Modern methods for investigating the stability of a pitching floating platform wind turbine

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Abstract. The QBlade implementation of the Lifting Line Free Vortex Wake method(LLFVW) was tested in conditions analogous to floating platform motion. Comparisons against two independent test cases, using a variety of simulation methods show excellent agreement in thrust forces, rotor power, blade forces and rotor plane induction. Along with the many verifications already undertaken in literature, it seems that the code performs solidly even in these challenging cases. Further to this, the key steps are presented from a new formulation of the instantaneous aerodynamic thrust damping of a wind turbine rotor. A test case with harmonic platform motion and collective pitch is used to demonstrate how combining such tools can lead to better understanding of aeroelastic stability.

1. Introduction

The proliferation of large wind turbine rotors has been accompanied by the need for accurate and computationally inexpensive aeroelastic simulation tools. For aeroelastic simulations, the aerodynamics of the wind turbine are most typically calculated using Blade Element Momentum based methods (BEM). In the scenario of offshore wind, particularly when designing for floating platforms, the significant motion of the rotor leads to complicated aerodynamics. Sebastian and Lackner [1] have made convincing cases that, even with secondary correction factors, floating platform wind turbine aerodynamics exceed the capabilities of BEM based simulation methods. A prime example of this is concerning cases of rotor - wake interaction. As the rotor transitions between wind mill and propeller states, a toroidal recirculation pattern can form, meaning essentially that the rotor is interacting significantly with it's own wake. As BEM does not explicitly solve the flow pattern of the wake, it is simply not possible to accurately represent such behaviour.

The Lifting Line Free Vortex Wake method (LLFVW) uses non-linear polar data to calculate the blade forces coupled with a free vortex wake formulation and serves as a good method of simulating cases where large rotor displacements and yaw misalignments occur (see figure 2). Recently an implementation of a LLFVW code was completed and included in the QBlade wind turbine simulation code [2]. Simultaneously to this study, the LLFVW solver is being extended to include an unsteady aerodynamics model [3] and is being coupled with the structural formulations of the FAST framework [4]. In this paper, a comparison is made between the LLFVW code and existing literature comparisons where higher order aerodynamic simulation techniques were used i.e. URANS CFD ([5, 1]). The comparisons and further test cases are made using the NREL 5MW turbine[6] which is undergoing prescribed harmonic motion (see figure 1).

After the validation of the LLFVW code for simulations involving a moving rotor plane, the aerodynamic damping of the rotor is investigated. For this analysis, a new formulation is presented for the instantaneous aerodynamic damping of the fore-aft motion degree of freedom. The formulation is a modification of an existing formulation that was first presented by Corke and Bowles [7, 8] and later applied by Lennie to an airfoil with microtabs [9]. For the first time, this new formulation makes it possible to look at the aerodynamic damping throughout the pitch cycle of the wind turbine - as opposed to the traditional approach where only cycled averaged values are inspected. Such a formulation is particularly useful in analysing aeroelastic instabilities where limit cycle oscillations are present. Limit cycle oscillations will have cycle averaged values that are neutral but could have occurrences of highly negative damping. Using this method on LLFVW data makes it possible to understand aeroelastic thrust stability of the rotor without the heavy linearisation applied in most stability analysis techniques. It is also a useful way of understanding the full effects of controller wind turbine interactions. An example will be presented showing the effect of collective pitch cycles during fore-aft motion of the rotor.

2. Rotor Motion

For the scope of this paper, prescribed motion of two varieties are considered. The first variety, pitching, is the more realistic representation where the rotor plane undergoes both pitch and linear translation. The second variety, fore-aft motion, assumes that the rotor plane pitching component is insignificant compared to the influence of the linear translation. Within the scope of this study, investigating the total rotor thrust, the difference between the assumptions is assumed to be small. There may be applications where this assumption is unsuitable. For the comparison cases, the motion profile is matched.

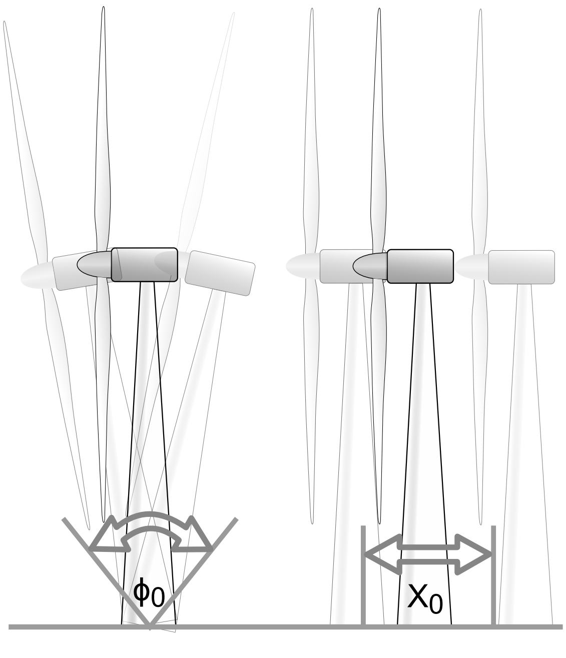

Figure 1: The two different assumed motions for the wind turbine. (Left: wind turbine pitching; Right: wind turbine fore-aft motion)

