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Free yawing stall-controlled downwind wind turbine with swept blades and coned rotor

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Abstract

This paper studies the effects of backwards sweep and coning angle on a 10 m blade for a 100 kW stall-controlled downwind 3-bladed horizontal axis wind turbine. The purpose of this study is to determine whether the yaw moment of the nacelle would induce a restoring force when an error between the nacelle orientation and the wind is introduced into the system. This will help to evaluate the use of different passive control systems for potential use in a free yaw system. It was found that a backwards swept blade combined with a 10 degree coning angle are most effective in increasing the yaw restoring moment, and that over almost all the wind speeds this moment is acting in the correct direction, to turn the nacelle back into the wind. Reductions of the restoring yaw moment were discovered in the 12 to 15 m/s range, and are suspected to be caused by the transition from the pre- to post-stall models.

Keywords: Swept blade, coning angle, free yaw, wind shear, downwind turbine

1 Introduction

As wind turbines are increasing in size, they are also becoming more and more complex. This causes an increase in operational and maintenance costs, an area which is expected to grow significantly in the future as wind farms become larger and more remote, including in deeper and deeper waters offshore. This investigation has been performed in an attempt to bring an old idea up to date and back into use, that of a free yaw system on a downwind turbine. This system is inherently robust due to its passive nature, reducing the need for maintenance. There are some down sides to a free yaw system, such as large yaw rates inducing considerable gyroscopic loads, and the unpredictability of the restoring moment responsible for turning the nacelle back into the wind. The aim of this study is to attempt to rectify or control these negative effects through passive means, in order to reduce the operational and maintenance needs of the turbine without sacrificing performance or stability. This will be investigated through the use of a coning angle and backwards swept blades on a downwind, stall-controlled 100 kW turbine. A coning angle is the angle by which the blades are offset from the rotor plane, c.f. Figure 4. In this case, the offset of the blades is in the downwind direction. A swept blade is a blade where the tip is offset from the blade centreline, either in the direction of the leading edge or trailing edge. Further geometrical description and an explanation of the effects of a swept blade can be found in Sections 2 and 4.3 below.

The effect of a coning angle on the restoring yaw moment of the turbine has previously been studied [1], and here it will also be combined with a swept blade. The concept of swept blades or wings has been around for some time [2], with their beneficial effects having been studied in depth on upwind pitch-controlled turbines [3] [4]. They have also been in use in small commercial wind turbines for several years. Only recently, however, has there been application on a larger-scale upwind pitch-controlled turbine, with one of the larger research projects conducted by SANDIA and Knight & Carver with their STAR blade, completed in 2010 [5].

2 System Description

The system modelled in this study is a downwind, three-bladed 100 kW stall – controlled horizontal axis turbine with a rotor diameter of 21 m. The yaw of the turbine can be both free and fixed.

Both backward sweep and coning are investigated in the model. The overall shape of the blade is illustrated in Figure 1, and the form of the sweep curve is based on some positive experiences as stated in [2]:

$$x = a\left(\frac{z-z_0}{z_e-z_0}\right)^b \qquad (1)$$

where x is the distance by which the blade should be offset towards the trailing edge at blade position z, a is the total amplitude of the sweep, z is the distance along the blade, z_0 is the total length of the blade, z_e is the starting point of the sweep along the blade, and b is the sweep exponent (shape of the sweep curve). A sweep exponent of b = 4 and sweep amplitude of a = 1.2 m is used in this study.

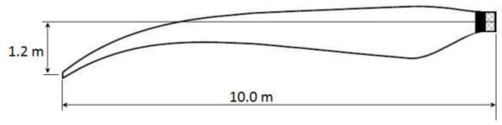

Figure 1: Outline of blade dimensions

Other key parameters of the turbine are as follows:

Parameter	Value
Rating	100 kW
Control	Variable speed stall
Hub Height	30 m
Cut-in wind speed	3 m/s
Cut-out wind speed	25 m/s
Rated wind- speed	11 m/s
Tower Shadow	Jet model

Table 1 : General parameters of the system

3 Methodology

Simulations were run in the aeroelastic code HAWC2 [6], developed by Risoe DTU National Laboratory for Sustainable Energy in Denmark. HAWC2 is a classical 3D multibody BEM code with Timoshenko beam elements, which includes engineering corrections for phenomena such as dynamic inflow, dynamic stall, skew inflow, shear effects on the induction and effects from large deflection. However it does not correct for the radial component of flow and the 3D effects of flow at the root, effects which are experienced when modelling a swept and coned blade. Traditionally, these 3D effects are incorporated in the aerodynamic coefficients (lift, drag and moment) describing the aerodynamic characteristics of the blade. In a recent code improvement effort, HAWC2's aerodynamic model under extreme yaw and sheared flows has become significantly more robust. Comparisons with actuator disc models verified the newly developed approach. These recent improvements are relevant for this investigation due to the asymmetric conditions imposed on the rotor plane by the wind shear, yaw error, yaw rate, coning angle and blade sweep.

