade chord is 4.05m. The rotor struts aerodynamics is not taken into account. The catenary mooring system is composed of three catenary mooring lines arranged as shown with continuous lines in Figure 4. A linear stiffness is added on the platform yaw following [3] to account for delta-lines that are not considered in the quasi-static mooring model (dashed lines in Figure 4). This mooring model was designed for a HAWT in the OC3 project. It is thus not optimised for VAWTs. All bodies are considered rigid.

**Figure 3.** 2-straight-bladed FVAWT**Figure 4.** Catenary mooring system layout

The wind turbine is considered in irregular waves defined by a JONSWAP spectrum with a significant height $H_s = 6m$, a peak period of $T_p = 10s$ and a peakness factor $\gamma = 3.3$. Two turbulent wind fields are generated at both $12m.s^{-1}$ and $18m.s^{-1}$ using a Kaimal spectrum. Wind and waves are aligned. The corresponding TSRs of the rotor are respectively 3.5, the optimal TSR, and 2 which is much lower. Simulations are run on 5000s and the transient regime is ignored. At high TSR, the rotor's angular frequency is $1.08rad.s^{-1}$. At lower TSR (2), it is approximately $0.93rad.s^{-1}$. The platform has six degrees of freedom (DOFs). It is recalled that the generator torque is computed by the control module. The rotor velocity is thus variable.

4. Results and discussion

4.1. Platform motion PSDs

The time-series are processed into Power Spectral Densities (PSDs) to show the distribution of motion energy on a frequency range. The PSDs of pitch and roll motions and of aerodynamic thrust and torque at high TSR are plotted on the left in Figure 5. The datasets for the low TSR are shown on the right. The curves obtained from the DMS and FVW solvers are respectively plotted in blue and green.

The motion PSDs in the wave and wind direction (e.g. pitch motion on Figure 5) are very similar in the two aerodynamic models. One can see a higher peak at natural pitch frequency at low TSR (at $0.27rad.s^{-1}$) with the DMS model. It shows that there is more aerodynamic damping with the FVW solver. The same conclusion can be drawn with the roll motion PSD. The agreement between both models at wave frequencies ($\omega \in [0.4, 1.0] rad.s^{-1}$) is very good. The agreement is also good at low frequency at the resonance peak associated to the mooring stiffness (below $0.2rad.s^{-1}$). At $18m.s^{-1}$ wind speed, a more important $2p$ peak can be observed around $2rad.s^{-1}$. Other degrees of freedom PSDs show globally the same agreement (surge, sway, heave and yaw).

For the aerodynamic thrust and torque, a good agreement is seen at both TSRs at low and wave frequencies. These harmonics are the thrust and torque oscillations induced by the platform motion. At the $2p$ frequency the agreement is poorer. There is a 33% relative difference on the thrust peak amplitude, and a 90% relative difference on the torque peak amplitude at high TSR. At low TSRs, the agreement between the two models is better. Also the power density distribution is much wider for the high TSR. This comes from the wind turbulence combined with the generator torque controller reaction.