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3. Comparison Cases

The QBlade LLFVW implementation has been previously tested for a range of standard HAWT and VAWT cases as can be found in existing literature [2][4]. When the wind turbine starts moving relative to the steady inflow, the wake will become distorted. In the case of a harmonic movement, the wake will display harmonic contractions and expansions (see figure 2) which induces velocity onto the rotor plane. The publications mentioned above have focused on verifying the performance of the QBlade LLFVW under stationary conditions and cases with yaw. This means that battery of verifications undertaken should be extended to include cases where platform motion is present, thus ensuring that LLFVW techniques are a suitable approach for floating platform wind turbine aerodynamics. A number of comparison papers have been

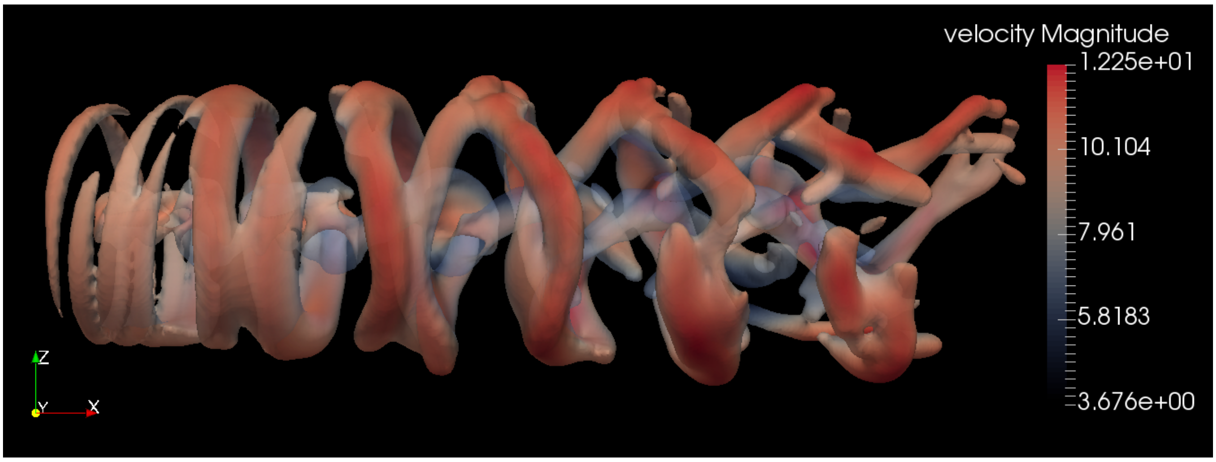

Figure 2: Snapshot of LLFVW simulation during pitching platform motion; vorticity isosurface of the wake coloured with velocity magnitude

sought from literature that test a horizontal axis wind turbine rotor in prescribed floating platform motion. For the scope of this paper, only rigid body motion will be considered. The comparison will be undertaken by replicating the simulations from literature which used higher order methods.

Two different papers were used as a basis for comparison; both investigating the NREL 5MW. Tran et al. [5] compares a number of techniques with virtual blade motion using multiple reference frames (CFD-MRF) and real rigid body blade motion (CFD-RBM). The highest order simulation is a 3D Unsteady RANS(URANS) CFD simulation with a $k-\omega$ shear-stress transport turbulence model. The blade rigid body motion was achieved using an over-set grid which is described at length including a discussion of the mesh convergence. The actual CFD simulations were conducted using commercial codes Fluent with StarCCM+ for meshing. It appears from the presented information that the simulations should be high quality, within the limitations of URANS.

Tran[5] also compared their results against lower order simulations using unsteady blade element momentum method. The Tran [5] implementation of the unsteady blade element moment method (UBEM) was taken from Hansen [10] with corrections for tip losses, wake unsteadiness and unsteady aerodynamics. This particular implementation took the platform motion into account by changing the relative inflow velocity. Further comparisons were made using modified versions of FAST[11] from the National Renewable Energy Laboratory; one comparision using a momentum balance for the wake solution (FAST-BEM) and the other using generalized dynamic wake (FAST-GDW). In both cases, the structural modes were locked and no controller was used, for more complete details, see the original paper from Tran [5].