The following simulations were run in an attempt to fully understand the behaviour of a free yaw system: a fixed yaw system (i.e. turbine without the capability to yaw) with deterministic wind, with and without coning angle and sweep, coning and sweep combined, and with and without wind shear. The goal of these fixed yaw load cases was to determine the direction and magnitude of the yaw moment produced by the various configurations (i.e. aerodynamic yaw stiffness). A free yaw system (i.e. a turbine that is free to rotate about the yawing axis) with deterministic wind was then investigated, with the same combinations of coning angle, sweep and wind shear described above. This was done in order to see what effect these various parameters have on the stability of the system, particularly on the yaw degree of freedom, and to determine what the yaw error will be under various circumstances. In some simulations, to further understand the causes of the behaviours seen, tower shadow was also turned off to determine whether it was contributing to the behaviour. All simulations were run for wind speeds from 3 to 24 m/s, in increments of 1 m/s.

The wind shear exponent considered in the analysis is 0.2.

4 Results and Discussion

The results for both fixed and free yaw with deterministic wind are discussed below. Note that due to a bug in the generator controller, for some high wind speeds the rotor speed was not set correctly resulting in clearly visible discontinuities when considering the fixed yaw cases. These results are not taken into account when discussing the yaw stability. Since yaw stability is mainly focussed around rated wind speed, the authors decided to disregard this minor error for the purposes of this study.

4.1 Average Yaw contribution as function of blade radius

By averaging the instantaneous yaw moment contribution of the 3 blades for several radial positions of the blade, Figure 2 can be drafted. Note that currently this approach holds a discretisation error since the blade forces and moments are only known for 15 points along the 10 m blade length. However, it should be sufficiently accurate for this purpose. In Figure 2, the static yaw moment is plotted for a negative yaw error while a positive yawing moment is required for static stability. Further it shows that mainly the inner blade contributes to the instability. Since the inner part of the blade is in deep stall around rated wind speed and the flow is highly influenced by 3D rotational effects, care should be taken in reading this result.

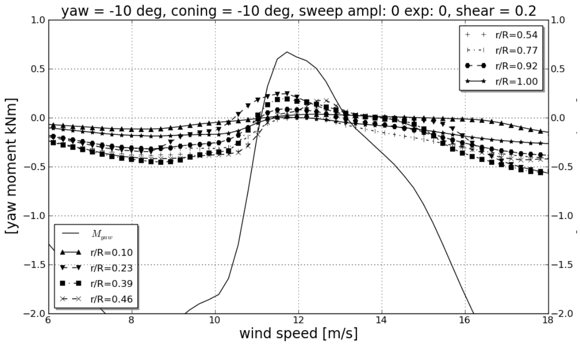

Figure 2 : Contribution to overall yaw moment by differing radial positions along the blade.

4.2 Effect of Coning Angle

General Principle

The effect of the coning angle on the stability of the yaw behaviour is relatively well known. The coning angle causes the blades on one side of the turbine to be more directly aligned with the flow, whereas the blades on the other side of the turbine are even less aligned with the flow then they would otherwise be. This increases the aerodynamic restoring moment above what it would be without the coning angle, see Figure 3 and Figure 4 for an illustration of this phenomenon.

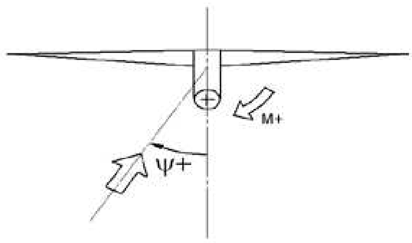

Figure 3 : Yaw error of ψ with a coning angle of 0°. Reproduced with permission from [1].