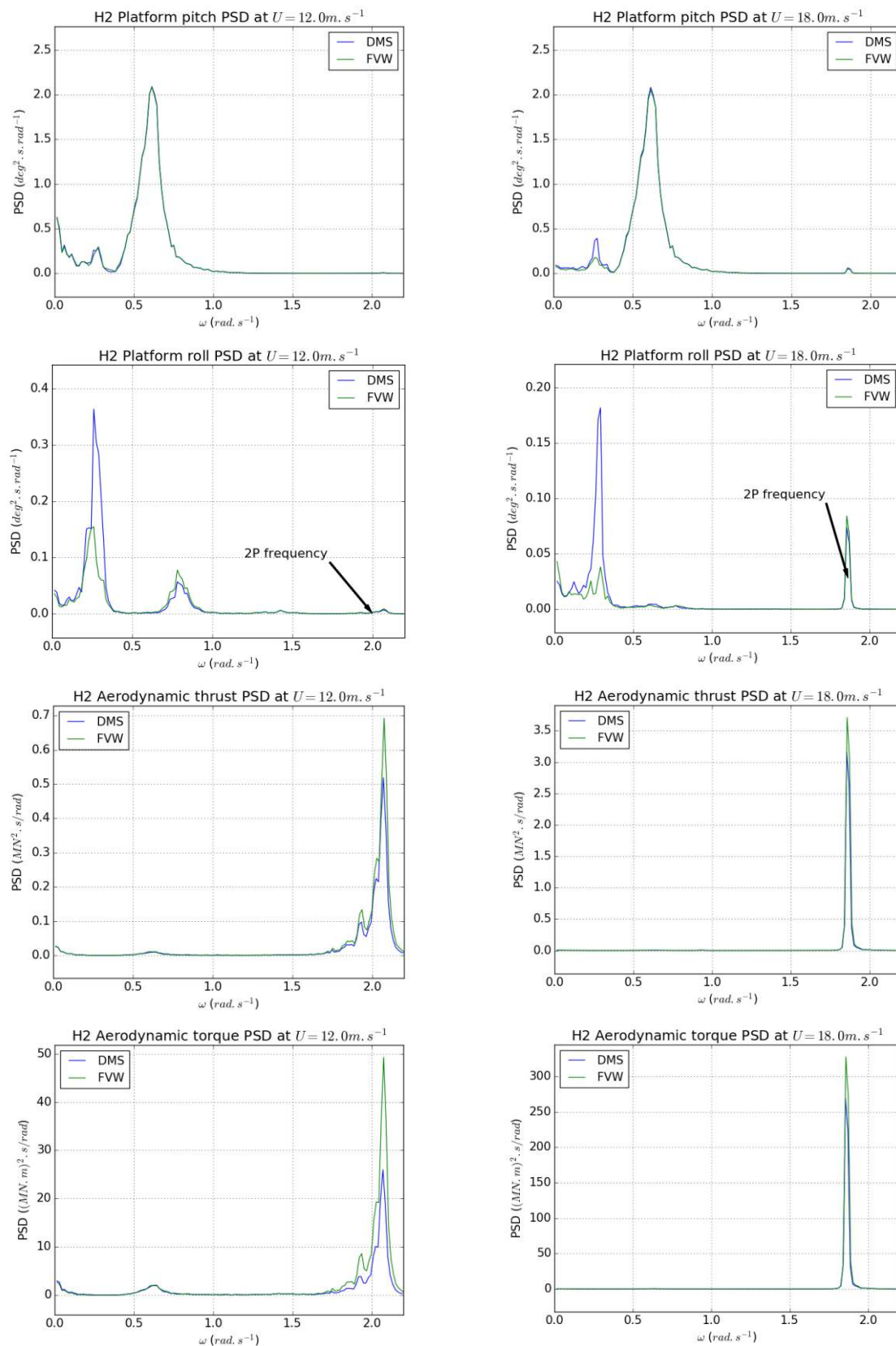


Figure 5. Power spectral densities at TSR 3.5 (left) and 2 (right)

4.2. Mean values and standard deviations

Let us consider the mean values and standard deviations (STDs) of the time-series (for which the distribution of power is not of interest).

For instance, aerodynamic thrust and side thrust coefficients at high and low TSRs are plotted in Figure 6. Torque and power coefficients are plotted in Figure 7. The high TSR results are on the left and the low TSR results are on the right. In both figures, a good agreement is observed at low TSR but the ranges of the dynamic response show differences at high TSR. Also the differences between the mean values are bigger at high TSR. The relative differences between aerodynamic thrust C_{Fx} , side thrust C_{Fy} and power coefficient C_p computed by both the FVW and the DMS solvers are presented in Table 1. It shows relative differences between mean and STD values for both solvers at high and low TSRs. One can easily see that the results are in good agreement only at low TSR. At high TSR, differences between computed mean thrust coefficients can grow up to 12%, while the STDs have 15% relative difference.

Those differences don't have impact on the motion PSDs as they only represent the energy distribution on a frequency range and not the mean value and/or the global dynamic response of the structure in time-domain. Relative differences in platform angles mean values and standard deviation are presented in Table 2. One can see that especially mean values at high TSRs don't agree well. Apparently, the DMS model fails to capture important unsteady aerodynamic effects that are mostly present at high TSR. Also, the dynamic response in roll seems to be different between the two solvers at both TSRs as can be seen in the PSDs.

The dynamic response in yaw is similar in both cases as the platform only responds at its natural yaw frequency. The differences between the mean yaw come from differences in rotor aerodynamic torques between the two models.

