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HIGH SPECIFICATION OFFSHORE BLADES

Phase 1 Report for ITI Energy

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Academic Perspective

This report outlines the current state of the art in offshore wind turbine blade aerodynamic design, along with the key technical limitations and possible technologies which may improve the aerodynamic design of blades and turbine rotors in the future. It is suggested that there are three principal areas in which aerodynamic improvements can be made to the design of offshore wind turbine systems: improved rotor system and blade tip design for operation at higher tip speeds, optimisation of wind farm design to alleviate aerodynamic interactions between individual turbines, and the aerodynamic feasibility of using structural mode coupling to achieve pitch and/or stall control of the loads on blades.

I. The Current State of Blade Aerodynamic Design

The wind turbines that are selected for use in offshore wind farms are relatively large, both in terms of swept area and power rating. They generally feature a three-bladed design, and are therefore consistent with the vast majority of onshore wind farms which are developed for the purpose of sourcing electricity into the national grid. At present there appears to be a limited market for wind turbines (and indeed blades) designed specifically for application to offshore farms. In general, the turbines proposed for use in offshore wind farms by the various leading manufacturers appear to be simply those toward the larger end of the spectrum of turbines available, both in terms of swept area and power rating.

Offshore wind turbines are predominantly rigid in design but permit power regulation through the use of pitch bearings, with individual blades often being actuated independently. Variable pitch is also the standard means of providing power control in gust conditions. Larger wind turbines generally operate in variable rotor speed mode and the permissible range can vary significantly between different turbine designs, with lower and upper limits being typically 7-10rpm and 15-20rpm respectively. The key attributes of an indicative set of wind turbines are given in Table 1.

The radii of offshore wind turbine blades may typically be within the range 40-50m; however, turbines with blade radii of up to approximately 60m (for example the LM Glasfiber[1] blades for the REpower 5M[2] turbine) are emerging onto the market and may be used in future offshore wind farms. The large variation in tangential velocity along the radius of the blade has resulted in wind turbine blades being tapered such that the tip chord length may be typically 30-50% of the chord at the root of the blade. The radial increase in tangential velocity generally results in more lift being developed toward the tip of the blades than at the root, resulting in large bending moments at the root of rigid blades such as those typically used on wind turbines. Taper is one mechanism by which these bending stresses may be reduced. The need to develop sufficient lift, and therefore torque, requires the angle of attack along the blade to be controlled to regulate aerodynamic stall. The rated tip speed ratios of most turbines (typically $\lambda=5$), coupled with the radial variation of tangential velocity, results in most turbines having a high level of nose-up twist toward the blade tip (up to 30-40º). Finally, the current market in larger wind turbines is populated, with the

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[1] www.lmglasfiber.com/Products/Performance/Curvature.aspx

[2] www.repower.de/index.php?id=237&L=1

exception of pitch control, by largely passive blade technology, with no widely used leading or trailing edge, or surface, aerodynamic actuators.

Manufacturer/Type	Rotational Speed [rpm]	Blade Radius [m]	Power Rating [MW]	Tip Mach Number Range
REpower 5M[2]	6.9-12.1	63	5.0	0.13-0.23
ENERCON E-82[3]	6-19.5	41	2.0	0.08-0.24
Gamesa G90[4]	9-19	45	2.0	0.12-0.26
Vestas V90[5]	8.6-18.4	45	3.0	0.12-0.25
Clipper LIBERTY C100[6]	9.6-15.5	50	2.5	0.15-0.24
Nordex N100[7]	9.6-14.9	50	2.5	0.15-0.23

Table 1: Indicative turbines

The optimisation of blade aerodynamic performance generally results in several different aerofoil sections being used along the radius of the blade. Aerofoil sections with a lower thickness-to-chord ratio are used at the blade tip in order to maximise the lift-to-drag ratio, whilst by necessity thicker sections are used towards the root of the blades in order to provide the necessary structural strength. A range of aerofoil sections including the NREL S-series, Delft University and NACA aerofoils are used for large wind turbine blades. The aerofoil sections used at the blade root are dictated by the dimensions of the load-bearing structure of the blades, and are typically very rounded, with a leading edge radius of 25-50% of chord. Toward the tip region the blades generally have a considerably sharper leading edge than at the blade root. Wind turbine blades are designed to be insensitive to roughness at the leading edge resulting from the accumulation of, for example, dirt and insects, particularly where stall is used for power regulation. Several options exist for improving wind turbine rotor and blade design, and these are to be discussed in the following section.

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[3] www.enercon.de/en/_home.htm

[4] www.gamesa.es/en/products/wind-turbines/catalogue

[5] www.vestas.com/en/wind-power-solutions/wind-turbines

[6] www.clipperwind.com/productline.html

[7] www.nordex-online.com/en/products-services/wind-turbines

II. Technical Limitations and Possible Improvements

A. Aerodynamic Performance

Higher Tip Speed

The operation of turbine rotors at higher tip speeds has the advantage that each blade will, if all other parameters are held constant, produce more lift. This has the implication that the same power output could be achieved with a reduced angle of attack, and therefore less lift and a lower torque. A lower operating torque would reduce the loads placed on the drive and gearbox mechanism and would offer two possible benefits: low initial capital costs resulting from reduced strength requirements and lighter-weight structures, and the reduced fatigue loads over the lifetime of the turbine. The increased lift which may be achieved using higher tip speeds means that, should the overall annual energy production for an individual turbine remain the same, a lower solidity rotor may be used. Lowering the solidity may be achieved through using fewer blades (two rather than three) or blades with a reduced chord length, both of which could reduce the initial capital cost of the turbine. Alternatively, for a given solidity, the annual energy production may be enhanced.

