Investigating Stall Flutter using a DS model-An application for HAWTs

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Abstract. As wind turbine blades become larger there is a tendency for the blade torsional stiffness to reduce, producing the possibility of dynamic instability at moderate windspeeds. While linearised methods can assess the envelope of allowable blade properties for avoiding classical flutter with attached flow aerodynamics, wind turbine aerofoils can experience stalled flow. Therefore, it is necessary to explore the possible effects of stall-flutter on blade stability. This paper aims to address methods for judging the stability of blade designs during both attached flow and stalled flow behaviour.

This paper covers the following areas:
(i) Attached flow model
A Beddoes-Leishman indicial model is presented and the choice of coefficients is explained in the context of Theodorsen’s theory for flat-plate aerofoils and experimental results by Beddoes and Leishman. Special attention is given to the differing dynamic behaviour of the pitching moment due to flapping motion, pitching motion and dynamically varying inflow.
(ii) Classical flutter analysis
The time domain attached flow model is verified against a linear flutter analysis by comparing time domain results for a 3D model of a representative multi-megawatt turbine blade, varying the position of the centre of mass along the chord. The results show agreement to within 6% for a range of flutter onset speeds.
(iii) Dynamic stall model
On entering the stalled region, damping of torsional motion of an aerofoil section can become negative. A dynamic stall model which encompasses the effects of trailing edge separation and leading edge vortex detachment is presented and validated against published experimental data.
(iv) Stall flutter
The resulting time domain model is used in simulations validating the prediction of reduced flutter onset for stalled aerofoils. Representative stalled conditions for a multi-megawatt wind turbine blade are investigated to assess the possible reduction in flutter speed. A maximum reduction of 17% is observed for the particular blade investigated.

1. Introduction
This paper presents the development of a time-domain dynamic stall algorithm implemented in Bladed [1], a commercial wind turbine code, and its application to assessing coupled bending-
torsional stability for multimegawatt wind turbines.

Traditionally, aerofoil aerodynamic models developed for use in wind turbine rotor aerodynamic codes have assumed that the blade is limited to relatively low frequency flapwise and edgewise bending modes and that any spanwise torsional motion is due to coupling with flapwise bending; such motion is, in general, aerodynamically well damped by the corresponding flapwise motion. Torsional motion is dominated by blade pitch which is also well damped by the properties of pitch drives. Simple aerodynamic models which are designed for such models of wind turbines, for example the Øye model [2], only use quasi-steady values for the lift and pitching moment coefficients when the flow is attached. This assumption does not lead to realistic predictions of a torsionally flexible blade, which is stable up to a certain value of windspeed at which aerodynamic forces cause the frequencies of a flapwise mode and a torsional mode to coincide. The dynamic variation in pitching moment coefficient due to changes in angle of attack has a stabilising effect and it is necessary to include these terms to make an accurate prediction of flutter.

Many flutter analysis methods have been based on assessment of traditional aircraft wing designs, which are not designed to work within stalled regimes in normal situations. Moreover, for those wings the steady trimmed solution is normally such that the assumptions of linear system is fulfilled. A linear description of the aerodynamic response based on the pre-stall lift slope would then be sufficient. However, the wind turbine design process includes load cases in which the blade stalls, either in everyday operation for a stall regulated turbine; or in extreme cases for a pitch regulated turbine.

Dynamic stall is a complex phenomenon; a linearised model might include features such as the lift curve slope of the aerofoil reducing on the approach to stall. This reduces the aerodynamic damping associated with flapwise motion, while also reducing the aerodynamic stiffness associated with a change in angle of attack. However, it is expected that including these features in a frequency domain model will be insufficient for assessing flutter because the amplitude of oscillations occurring when a wind turbine aerofoil enters stall is likely to be large enough to involve highly non-linear hysteresis cycles. Whereas in the linear regime an unstable solution is likely to lead to very high amplitude oscillations, the limits of the amplitude in the stalled region may prove to be important for design (for example, see [3] for details of aerofoil flutter speeds reducing in lightly stalled flow before increasing at higher angles of attack).

2. Attached flow model

The mechanism of flutter in aerofoil sections was first mathematically described by Theodore Theodorsen [4] working at NACA in 1935. While Theodorsen’s report considered an aerofoil section with three degrees of freedom: flapwise deflection, torsion and aileron motion, this paper will be restricted to investigation of coupling between flapwise and torsional deflection. Although torsion and flapwise motion are of primary interest, both the frequency and time domain models include the effects of edgewise motion on the relative windspeed and the structural models are also able to include axial motion.