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Tran[5] simulates the pitching of the wind turbine as shown in figure 1(see left hand side). Two cases were simulated with platform pitching amplitudes of 1° and 4°; and a constant harmonic pitching frequency of 0.1Hz. The calculations were performed at a steady inflow speed of 11m/s with a constant rotational speed of 12rpm and a constant blade pitch angle of 0°. From this paper it was possible to compare thrust, power and integrated blade forces.

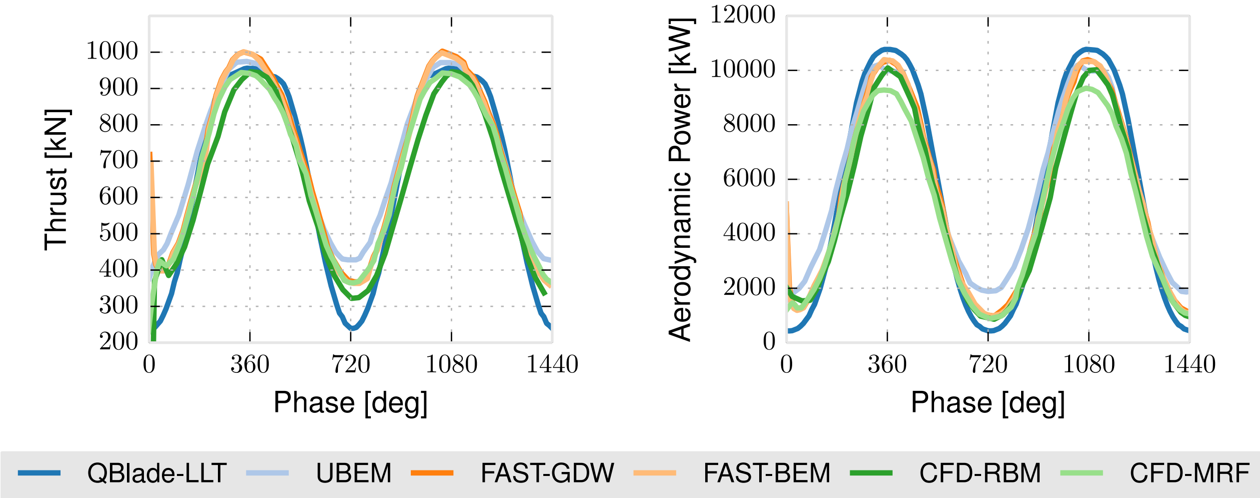

Figure 3: Thrust and power over phase angle for pitching platform motion (4° pitch amplitude) Comparison Case: Tran [5]

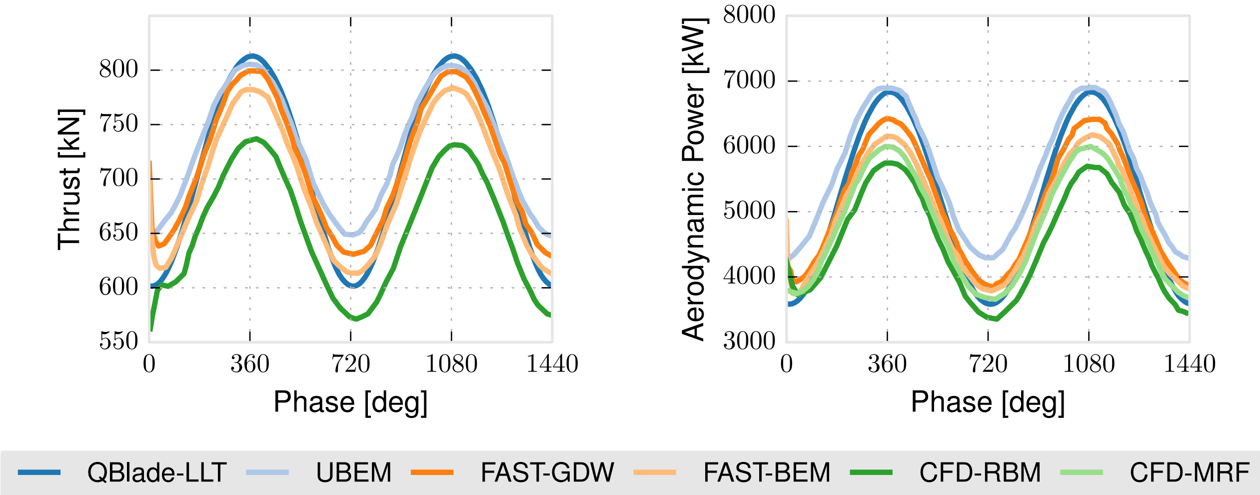

Figure 4: Thrust and power over phase angle for pitching platform motion (1° pitch amplitude) Comparison Case: Tran [5]