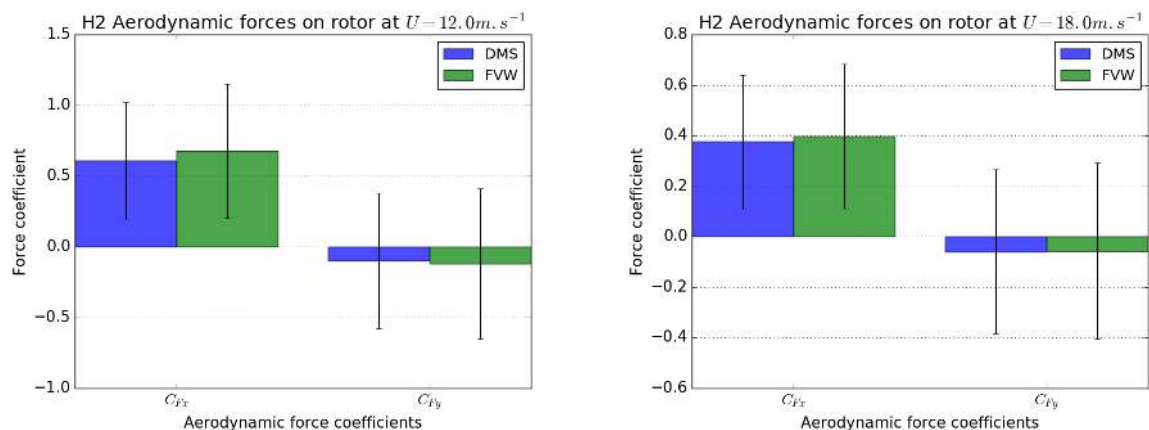


Figure 6. Aerodynamic thrust and side thrust coefficients at high and low TSRs

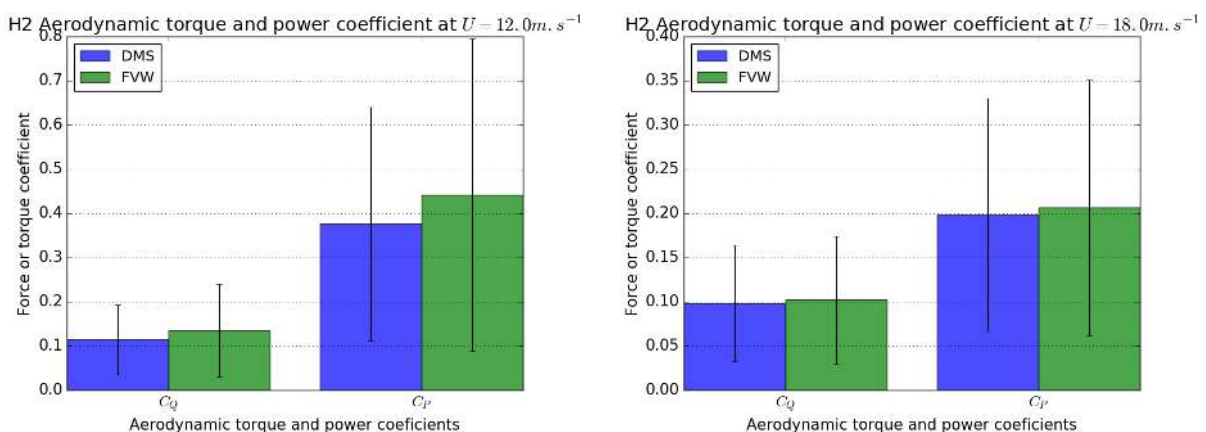


Figure 7. Aerodynamic torque and power coefficients at high and low TSRs**Table 1.** Relative differences between the DMS and FVW for the aerodynamic forces and power statistics at high and low TSRs

Rel. diff. on:	C_{Fx}		C_{Fy}		C_P	
$U_\infty (m.s^{-1})$	mean	STD	Mean	STD	mean	STD
12	12%	15%	19%	11%	17%	33%
18	6%	6%	5%	8%	4%	10%