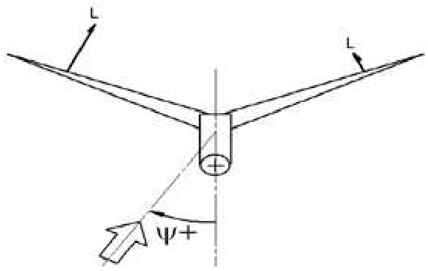

Figure 4 : Yaw error of ψ and blades with a coning angle, the coning angle causes the blade on the left side to become more aligned with the flow than that on the right, increasing the restoring moment. Reproduced with permission from [1].

As Observed in the Fixed Yaw System

One can see in Figure 5 the effect of the coning angle in enhancing the restoring moment, except for an area around 12 m/s where coning seems to leave the moment unaffected, or slightly reduced. This may be due to the transition between pre- and post-stall. It is likely that as the side of the rotor facing more directly into the wind approaches stall, the a drop in the lift coefficient evident in Figure 6 actually decreases the lift generated on that side of the rotor, reducing the restoring moment. As one side of the rotor is more aligned with the flow with a coned rotor, one would expect this decrease in yaw moment to occur at a lower wind speed than with an un-coned rotor, which is also in evidence in Figure 5. This would explain the drop in restoring moment around this 12 m/s area.

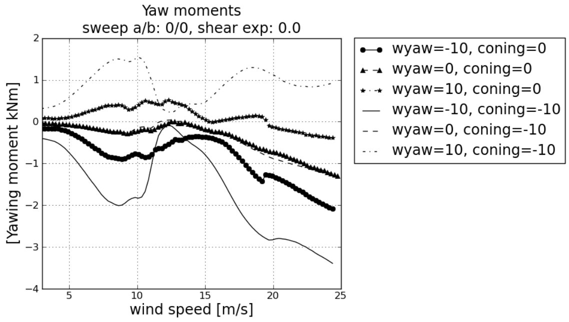

Figure 5 : Effect of coning angle on yaw moment. No sweep and no wind shear considered.

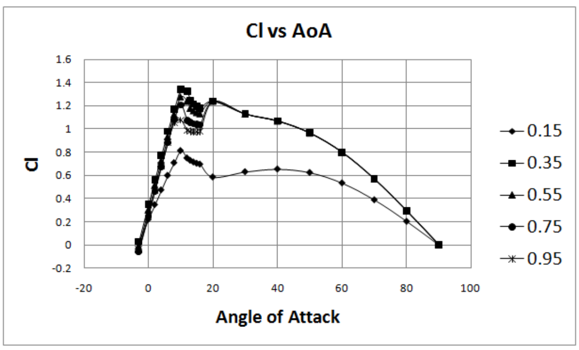

Figure 6 : Variation of the lift coefficient with the angle of attack of the blade. The numbers in the legend represent r/R, or radial placement along rotor.

As Observed in the Free Yaw System

One can see the effect of coning angle in enhancing the restoring moment for most wind speeds. Instabilities are demonstrated around the 12 to 13 m/s mark, as was suggested by the fixed results and relatively low restoring moment around those wind speeds. Instability could be caused by the fact that the average restoring moment is quite low, so any variations of this moment would cause the moment to oscillate from positive to negative, causing the extreme changes in yaw position as observed in Figure *7*. However as can be seen in Figure 9, the effect of the coning angle is visible due to the reduced oscillations in the yaw error (compare to Figure *7*). Figure 8 indicates an effective damping of the yaw error under the same conditions. However, this damping is not present anymore when wind shear is added.

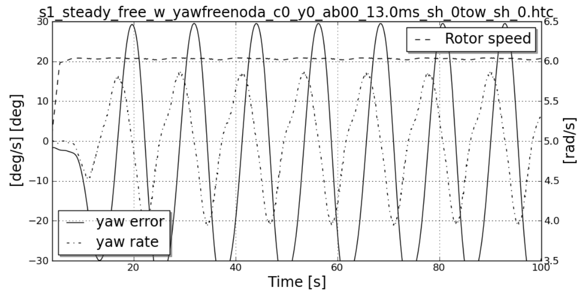

Figure 7 : Yaw error and yaw rate at wind speed of 13 m/s, without coning or tower shadow.