The QBlade simulations were run with the same conditions as described above. The unsteady aerodynamic model [3] without vortex lift was enabled as the wind turbine is operating at near rated speed without yaw. The standard NREL 5MW model [6] was set-up according to the definition[1]. The following settings were used for the simulation;

[1] The standard 5MW project file is available for download with the standard QBlade package

Wake Age in Revolutions	8
Full Wake in Revolutions	0.5
Fine Wake in Revolutions	4
Wake Thin Factor	2
Min Gamma Factor	0.4
First Row Length Fraction	0.3
Bound Vortex Location	0.25 c
Timestep	0.1 Sec

The LLFVW (figure 2) shows good agreement for all cases, which can be seen in figures 3, 4 and 5. It is interesting to note that steady and even unsteady BEM simulations, when compared to CFD or LLFVW results, under predict the magnitude of the load cycle in most cases. In this case, the LLFVW appears to perform well.

In the publication chosen for a second comparison, Vaal et al.[12] uses a moving actuator disc CFD hybrid method which allows for a good comparison of the unsteady wake induction between CFD and the LLFVW. The moving actuator disk model essentially places a moveable actuator disk into a CFD simulation (Implemented in Fluent). In practice this means that the actuator disk acts as a volume force onto the surrounding cells. It is argued by Vaal [12] that, because this method explicitly solves the wake rather than relying on simplified relations, the method should be more robust than the commonly used methods such as the Pit-Peters model [13] or the Stig-Oye model [10]. Vaal [12] presents a number of investigations into the relative performance of the models, for this paper, the rotor plane induction is the most interesting to compare.

Vaal [12] undertook a sensitivity study showing the wake velocity before and after the rotor at different phases for different operating conditions. From this study, the authors choose the largest amplitude (16m) of fore-aft movement (right hand side of figure 1). The fore-aft motion was harmonic with a frequency of $0.08Hz$, the inflow speed was 11.2m/s, the blade pitch was 0° and the rotor speed was a constant $0.2Hz$. Vaal [12] allowed several oscillations to pass in order to let the wake effects develop. The grid extended 10 rotor diameters up and down stream. It would appear that the approach and settings used by Vaal [12] will provide good quality results

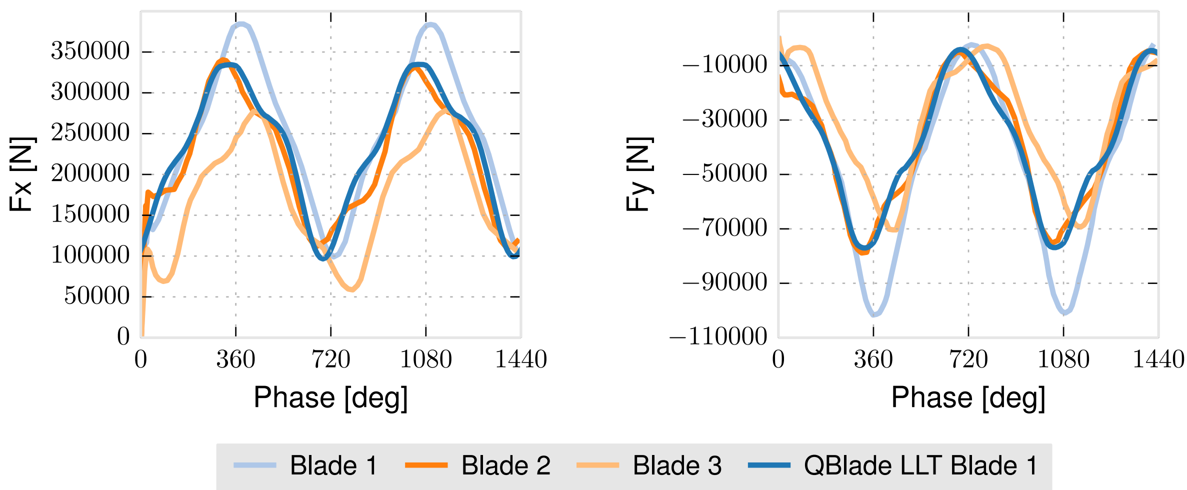

Figure 5: Integrated blade forces at blade root for pitching platform motion (4° pitch amplitude) Comparison Case: Tran [5]

