Flap-torsion divergence analysis in rotor blade design

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1 INTRODUCTION

The trend for offshore wind energy develops towards large size wind turbines. The increase in scale of rotor blades is faced with problems of increased dynamic weight loading and increased mass of the rotor. Wind turbine designers are putting much effort to design rotor blades that are still relatively light and cost-effective. As result large rotor blades are fairly slender and consequently also more flexible.

For rotor blades the increased flexibility introduces problems related with vibrations and aeroelastic instability. Among the aeroelastic instabilities are the static instability 'torsion divergence' and the dynamic instability 'flutter'. These instabilities are well known for the wings of fast flying airplanes, and for helicopter rotors, see Bramwell's Helicopter Dynamics [1]. For wind turbine rotor blades several prediction tools exist for the rotor speed at which 'torsion divergence' occurs. The phenomena of 'flutter' is generally analysed by performing an overspeed calculation, which a detailed aeroelastic design program such as Bladed or Phatas [4]. The application of Phatas for flutter has been validated by comparison with analytical solutions and was presented in [3]. The general perception is that the rotor speed at which divergence takes place --the divergence speed-- is far above the rotor speed at which flutter occurs --the flutter speed--. Here it should be noted that the 'divergence speed' and the 'flutter speed' are analysed with only the rotor rotation as basis of the inflow velocity of the blades, similar as for helicopter rotors. The conditions at which large wind turbines are subjected also include the external wind loading. Large rotor speeds together with a transverse component of the wind loading adds another contribution of flap bending deformation to the divergence of rotor blades. This means that when considering torsional deformation only over-estimates the divergence speed.

2 APPROACH

The stability of rotor blades is described in terms of flatwise bending and torsional deformation, rather than with torsional only. This stability includes angle-of-attack variations from flow perpendicular to the airfoils (from rotor rotation) and angle-of-attack variations from spanwise flow components (from in-plane wind). The aerodynamic load variations are related with the angle-of-attack variations by a 'slope' of $2\pi$. These equations are solved in a design tool that increases the rotor rotational speed until divergence is found. Because the spanwise flow component depends on the position of the rotor blade with respect to the wind the divergence speed is solved for a series of rotor azimuth positions. The smallest divergence speed for the several rotor azimuth positions is considered as design driving. The resulting computer program was named AEstab (AeroElastic stability). The program AEstab works in batch mode and can be included easily in an optimisation process to check the stability of a design. The tool is addressed to application in the structural design process (optimisation) of a rotor blade.

3 MAIN BODY

The stability equations for flap-torsion divergence form a set of 3 first order equations. Although this set of equations is more complicates than the case for torsional deformation only, they can easily be solved for the 2-point boundary value problem of a rotor blade. It should be noted that terms for bend-twist coupling of rotor blades are also included.
The stability equations are solved in a computer program named AEstab (Aero-Elastic stability). In this solution process the rotor speed is increased until a solution for the torsion divergence is found. This solution process is repeated for various values of the rotor azimuth. The smallest values over the azimuth range is returned as the ‘divergence speed’.

Analyses on the NREL 5MW rotor with the existing tool Blademode [2] give a torsion divergence speed of 70rpm, which is fairly safe. Analyses with the tool AEstab for a completely perpendicular wind on the rotor plane (so using a wind inclination that compensates the 5deg tilt angle) shows the same divergence speed. This means that for blades without bend-twist coupling without in-plane wind components the divergence speed from AEstab is similar as the conventional torsion-divergence as solved with Blademode.

Next the NREL 5MW rotor blades are analysed for the external conditions of some IEC load cases. In general the predicted values for the torsional divergence speed are little below the 70rpm. Only for DLC7.1 the divergence speed was seriously lower although still above rated rotor speed.

Finally a modified model of the NREL 5MW rotor was edited in which the ‘shear centre’ was shifted towards the leading edge in order to obtain inherent stability for blade torsion only. For this modified rotor the divergence speed was analysed with AEstab including some in-plane wind component. This analysis showed that a finite divergence speed occurs, which means that ‘inherent stability’ is harder to achieve than one may usually expect.

4 CONCLUSION

Already it was known that the rotor blades for wind turbines with a diameter over 100m the rotor speed at which flutter occurs is often less than 50% above the rated rotor speed. Also it was generally accepted that the rotor speed at which torsion divergence occurs is usually above the flutter speed, while some designs are have an inherent torsional stability.

After the development of a divergence prediction tool that includes the flatwise blade deformation and oblique wind components several analyses are performed on the blades of the NREL 5MW reference wind turbine. From the results of these analyses it was found that:

- Blades that show inherent torsional stability when analysed with rotor rotation only, may have a finite divergence speed in combination with transverse wind components.
- The smallest ‘divergence speed’ is found if the rotor blade is on the up-wind side of the rotor and advancing the wind. This is similar to an aircraft with forward swept wing.
- Small oblique wind inflow components (from the 8deg yaw misalignment in normal operation) have marginal effect. The most serious differences are for parked (idling) conditions with yaw misalignment. Large misalignment values during operation may
occur short after yaw failure, such as described by DLC2.2 of IEC 61400-1 ed.3 [7]. During other conditions high rotor speed values may occur in case of faulted pitch, such as in the IEC load cases DLC7.1 [7].

- If the divergence speed based on blade torsion only is already very high, one may expect that an analysis including cross-wind and flatwise bending in the instability will lead to a serious drop in the divergence speed.
- The worst conditions for flap-torsion divergence occur for ‘rare events’ such as both a pitch failure and a yaw failure. It is expected that the safety system of most wind turbine avoid situations of multiple failures.
- The resulting design tool allows for a fast analysis of the flap-torsion divergence. This analysis includes the effects of bent twist coupling of rotor blade laminates, such as investigated by Kooijman [5] and Capellaro [6].

A main conclusion is that for a safe analysis of the divergence speed all wind conditions with some side wind on the rotor have to be considered while the divergence speed itself should include torsional and flatwise deformation.

It should be noted that modern large size rotor blades are much more slender than the NREL 5MW reference. This means that during the structural design of large wind turbine rotor blades special attention should be paid to aeroelastic stability analyses on torsion divergence, but also on flutter, and torsion stall instability of a parked rotor.

5 LEARNING OBJECTIVES

The aim of this paper is to show that aeroelastic instabilities of large slender rotor blades should not be analysed with torsional deformation only but also including flatwise bending. This is associated with the effect of the transverse wind velocity components on the rotor.

Another objective of this paper is to support the wind turbine designers with design tools for aeroelastic stability checks that can be implemented easily in the design process.

The development of the tool AEstab aims to provide the wind community with design tools that can be applied in a simple and easy manner.

Future development in the field of aeroelastic stability of rotor blades is on a design tool for the analysis of flutter of rotor blades. Also this tool should allow a fast flutter check early in the design phase.
REFERENCES