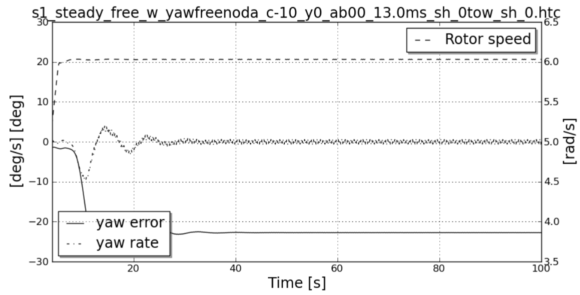

Figure 8 : Yaw error and yaw rate at 13 m/s, without tower shadow applied, no wind shear and with coning.

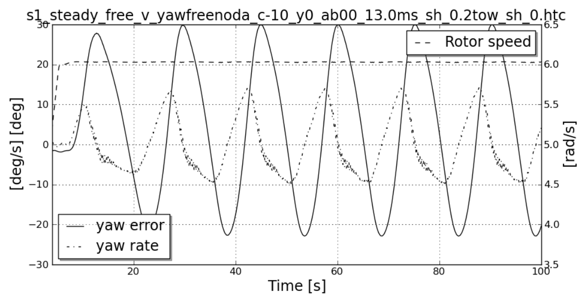

Figure 9 : Yaw error and yaw rate at wind speed of 13 m/s, with coning and wind shear applied.

4.3 Effect of Backward Sweep

General Principle

It should be noted that a swept blade will perform very differently when compared to the original straight blade. In this particular case, the original blade is designed and optimized as a stiff structure. By introducing a swept planform, there are two significant changes to the blade which will result in changed operating conditions: locally, the flow component perpendicular to the chord is now reduced due to the local sweep angle, and the torsional deformation will change the blade's pitch distribution dynamically as function of blade loading (bend-twist coupling). As with backward sweep, the latter will cause feathering: a reduction in angle of attack under increased loading. In [7] it is demonstrated that designing for a blade with a bend-twist coupling (although achieved via structural couplings rather than a swept planform) holds a significantly different result. It is considered beyond the scope of this research paper to propose a redesigned swept blade.

The sweep also has the effect of slightly increases rotor solidity, which may help to enhance the effect of coning when the two are combined. However because the effect of the slightly increased rotor solidity is assumed to be relatively small when compared to the other contributions of the swept blade, this has not been further investigated in this study.

As Observed in the Fixed Yaw System

Due to the twist to feather behaviour of the swept blade, the response at different wind speeds will be smoothed when compared to the behaviour of the original straight version: cyclic blade loading and hence resulting yawing moment has a lower amplitude. The feathering will cause the swept blade to stall at higher wind speeds, and to spread out the effects of stall radially along the blade as stall is induced later at the tip than at the root. It is because of this dynamic feathering, a direct consequence of sweep, that this improved static yaw stability is in evidence in Figure 10.

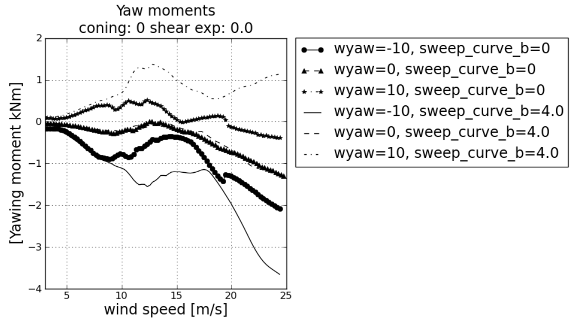

Figure 10 : Effect of backward sweep on yaw moment. This is not considering coning or wind shear.

As Observed in the Free Yaw System

One can see that the instabilities are in fact delayed by 1 m/s or so, and that they occur over a smaller range of wind speeds. This indicates that the pitch to feather is in fact delaying the onset of stall or transition between pre- and post-stall, and smoothing out the effects as different parts of the blade enter into stall at different times, reducing the effect of the instabilities.

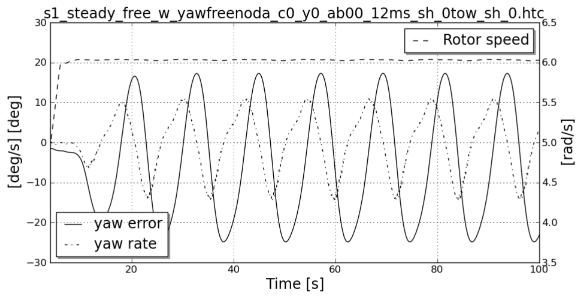

Figure 11 : Yaw error and moment at 12 m/s without sweep or tower shadow.