There are three primary problems associated with increasing the tip speed of wind turbine rotors: increased noise, proportionally more lift being developed in the tip region, and compressibility losses. Increases in the overall level of noise result largely from the increases in the component associated with blade thickness which becomes particularly prevalent at higher speeds. However, given that the tip Mach numbers at which wind turbines operate are well within the subsonic range (see Table 1), the significant increases in thickness noise which can pose severe problems for helicopters due to the proximity of the tip speed to Mach 1 will not be experienced by an increase in wind turbine tip speed; instead, more modest increases in noise will occur as the tip speed is increased. It should be considered, however, that the location of offshore wind turbine arrays will alleviate the constraints placed on the aerodynamic design of the blades as a result of noise.

If the tip speed of wind turbine blades is increased there will be a general tendency for a greater proportion of the lift developed by the blades to be developed near to the tips of the blades as a result of the sensitivity of lift to the square of the tangential velocity at each cross-section of the blade. This would be likely to result in increases in bending within the blade when rotating at higher rotational speeds, but could feasibly be alleviated by improved blade design, or by adopting and two-bladed teetering rotor in which bending loads are alleviated by the use of mechanical flap hinges.

Compressibility losses result in reductions in torque, and therefore power. However, it is likely that the modest increases in tip Mach number over those indicated as the ‘state of the art’ in Table 1 would not result in the severe compressibility effects that occur at the tips of helicopter rotors. The drag divergence which is associated with shock wave formation is likely not to occur unless the blade tips operate within the vicinity of Mach 1. If increases in tip speeds were to be accommodated, it would be necessary to optimise blade tip design accordingly, in order to alleviate any adverse effects and obtain the full benefits of higher speed performance.

Wake Interaction in Offshore Arrays

Offshore wind turbines are typically arranged in regular patterns (for example Horns Rev, Denmark) and it is known that some level of interaction exists between turbines, particularly in the form of wake ingestion by downwind turbines[8]. The extent to which the performance of one turbine is degraded by the ingestion of the wake of one or more upwind turbines is dependent on several factors such as rotor orientation and height above the ground, wind direction and the proximity of the turbines to each other. Whilst it is known that rotor wakes are composed of strong trailed vortices which form behind the blade tips, the detailed mechanisms by which the vertical wake from one rotor effects the performance of the other rotors is not well understood. Recent literature has suggested power losses of 10-20% from large wind farms, solely as a result of wake interactions[9]. With power losses of this size, it is likely that any gains in efficiency and reductions in cost achieved by advanced blade design could be eliminated by poor wind farm design.

Improvements in offshore array design and yaw control optimisation strategies to mitigate the effects of interaction could yield substantial increases in annual energy production. Due to the unsteady nature of the wake interactions, they are known to contribute to the fatigue loads experienced by the blades and the rotor hub.

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[8] Crespo, A., Hernández, J., and Frandsen, S., “Survey of Modelling Methods for Wind Turbine Wakes and Wind Farms,” Wind Energy, Vol. 2, No. 1, 1999, pp. 1-24.

[9] Barthelmie, R.J., Frandsen, S.T., Rathmann, O., Hansen, K., Politis, E.S., Prospathopoulos, J., Cabezón, D., Rados, K., van der Pijl, S.P., Schepers, J.G., Schelez, W., Phillips, J., and Neubert, A., “Flow and Wakes in Large Wind Farms in Complex Terrain and Offshore,” European Wind Energy Conference, Brussels, Belgium, 31 March-3 April, 2008.

Optimising wind farms so that these fatigue loads are reduced could reduce both the initial capital and annual operating expenses of large offshore wind turbines. Indeed, to achieve the largest cost savings within the manufacture of large wind turbines, strategies should be pursued which aim to reduce the cost not only of the blades themselves but also the mechanical drive-train, and perhaps the tower and nacelle and yaw system as these components account for a similar of greater percentage of the total cost of manufacturing large wind turbines[10]. The optimisation of offshore wind farms requires the accurate modelling of the wakes induced by a large number of turbines operating within an array and the effects on the annual power output of both individual turbines and the wind farm as a whole. Modern numerical wake modelling techniques are becoming available which lend optimism to the ability to improve offshore wind farm design[11, 12].