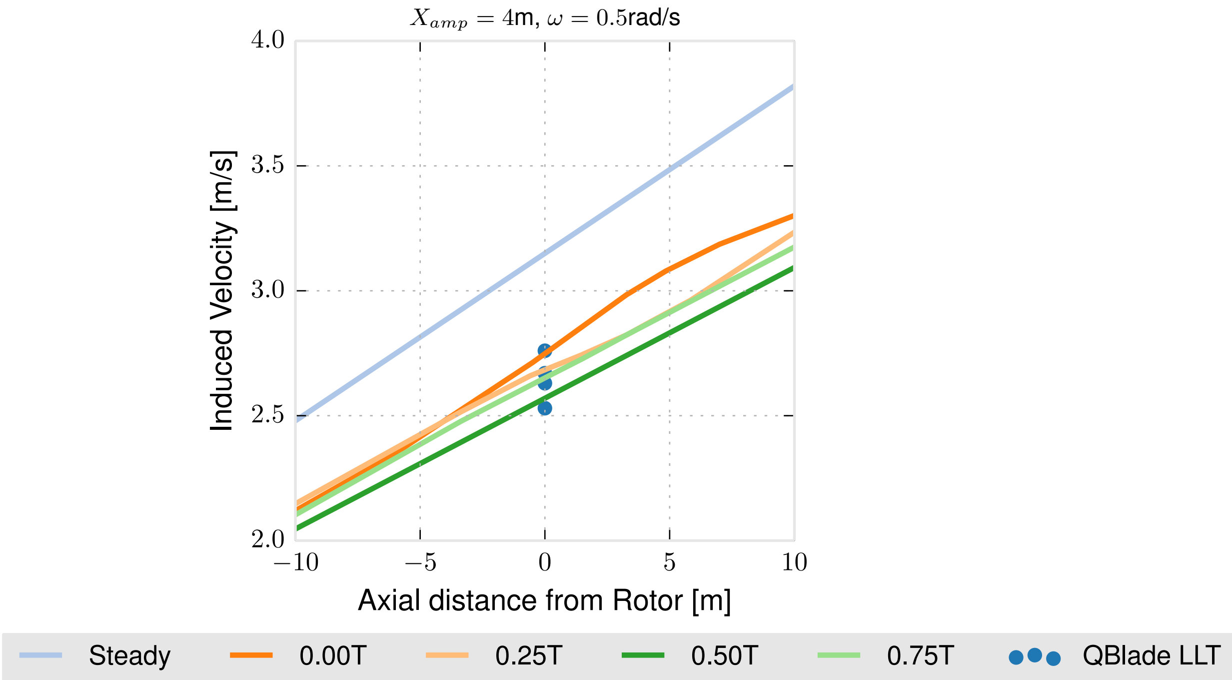

Figure 6: Induction Plot compared to Moving Actuator Disc CFD Hybrid from Vaal [12]

for comparison.

The QBlade simulations were conducted again, using the settings stated above, with prescribed linear rotor plane movement. Like Vaal [12], a number of oscillations were simulated before finally extracting the data. The comparison was made at the exact rotor plane where the axial velocity could be sampled over an area determined by the rotor radius. There was not enough information provided by Vaal [12] to ensure consistency of the sampling area for the induced velocity. In the context of a wake with expansion and contraction occurring, the assumptions have a distinct effect on the induction results. Therefore, no upstream or downstream comparisons were attempted. A rotor plane axial velocity field snapshot was taken at equally spaced points within the cycle. The results, shown in figure 6, show that the rotor plane induction for the two methods matches well over the four snapshots. It seems therefore that there is a good agreement between the two methods for the most challenging test case presented by Vaal [12].

From the two verifications performed here it seems that the QBlade LLFVW simulation model produces results that are comparable to other higher order or hybrid methods. These results and the results already published give a high degree of confidence in the simulation tools ability to model wind turbines undergoing platform motion.

4. Using the hilbert transform method to obtain instantaneous aerodynamic damping of a pitching rotor

The following section briefly outlines a reformulation of the instantaneous damping calculation method outlined by Bowles and Corke [7][8]. The original reference by Bowles et al. [7] describes the original method in complete detail and Lennie [9] provides an application of the method to an airfoil with microtabs and gurney flaps. In the reformulation described here, the instantaneous damping calculation is applied to the fore-aft motion of the whole rotor, a situation particularly interesting for floating platform wind turbines. The full derivation is lengthy and requires many detailed explanations, therefore only the key results will be presented here. It is assumed for this paper that a small pitch angle means that the linear motion will have a greater effect on the wake than the pitching of the rotor plane. The formulation therefore examines the aeroelastic damping in the thrust degree of freedom in the linear sense.

At first, we use the hilbert transform to obtain the analytical signal of the thrust coefficient. A comparison between the thrust forces and motion phase reveals whether the aeroelastic damping is positive or indeed negative. Essentially the complex quadrature of the thrust force is the source of positive or negative aerodynamic damping. The formulation for this process is as follows.