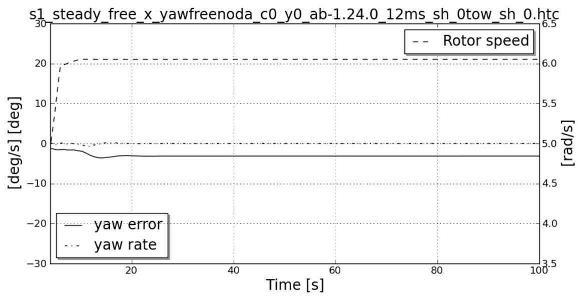

Figure 12 : Effect of backward sweep on yaw error at 12 m/s, demonstrating the delay of the instability.

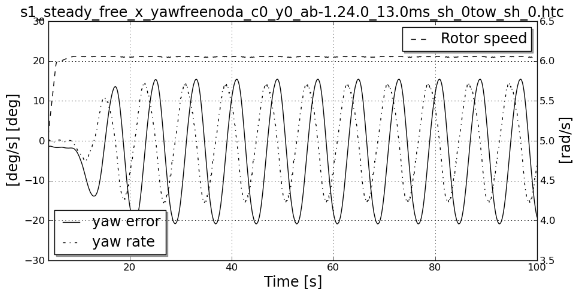

Figure 13 : Effect of backward sweep on yaw error and rate at 13 m/s, no tower shadow applied. Applying tower shadow has little to no effect on this result.

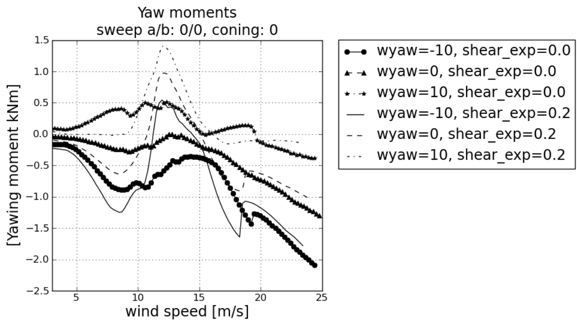

Figure 14 : Effect of wind shear on yaw moment. Not considering effects of sweep or coning angle.

4.4 Effect of Wind Shear

General Principle

Wind shear causes an uneven force on the rotor plane, with the upper portion of the rotor (above the hub) experiencing generally higher wind velocities than the lower portion of the rotor (below the hub). This asymmetric force creates an imbalance in the lift generated by the upper and lower portion of the rotor, inducing a negative yaw error in a free yawing system, or an additional negative yaw moment in a fixed yaw system. One can observe this tendency Figure 14, except for the "unstable" region between 12-14 m/s, where it becomes positive. This could be due to the fact that as the top portion of the rotor is entering into stall with larger wind speeds, the lift coefficient starts to drop, so this effect is actually reversed – there is larger lift on the bottom portion of the rotor, reversing the induced yaw moment. Then as stall deepens, this trend reverses itself once more, again as exemplified in Figure 14. This phenomenon should be more thoroughly investigated in future work.

As Observed in the Fixed Yaw System

The effect of wind shear on the fixed yaw system is described above. This behaviour is confirmed by the results in Figure 14.

As Observed in the Free Yaw System

When looking at the yaw behaviour at individual wind speeds, wind shear simply creates a shift in yaw error instability. The amplitude remains the same, however when compared to Figure *7*, one can see that the mean value is shifted slightly in a positive direction.

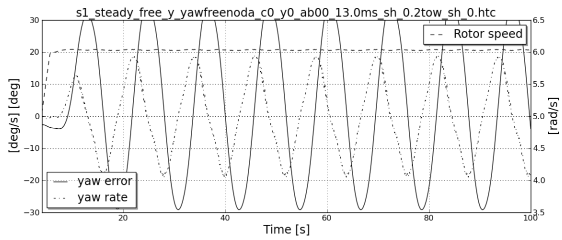

Figure 15 : Effect of wind shear on yaw rate and yaw error, no tower shadow applied.

At lower, stable wind speeds however, the effect is generally to create a larger yaw error than would be found without shear. This will be demonstrated by figures in Section 4.5.

4.5 Combination of Coning, Sweep and Wind Shear

As Observed in the Fixed Yaw System

The effect of coning and sweep combined is displayed in Figure 16, whereas the effect of coning, sweep and wind shear combined is demonstrated in Figure 17. This distinctly demonstrates the tendencies of wind shear previously discussed in Section 4.4.