Theodorsen approaches the problem in the frequency domain and presents the expression for the force acing perpendicular to the aerofoil section, \( P \), as well as the pitching moment, \( M \), on the section about its axis of rotation which is at a distance \( a \) from the centre of the aerofoil, positive towards the trailing edge. The result is in terms of the flexural displacement \( h \), the torsion, \( \alpha \), the semi-chord, \( b \), the air density, \( \rho \), the incident velocity, \( v \), and the Theodorsen function, \( C \) which is a function of the reduced frequency, \( k = \frac{V}{b} \):

\[
P = -\rho b^2 \left( v \pi \dot{\alpha} + \pi \ddot{h} - \pi b a \dot{\alpha} \right) - 2 \pi v b C \left\{ v \alpha + \dot{h} + b \left( \frac{1}{2} - a \right) \dot{\alpha} \right\}
\]  

(1)
\[ M = -\rho b^2 \left[ \pi \left( \frac{1}{2} - a \right) v b \dot{\alpha} + \pi b^2 \left( \frac{1}{8} + a^2 \right) \ddot{\alpha} - a \pi b \dot{h} \right] + 2 \rho v b^2 \pi \left( \frac{1}{2} + a \right) C \left\{ v \alpha + \dot{h} + b \left( \frac{1}{2} - a \right) \dot{\alpha} \right\} \] (2)

The frequency domain solution is generally translated into the time-domain using an indicial formulation such as the one used by Beddoes and Leishman [5].

2.1. Indicial Approximations for Time Domain Simulation

The frequency domain solution developed by Theodorsen can be translated into the time-domain response for a step change in angle of attack by means of a lag or deficiency function. There are various deficiency functions corresponding to step changes in angle of attack, pitch angle of the aerofoil, incoming windspeed parallel and perpendicular to the chord line. These are discussed in detail in [6]. Of interest for flutter analysis are the step responses due to flapping motion and torsion of the blade.

(i) **Flapwise deflection: the Wagner function**

Wagner’s problem consists of an aerofoil experiencing a step change in angle of attack which is uniform along the chord line. This inflow condition is consistent with that which would be caused by a discrete change in flapwise velocity. The analytical function commonly used to approximate Wagner’s solution is termed Jones’ approximation written in terms of \( s \), the distance travelled by the aerofoil section (or alternatively the incoming wind) in semi-chords.

\[ \phi_W(s) = 1 - A_1 e^{-b_1 s} - A_2 e^{-b_2 s}; A_1 = 0.165, A_2 = 0.335, b_1 = 0.0455, b_2 = 0.3 \] (3)

(ii) **Torsional motion**

The indicial response due to torsional deflection is complex because it causes the angle of attack to vary over the aerofoil. The derivation of an indicial model is presented in the NACA report by Mazelsky [7] and the results are found in the full Beddoes-Leishman model.

(iii) **Beddoes-Leishman Model**

The Beddoes-Leishman model adds complexity to the problem by considering effects due to compressibility. This was necessary because it was designed for modelling helicopters; blade sections for helicopters could be travelling at significant fractions of the speed of sound in air.

When transformed back into the frequency domain, the Beddoes-Leishman model may have a different response from the original Theodorsen equations. The frequency domain response is given in terms of the reduced frequency, \( k = 2V/c \), where \( V \) is the incoming velocity and \( c \) is the chord of the aerofoil section. For the normal force, the Theodorsen model predicts \( \pi k \) for flapwise oscillations and \( i \pi k - \frac{1}{2} \pi k^2 \) for torsional oscillations. There are a number of different parameters for the Beddoes-Leishman model informed by different experimental results; this indicates that there may be important variations for real aerofoil sections.

3. Classical flutter analysis

A frequency domain tool has been developed which uses the structural mode shapes produced by a commercial wind turbine simulation code, Bladed, and linearised aerodynamics based on the Theodorsen model. The time domain simulations carried out using Bladed use a time-domain, indicial formulation which include the effects of compressibility.

The theory used by the code and its implementation are described in detail in the following the references of this report [11]. The method used applies the frequency domain model of the lift force derived by Theodorsen but including a correction to account for the drag force. The
Figure 1. Planform of the NREL 5MW blade as used in Bladed

aerodynamic forces at different sections along the blade are transformed into modal coordinates and the virtual work of the whole blade is calculated. In order to solve the resulting equations for the eigensolutions, the matrix of aerodynamic forces is written in the Laplace domain and Roger’s approximation is used in order to perform a least squares fit and allowing them to be written in the state space formulation. Finally, with the whole set of equations written in the state space domain, Matlab routines were used to find the eigenvalues.