A hilbert transform of the thrust coefficient time series $C_t(t)$ is taken.

$$\tilde{C}_t(t) = \mathcal{H}[C_t] = -\frac{1}{\pi}\mathcal{P}\int_{\inf}^{\inf} \frac{C_t(\tau)}{\tau - t} dt \tag{1}$$

Where $\mathcal{P}$ is the Cauchy operator and $\tilde{C}_t(t)$ is the Hilbert Transform of the thrust coefficient time series. Hilbert Transforms are intended to analyse narrowband signals. It was previously established in Lennie [9], that numerical or experimental noise doesn't cause problems for this formulation - therefore no signal filtering will be applied.

In practice, a single oscillation was selected once the start wake effects had fully developed. For quasi-steady simulations without stochastic effects, for example inflow turbulence, this simplification is sensible. By taking hilbert transform of the thrust data, we can find the analytical thrust signal which has a magnitude; [2]

$$A_{C_t} = \sqrt{C_t^2 + \tilde{C}_t^2} \tag{2}$$

and with some manipulation the phase difference between the lift and the fore-aft motion is given as;

$$\psi(t) = \phi(t) - \omega t \tag{3}$$

where the phase of the analytical signal is given by:

$$\phi(t) = arg(Y(t)) = arg(C_t + \tilde{C}_t) \tag{4}$$

These parameters are then used to estimate the instantaneous aerodynamic damping;

$$\Xi(t) = -\frac{A_{C_t}(t)}{X_0} \sin\psi(t) \tag{5}$$

where the platform motion is given by,

$$X(t) = X_0 e^{i\omega t} \tag{6}$$

The time averaged damping then gives us the cycle damping:

$$\Xi_{avg} = -\frac{1}{T}\int_0^T \Xi(t) dt \tag{7}$$

Like previously undertaken in Bowles and Corke [7][8] and Lennie [9] the cycle averaged damping formulation provided by Carta and Niebanck [14] can be used. In this case, again the formula

[2] The thrust force was normalized using the free stream velocity

will have to be reformulated for the thrust degree of freedom. Following the logic set down by Carta and Niebanck [14], the cyclic thrust damping can be shown to be;

$$\Xi_{cycle} = -\frac{1}{\pi X_0^2} \oint_{\alpha_{min}}^{\alpha_{max}} C_T(\alpha) dx_{norm} \tag{8}$$

Agreement between the two calculations provides a useful verification that the analytical signal is well conditioned and that no implementation errors are present. Verifications undertaken in Lennie [9] for the original formulation showed less than $< 1\%$ variation between the methods, Bowles and Corke [7] also remarked on the good agreement. In the cases investigated in the following section, the error was calculated to be consistently $\sim 3.5\%$.

5. Demonstration Case: Collective Pitch

Having now presented the analysis methods, it is possible to use use these methods to investigate an example case of of floating platform wind turbine aeroelasticty. A case was selected that should demonstrate more complicated thrust damping behaviour, the case chosen is harmonic collective pitch in the presence of platform translation. Further potential test cases for future work would include harmonic platform movement in combination;

- yawed inflow
- inflow turbulence
- gusts or sudden changes in direction
- changes in airfoil performance through simulated active flow control
- non-synchronous pitch and platform movements

Harmonic collective pitch in conjunction with platform movement is a complicated test case, but it is still simple enough to give a good demonstration of this particular tool chain.

The collective pitch motion was prescribed using the formula

$$\alpha = \alpha_0 \sin(\omega t + \phi_{pitch}) \tag{9}$$

The test case settings were as follows;

Rotor speed[rpm]	12.1
$\alpha_0[^\circ]$	0.5
ϕ_{pitch} [-]	$0, 0.5\pi, \pi, 1.5\pi$
Inflow velocity [m/s]	11.4
ω_{pitch}, $\omega_{platform}$[rad/s]	0.5

The collective pitch cycle chosen is not a realistic control regime, it was chosen to give a clear demonstration of the method. The LLFVW simulation was run for 60 seconds with a single cycle chosen for analysis after the initial wake effects had died out. The instantaneous damping was calculated from the thrust data using the method already discussed. As a verification the two cycle average values were compared and had good agreement, the values are presented in table 5.

The cycle averaged aerodynamic damping values do in fact show that collective pitch does have an effect. While thrust damping tends to be positively damped (with this sign convention, that means good damping), we can see that the magnitude of the damping is altered. In figure 7, it is possible to follow the chain of logic that leads to these changes. In the thrust force sequences, it is possible to see that while there are some magnitude shifts, the more important feature is that the phase of the thrust force is shifted. This then manifests as changes to the aerodynamic damping.