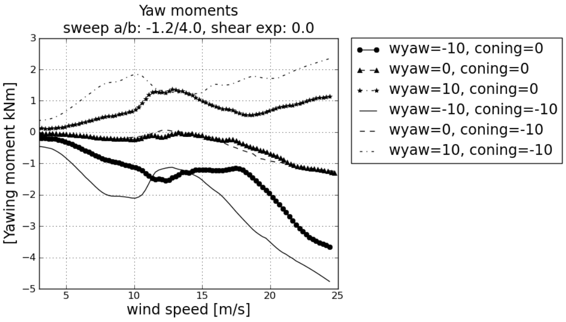

Figure 16 : Effect of coning and sweep on yaw moment, without shear

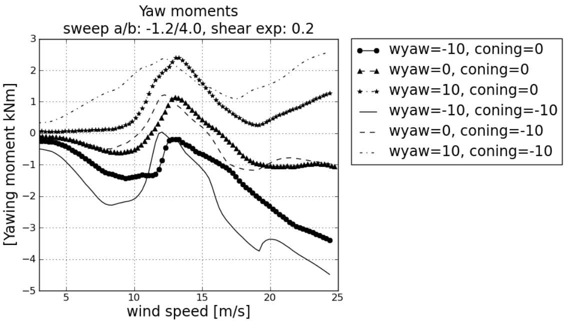

Figure 17 : Effect of coning, sweep and wind shear on yaw moment

As Observed in the Free Yaw System

The results of the free yaw system mirror those that were obtained when observing sweep, coning and wind shear separately. Figure 18 demonstrates that shear causes an increased yaw error, particularly in the 12-14 m/s range. Sweep does a relatively good job smoothing out the significantly changing inflow conditions (reduced standard deviations on the yaw error in Figure 19, also see Figure 20), and coning angle reduces the yaw error but doesn't contribute to any yaw damping. Figure 18 shows the standard deviation of the yaw error listed in Figure 17, giving an indication of what the amplitude of the oscillating yaw error is in the unstable regions, as has been previously demonstrated.

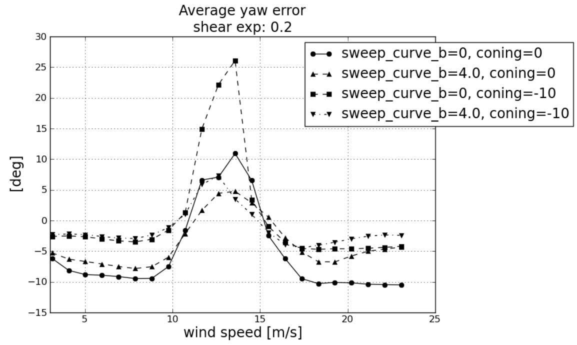

Figure 18 : Average yaw error with wind shear applied, coning and sweep applied separately and together.

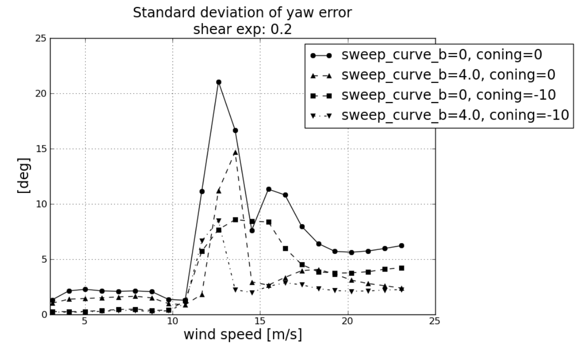

Figure 19 : Standard deviation of the yaw error in Figure 18.

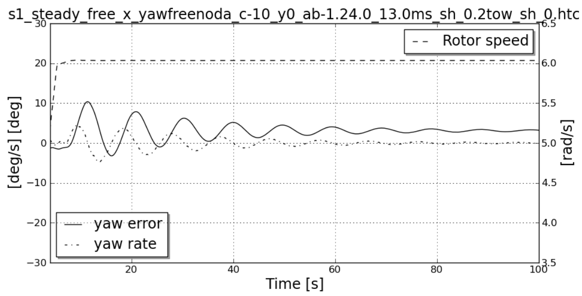

Figure 20 : Sweep, coning and wind shear included at 13 m/s – the damping effect of the sweep on the instability is demonstrated.