The code has been used to predict the flutter wind speed for wind turbine blades in the frequency domain and compared with time-domain results from simulations using Bladed. The frequency domain tool has so far been developed to consider the vibrations of a three-dimensional, stationary (i.e. non-rotating) blade with a uniform incoming wind speed.

Wind turbine blades have a varying aerodynamic twist which can typically vary by 15° over the blade length; this is sufficient to move beyond the linear region of attached flow aerodynamics. For comparison with the frequency domain model, which assumes attached flow aerodynamics, the blade model used in time domain simulations with Bladed has been altered to maintain linear aerodynamics. This is done by altering the aerodynamic twist to obtain an angle of attack close to zero, while keeping the structural twist the same as in the original model to preserve the structural modes.

The blade that has been analysed is the NREL 5MW blade [8], being a publicly available blade representative of multi-megawatt offshore wind turbines.

The original blade design shown in Figure 1 has been altered in order to allow investigations of flutter at lower windspeeds. It shall be assumed that as offshore wind turbine technology progresses, blades will become torsionally more flexible and tip-speeds could increase leading to flutter speeds closer to the rated rotational speed of a turbine.

According to [4], the flutter boundary for a system involving torsion and flapping motion is defined by the parameter defined as the square of the ratio of the flap and torsion frequencies, divided by the square of the radius of gyration of the section. Therefore, in order to synthesise a blade with a lower flutter boundary, with a blade as similar as possible to the NREL 5MW blade, a choice has been made to move the position of the mass axis towards the trailing edge. Mass axis offset relative to the original was increased in steps of 20% of the original distance to the trailing edge. The inboard 10 metres had the mass axis interpolated between the original and new values so that the mass axis at the root was always at 50% of the chord. The mass axis distribution for the case of an 80% shift towards the trailing edge is described in Table 1.

Five blade variants were analysed with both the frequency domain tool and Bladed. The frequency domain tool provides the real and imaginary part of the eigenmodes of the aeroelastic
Table 1. Mass axis distribution in the modified NREL blade (80% shift towards trailing edge).

| Distance along pitch axis m | 0.20  | 2.20  | 4.20  | 6.20  | 8.20  | 10.20 | 12.20 | 14.20 |
|-----------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Mass axis position %        | 50.00 | 49.60 | 49.80 | 46.49 | 46.49 | 43.18 | 44.18 | 43.20 |

| Distance along pitch axis m | 16.20 | 20.20 | 24.20 | 28.20 | 32.20 | 36.20 | 40.20 | 44.20 |
|-----------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Mass axis position %        | 42.98 | 42.17 | 42.15 | 41.44 | 41.14 | 41.58 | 42.98 | 46.35 |

| Distance along pitch axis m | 48.20 | 52.20 | 55.20 | 57.20 | 58.20 | 59.20 | 60.20 | 61.20 |
|-----------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Mass axis position %        | 45.94 | 46.30 | 47.69 | 44.80 | 42.51 | 42.70 | 42.72 | 49.02 |

The system. The imaginary part corresponds to the frequency of the mode; the real part does not correspond exactly to the damping but at the zero-crossing point the oscillation magnitude can be assumed to be stationary and the damping exactly zero; zero-crossings therefore correspond to the borders of unstable oscillations. The results of frequency domain analysis are presented graphically for the original NREL 5MW blade and also for the blade with the mass axis described in Table 1 in Figures 2 to 5. Clearly, it can be seen that the original NREL 5MW blade is stable with respect to flutter in design situations; the rated tip-speed of the blade is only 80 m/s, less than half of the predicted flutter speed. Incoming windspeeds even in a Class I site according to the IEC 61400-1 standard [9] would only reach 70 m/s during a gust and this is still well below the flutter speed of the blade with the mass axis moved 80% towards the trailing edge.

Figure 2. Frequencies of the first 10 modes of the original NREL 5MW blade.

Figure 3. Real part of the eigenvalue for the first 10 modes of the original NREL 5MW blade.

In order to find the flutter onset speed from the time domain simulations carried out with Bladed, 200 second simulations were run with spatially uniform wind rising from 0.1 m/s to 200 m/s, incident on a wind turbine blade fixed at its root, oriented perpendicular to the flow in order to achieve an angle of attack of 0°, with no gravitational loads. The results are shown in Figures 6 and 7 for the original blade and the blade with mass axis moved 80% towards the trailing edge respectively. Both plots show the blade torsion starting to oscillate, shortly followed by motion in the flapwise (y) direction with some vibration also present in the edgewise (x) direction.