B. Rotor Design and Load Alleviation

Number of Blades and Hub Design

The adoption of higher tip speeds would raise the possibility of reducing the solidity of the turbine rotors. There are several ways in which the solidity of the rotor may be reduced including reducing the number of blades, reducing the length of the chord or increasing the radius of the blades. Reducing the chord or increasing the radius would have significant implications for the structural stiffness and rigidity of the blades. For significant increases in blade tip speed and the associated improvements in aerodynamic performance, it may be necessary to change from the conventional three-bladed design to a two-bladed design. The use of a two-bladed rotor would allow the adoption of a teetering hub design, with the advantage of lower bending moments at the roots of the blades and some level of alleviation of the large variations in polar moment of inertia about the tower of the turbine which occurs as the blades rotate.

Teetering rotors are mechanically more complicated than rigid rotors, however, they require less structural strength within the blades themselves and therefore the blades may be lighter and cheaper. Reducing the number of blades to two would decrease the number of parts and would therefore reduce maintenance costs and improve

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[10] Hau, E., Langenbrinck, J., and Paltz, W., “WEGA Large Turbines”, Springer-Verlag, Berlin, 1993.

[11] Brown, R.E., “Rotor Wake Modeling for Flight Dynamic Simulation of Helicopters,” *AIAA Journal*, Vol. 38, No. 1, 2000, pp. 57-63.

[12] Brown, R.E., and Line, A.J., “Efficient High-Resolution Wake Modeling using the Vorticity Transport Equation,” *AIAA Journal*, Vol. 43, No. 7, 2005, pp.1434-1443.

reliability and maintainability. It should be noted, however, that unless blades are significantly re-designed, increasing the tip speed would result in the tip region producing a greater proportion of the overall lift on each blade and hence increasing the bending moments at the blade root. If the total amount of power is to be held constant, reducing the number of blades would increase the strength of the tip vortices and increase the degree of interaction between the turbines in a typical offshore array.

Wind Compliant Strategies

The anisotropy which may be built in to glass or carbon fibre composite blades may be utilised to couple the torsion response of the blades to the bending and extension deformation. The twist in the blades which results from this coupling may be used in several ways to alter the angle of attack of the blades. In one case, the blades may be twisted under bending loads to reduce the angle of attack, thus reducing the power obtained from the blades. An alternative strategy is to reverse the sense of the coupling so that high bending loads will induce higher angles of attack along the blade and therefore promote stall, which would induce a rapid loss of torque, and therefore power output. The use of bend-twist coupling to vary the angle of attack of the blades is preferable since the blades would operate within the linear portion of the lift vs. angle of attack curve. Blade loads are considerably easier to predict within the linear aerodynamic range than in the post-stall regime.

In gust conditions, it would be desirable to rapidly reduce the torque generated a turbine, which may be best achieved by forcing large portions of the blades to stall. However, in normal operating conditions where the principal requirement is to maintain a steady power output from the turbine, using bend-twist coupling to vary the angle of attack within the linear aerodynamic range is preferable as the resulting change in lift from small changes in angle of attack can be more easily predicted. It may be feasible to use a combination of the strategies discussed above, whereby part of the blade is pushed into stall in gust conditions whilst the angle of attack of the remainder of the blade is controlled within the linear aerodynamic range. Twisting blades in order to induce greater amounts of stall has been used in the past on constant-speed rotors to allow turbines with larger diameters to be used and therefore for the energy capture to increase without increasing the maximum rating of the drive-train and other components of the system[13]. This experience suggests stall could be used as a reliable part of the power control strategy.

Some research has suggested that the control of angle of attack within the linear aerodynamic range can yield significantly greater reductions in the maximum loads than stall control, whilst also significantly reducing the fatigue damage to the turbine[13]. Other research has suggested, however, that it may not be feasible to induce the kind of torsional deformations in the blades as a result of bend-twist coupling to achieve the changes in blade angle of attack necessary to provide comprehensive power control in normal operating and gust conditions[14]. Overall, it is likely that the aeroelastic optimisation of blades to utilise passive power control is an area where it is likely that substantial improvements in blade design, and therefore reductions in the cost of energy, can be achieved.

III. Summary

Three areas have emerged which offer the potential to yield valuable IPR by improving the aerodynamic performance of, and reducing the cost of energy associated with, offshore wind turbines:

1. The design of turbine rotors, including the method by which the blades are attached to the hub and the way in which the pitch of the blades is controlled, along with the design of the blade tips, can be optimised to allow the rotor to operate at higher tip speeds. Technology Readiness Level: 2
2. The orientation and proximity of each of the turbines in an offshore wind farm can be optimised at the design stage, and the yaw of those turbines may be controlled during operation, in order to reduce the power losses associated with the interaction of the wakes induced by upwind turbines. Technology Readiness Level: 1
3. The aerodynamic feasibility of using bend-twist, or extension-twist, coupling to provide control of the blade angle of attack using the linear aerodynamic range and/or stall for power regulation and control of gust loads. Technology Readiness Level: 2

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[13] Lobitz, D.W., Veers, P.S., Eisler R., Laino, D.J., Migliore, P.G., and Bir, G., "The Use of Twist-Coupled Blades to Enhance the Performance of Horizontal Axis Wind Turbines," SANDIA National Laboratories Report SAND2001-1303, 2001.

[14] Lee, A.T., and Flay, R.G.J., "Compliant blades for wind turbines," *IPENZ Transactions*, Vol. 26, No. 1, 1999, pp. 7-12.