4.6 Effect of Coning, Sweep and Wind Shear on Loads and Power Curve

The effect of a coning angle, backward sweep and wind shear are investigated in this chapter. A model with a fixed yaw system is run with deterministic wind to more easily observe the behaviour of the system.

Coning Angle Only

The effect of the coning angle on flapwise blade root bending moments is significant. This is due to the centrifugal force on the rotating blade – as the blade rotates, the centrifugal force acts in the opposite direction of the loads induced by the flow, reducing the flapwise bending moment. Figure 21 shows a significant reduction on the flapwise loads, as expected.

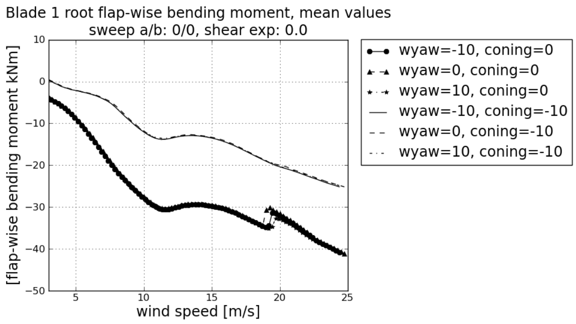

Figure 21 : Effect of coning angle on flapwise blade root bending moment.

Introducing the coning angle reduces power output by a few percentages due to the slightly offset created with the rotor plane perpendicular to the wind.

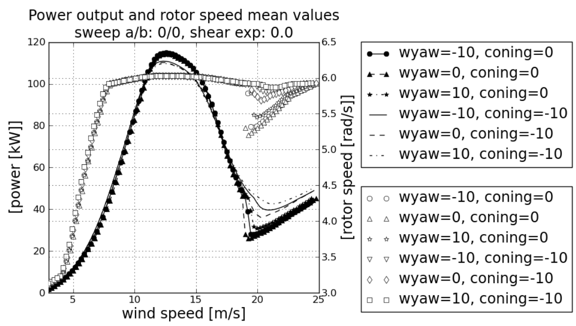

Figure 22 : Effect of coning on power production and rotor speed, no sweep or wind shear considered.

Sweep Backward Only

While backward sweep is traditionally known to reduce fatigue loading on the blade root in a turbulent scenario by reducing the angle of attack during gusts through the bend-twist coupling, Figure 23 demonstrates that with a deterministic wind, the reductions in loading are minimal.

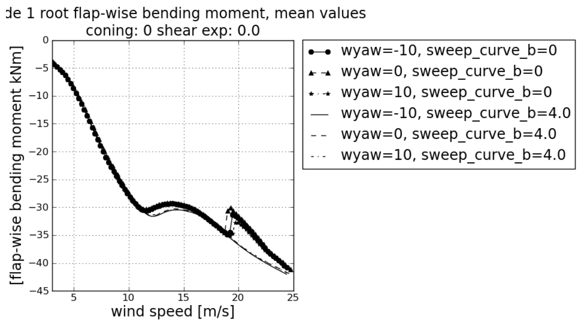

Figure 23 : Effect of sweep on flapwise balde root bending moment

Backward sweep seems to have a large effect on the power curve at higher wind speed, increasing rated power. The feathering behaviour of the swept blade will delay stall while under full load at rated conditions. As a result, the rated power is increased as stall is postponed to higher wind speeds.

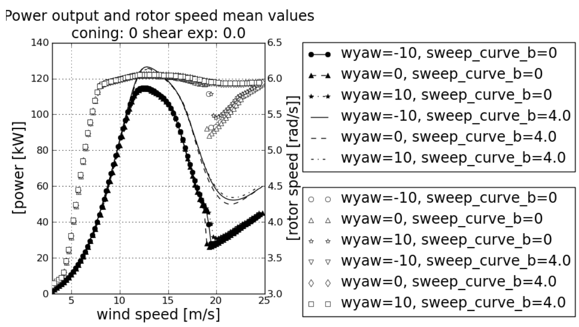

Figure 24 : Effect of backward sweep on power production and rotor speed, no coning or wind shear considered

Wind Shear Only

The effect of wind shear on the average blade root bending moment is negligible. This is expected, as a single blade passes through areas of slightly higher and lower wind velocities as it rotates around the hub, creating an average wind velocity that is similar to that with no wind shear.