A closer inspection reveals an interesting feature, that a 0.5π (green) phase shift of the pitching sequence leads to an almost constant thrust force. This may appear to be favourable to reduce the fatigue loads of the wind turbine. However, what has effectively happened is that there is no force in phase with the velocity of the movement, therefore there is no complex term, thus slightly negative aerodynamic damping. In this case, the system would be relying on the other sources of damping[3] to reduce the amplitude of oscillation.

In the opposite case with a pitch phase shift of 1.5π (yellow), the thrust force is more in phase with the velocity, thus opposing the movement of the rotor is enhanced. The cycle averaged damping reflects this with a stronger damping value. The instantaneous damping value starts to show some departure from a pure harmonic signal. This can be traced to the matching non-linearity in the thrust force which could arise from rotor wake interactions, it is these effects that are difficult to account for in a cycle averaged value. In the literature examples where a pitching airfoil was examined [7][8][9], the non-linearities were very strong due to dynamic stall and caused strong spikes of aerodynamic damping. In simulations where sudden changes of operating conditions are present, the instantaneous damping method will highlight sudden drops in aerodynamic damping when they occur, even if they don't show up in the cycle averaged values.

	Averaged Instantaneous Damping	Cycle Averaged Damping	Error
$\phi_{Pitch} = 0$	0.030	0.031	3.5%
$\phi_{Pitch} = \pi$	0.036	0.038	3.5%
$\phi_{Pitch} = 1.5\pi$	0.060	0.062	3.5%
$\phi_{Pitch} = 0.5\pi$	-0.001	-0.001	3.5%
Baseline	0.036	0.037	3.5%

6. Conclusion

The QBlade implementation of the Free Vortex Lifting Line method(LLFVW) proved to be a useful tool for analysing floating platform wind turbines. Comparisons against two independent test cases, using a variety of methods showed an excellent agreement in thrust forces, rotor power, blade forces and rotor plane induction. Alone with the many verifications already undertaken in literature, it seems that the code will perform solidly even in these challenging cases. Further work is required to extend the same analysis with flexible blades, tower and eventually platform rather than prescribed motion; some of these topics are already under way.

The key results were presented from a new formulation of the instantaneous aerodynamic thrust damping of a wind turbine rotor. A test case showed that the method can help understand aeroelastic stability in complicated cases which may be cyclically damped, but instantaneously unstable. The two different methods of obtaining the cyclic damping agreed giving some manner of confidence in the method. Further work is required to fully detail the entire derivation and to explore many more test cases.