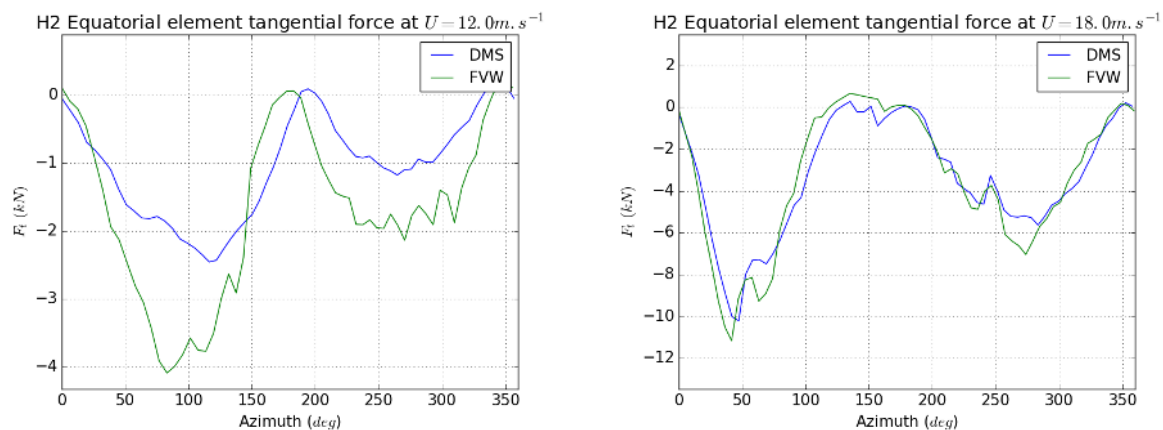
Table 2. Relative differences between the DMS and FVW for the platform rotations statistics at high and low TSR

Rel. diff. on:	Roll		Pitch		Yaw	
$U_\infty (m.s^{-1})$	mean	STD	mean	STD	mean	STD
12	13%	14%	10%	0%	19%	1%
18	6%	24%	5%	2%	4%	2%

4.3. Impact on floating VAWT design

The important differences in the numerical predictions of the motion response between the DMS and FVW models could lead to important floating VAWT design issues. For instance, an error in the mean platform position would lead to substantial differences in mooring pre-tensions (not presented here as the mooring model is not accurate enough) or on the umbilicals. The aerodynamic forces have to be accurately computed at all operational conditions to design the blades structure. Important differences between the two models aerodynamic forces were here observed at the optimal TSR. For example, the tangential force on an equatorial (mid-span) blade element is plotted on Figure 8 at both high and low TSRs with both aerodynamic models.

One can see important differences in the fluctuations of the aerodynamic forces at high TSR. Here the relative difference between mean value and standard deviation at high TSR are respectively 25% and 37%. If blades were considered flexible in *InWave*, these differences could be even more important and differences in blade deflection would probably be as important. On this aspect, it could be especially of interest to compare those results to those from an Actuator Cylinder theory-based solver, which is of intermediate flow representation complexity between the DMS and the FVW.

**Figure 8.** Blade element tangential loading along a rotor revolution at high and low TSRs

5. Conclusions

Two different aerodynamic models for VAWTs' dynamic response simulation have been compared considering a 2-straight-bladed VAWT on the *OC3Hywind* SPAR platform in the OC3 load cases. On the one hand, the fast DMS solver assumes a steady flow on the rotor. On the other hand the FVW code is inherently unsteady. Load cases include irregular waves and two different turbulent wind fields

with mean wind speeds of 12 m.s^{-1} and 18 m.s^{-1} , corresponding respectively to high (3.5) and low (2) TSRs as rotor operating conditions.

Computed platform motions have been processed into PSDs, which show a good agreement at both TSRs. However, higher motion harmonics at platform natural frequencies show a lower aerodynamic damping in the DMS solver. The aerodynamic forces harmonics at $2p$ frequency show some discrepancies between the two aerodynamic models, but induced differences in the platform motion PSD at those frequencies are hardly visible.

The comparative study also shows important differences between aerodynamic forces at high TSRs, leading to differences in platform mean positions and angles. It could lead to problems in stability and mooring design. Also the FVW dynamic loads on the blades are significantly higher than those computed with the DMS code. The DMS solver seems to be unable to capture essential unsteady effects that happen especially at high TSRs when the rotor strongly interacts with its wake. This could lead to substantial issues in blade design.

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