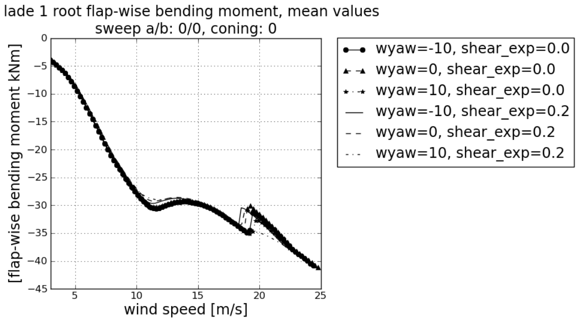

Figure 25 : Effect of wind shear on blade root flapwise bending moment.

Wind shear also seems to have little effect on the power curve at low wind speeds, as is evidenced by Figure 26. There is a difference at higher wind speeds, however, where the asymmetric inflow conditions become more important.

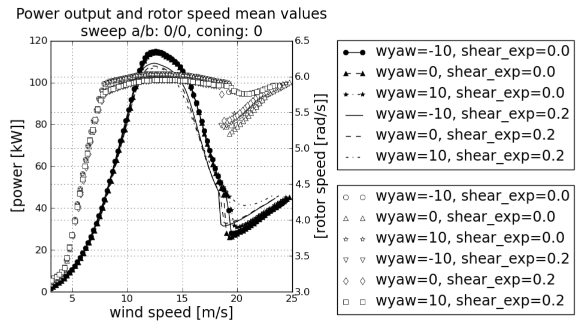

Figure 26 : Effect of wind shear on power output and rotor speed, no coning or sweep considered

Combination of Coning, Sweep and Wind Shear

As anticipated by the previous results, it is the coning angle that provides the largest reduction in flapwise blade root bending moment.

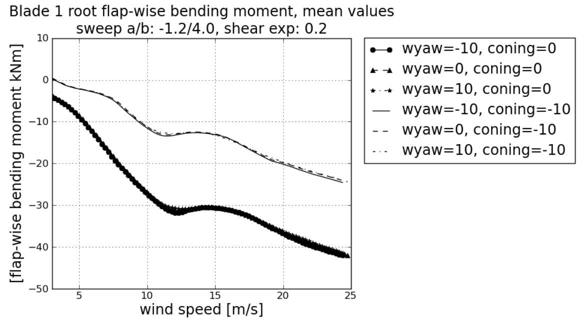

Figure 27 : Effect of coning angle, backward sweep and wind shear combined on the flawpwise blade root bending moment

The power output at low wind speeds is increased over the baseline, due to the stall delay of the sweep. The rated power is very similar to that of the baseline, as the decrease in power due to the coning seems to be offset by the increase in power due to the sweep. Overall, this indicates an increase in performance over the baseline.

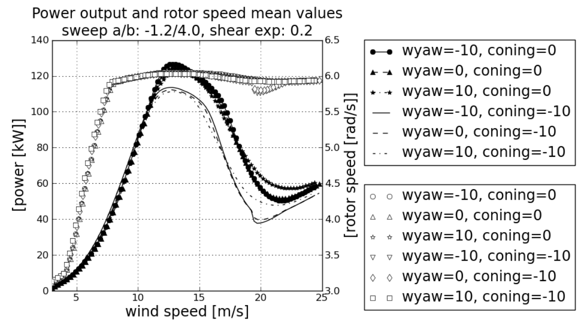

Figure 28 : Effect of coning, sweep and wind shear on power output and rotor speed

5 Conclusion

This investigation has shown that a three bladed, downwind, free yawing turbine encounters yaw stability issues around rated wind speed. When investigating the influence of coning angle, blade sweep and sheared inflow it can be concluded that:
* from the static cases it seems that the inner part of the blade, being in deep stall, contributes heavily to the destabilizing yaw moment
* there is no aerodynamic damping visible for the free yawing system

* wind shear always enhances yaw instability due to larger azimuthal variations in inflow conditions and hence more significant variations in yaw moments
* for some cases around rated wind speed blade sweep and its corresponding feathering behaviour damps out the yaw. It is argued that the significantly changing inflow conditions and its effect on the blade loading is tempered by the sweep's feathering effect.

*combination of sweep and coning showed the most promising results for this study. However more work has to be done in order to further understand the dynamics of this complicated free yawing turbine concept.

Further investigation should be performed to more fully study the effect of the pre- to post-stall transition on coning and wind shear, as well as further study in turbulent wind and methods including yaw friction and damping to attempt to regulate these instabilities.

6 References

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