[3] i.e. structural or that provided by the floating platform

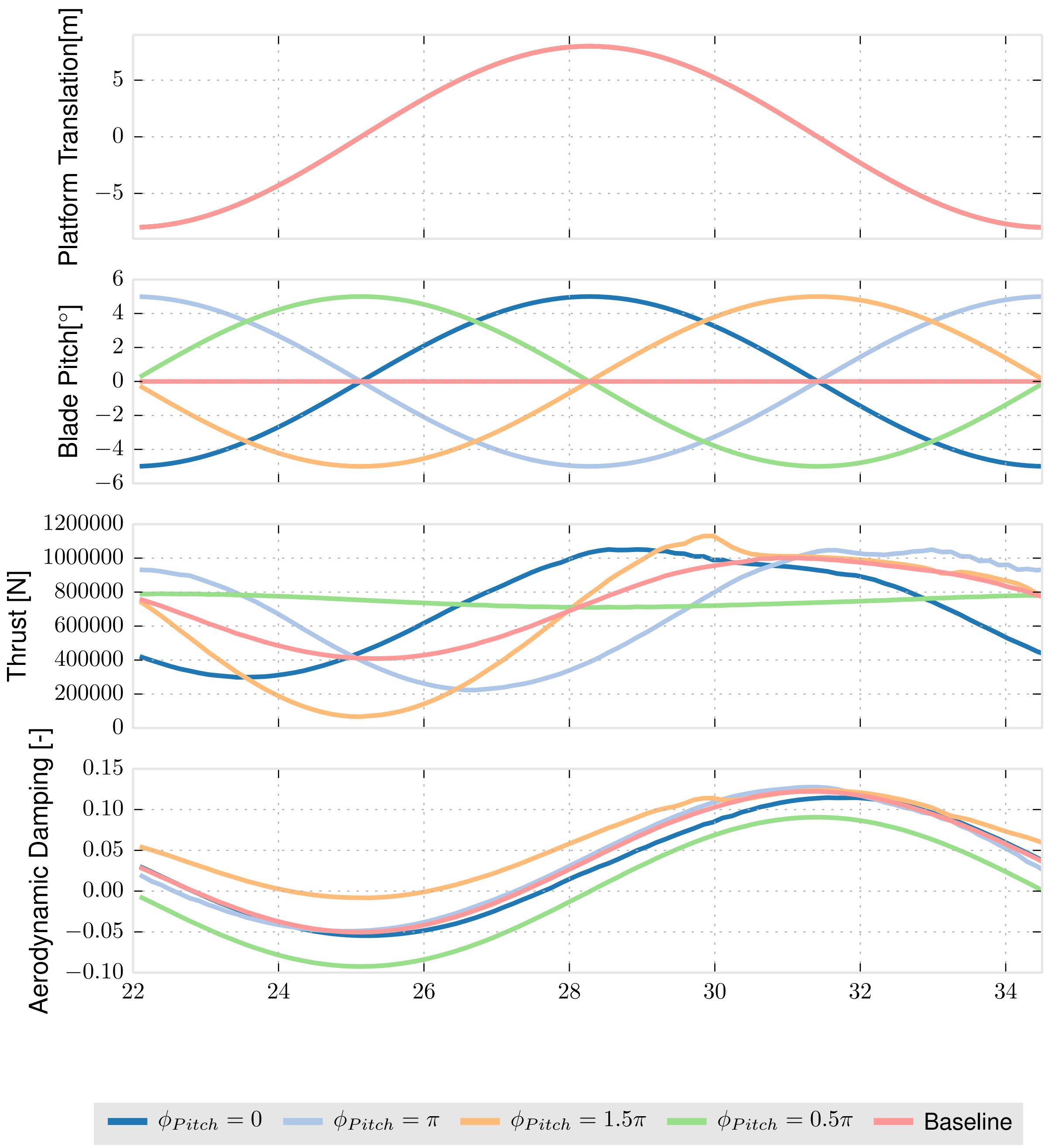

Figure 7: Collective Pitch Damping Cycles

References

[1] T Sebastian and M A Lackner. Characterization of the unsteady aerodynamics of offshore floating wind turbines. (March 2012):339–352, 2013.

[2] David Marten, Matthew Lennie, Georgios Pechlivanoglou, Christian Navid Nayeri, and Christian Oliver Paschereit. Implementation, Optimization, and Validation of a Nonlinear Lifting Line-Free Vortex Wake

Module Within the Wind Turbine Simulation Code qblade. *Journal of Engineering for Gas Turbines and Power*, 138(7):072601, 2015.

[3] Juliane Wendler, David Marten, Christian Navid Nayeri, George Pechlivanoglou, and Christian Oliver Paschereit. Gt2016-57184 Implementation and Validation of an Unsteady Aerodynamics Model. In *Proceedings of ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition*, pages 1–10, 2016.

[4] Joseph Saverin, David Marten, Georgios Pechlivanoglou, Christian Navid Nayeri, and Christian Oliver Paschereit. GT2016-56290 Coupling of an unsteady lifting line free vortex wake code to the aeroelastic HAWT simulation suite FAST. In *Proceedings of ASME Turbo Expo 2016*, Seoul, South Korea, 2016.

[5] Thanhtoan Tran, Donghyun Kim, and Jinseop Song. Computational Fluid Dynamic Analysis of a Floating Offshore Wind Turbine Experiencing Platform Pitching Motion. *Energies*, 7(8):5011–5026, aug 2014.

[6] Jason M Jonkman. NREL Offshore Baseline 5MW _Onshore with Compiled Controller, 2013.

[7] Patrick O. Bowles, Thomas C. Corke, Dustin G. Coleman, Flint O. Thomas, and Mark Wasikowski. Improved Understanding of Aerodynamic Damping Through the Hilbert Transform. *AIAA Journal*, 52(11):2384–2394, nov 2014.

[8] TC Corke and FO Thomas. Dynamic Stall in Pitching Airfoils: Aerodynamic Damping and Compressibility Effects. *Annual Review of Fluid Mechanics*, 47(1), jan 2015.

[9] Matthew Lennie, Alena Bach, George Pechlivanoglou, Christian Nayeri, and Christian Oliver Paschereit. The Unsteady Aerodynamic Response of an Airfoil with Microtabs and it's Implications for Aerodynamic Damping. *34th Wind Energy Symposium*, (January):1–12, 2016.

[10] M O L Hansen. *Aerodynamics of Wind Turbines*. Earthscan LLC, 2008.

[11] J M Jonkman. Fast Users Guide.

[12] J B De Vaal, M O L Hansen, and T Moan. Effect of wind turbine surge motion on rotor thrust. (October 2012):105–121, 2014.

[13] D. M. Pitt and D. A. Peters. Rotor Dynamic Inflow Derivatives and Time Constants from Various Inflow Models. In *9th European Rotorcraft Forum*, pages 1–24, 1983.

[14] Franklin O. Carta and Chares F. Niebanck. Prediction of rotor instability at high forward speeds. Technical report, USAAVLABS TR, 1969.