The flutter windspeeds obtained using both methods are presented in Table 2. The agreement
is within 6% for all of the cases which is lower than the safety factor of 15% which is commonly used in the aircraft industry [10]. The simulations with Bladed included only 10-14 modes to limit simulation time; it is possible better agreement could be found by increasing the number of modes.

4. Dynamic stall model
Bladed models airfoil dynamic stall with the Beddoes-Leishman dynamic stall model [5]. The behaviour of the normal force and chordwise force are calculated with a delayed trailing edge separation position, and a leading-edge vortex lift component which grows and decays. The normal force and chordwise force is used to derive the dynamic lift coefficient. Up to and including version 4.2 of Bladed, no leading-edge vortex separation was included in the model and drag and pitching moment coefficients were taken as the quasi-steady values.

In the latest version of the code (version 4.3), the critical normal force coefficient has been
Figure 7. Bladed simulation of the modified (80% shift of mass axis) NREL 5MW blade

Table 2. Flutter onset wind speeds predicted by a frequency domain tool and Bladed.

| Percentage offset of mass axis | Frequency domain flutter onset speed (m/s) | Bladed flutter onset speed (m/s) | Difference (%) |
|-------------------------------|------------------------------------------|---------------------------------|----------------|
| 0                             | 162.58                                   | 163                             | −0.3           |
| 20                            | 116.86                                   | 121                             | 3.5            |
| 40                            | 104.14                                   | 107                             | 2.8            |
| 60                            | 93.34                                    | 95.5                            | −2.3           |
| 80                            | 80.73                                    | 85                              | 5.3            |

derived from the aerofoil data in order to predict the onset of convection and subsequent separation of the leading-edge vortex from the trailing edge; repeated vortex shedding is possible. In addition, the pitching moment and drag coefficients are now based on the dynamic separation position and also include contributions from the vortex lift. The implementation of the pitching moment coefficient is similar to that of Beddoes and Leishman but includes an interpolation of properties between linear and quasi-steady based on separation position rather than a function fit to the quasi-steady pitching moment coefficient as described in [5].

Simulations have been run with Bladed to attempt to replicate the experimental results by Beddoes and Leishman [5] using the NACA0012 aerofoil with an incoming windspeed of 126 m/s and a pitch angle, $\beta$, described by the following equation with $\omega$ corresponding to a frequency of 29.7 Hz (which corresponds to the reduced frequency used by Beddoes and Leishman in the original experiments):

$$\beta = 79.7^\circ - 8.1^\circ ((1 - 0.08) \sin \omega t + 0.08 \sin (3\omega t - \pi))$$

These experiments have been used for validation because of the detail of the results for varying degrees of stall. The behaviour of different aerofoil sections has been well covered in other work such as [12]. The aim of this paper is to study the effect of including a time-domain stall model on the flutter boundary. The results of the Bladed simulations for lift, drag and pitching moment are presented in Figures 8 to 10. There are differences between the results and those presented...
in [5]; it is assumed that these are due to differences in the assumed aerofoil quasi static data along with the amount of 3rd harmonic signal present in the experimental apparatus reported by Beddoes and Leishman [5].

5. Stall flutter
While most modern wind turbines are now pitch-regulated with aerofoils designed to operate in the linear aerodynamic regime, the high levels of turbulence which must be considered in design situations, along with high wind speed non-operational cases with the turbine unable to control the angle pitch of the blades, mean that part or all of the blade may enter stall, either transiently or for an extended period. Therefore, when considering potential instabilities, assuming linear aerodynamics is not sufficient. Work at NACA in the 1940s looked at the stall-flutter effect in the blades of axial flow compressors and turbines [3]. This concluded that the decrease in the lift-curve slope in the stall region results in an aerodynamic lag reducing the damping of torsional motion of an aerofoil section. This lag is given by the expression:

$$\phi = K \left[ \left( \frac{dC_L}{d\alpha} \right)_{\alpha=\alpha_0} - \frac{dC_L}{d\alpha} \right] = \frac{1}{4} \left[ 2\pi - \frac{dC_L}{d\alpha} \right]$$  \hspace{1cm} (5)
Figure 10. Pitching moment coefficient for the NACA0012 aerofoil (left Bladed, right Beddoes-Leishman).

Table 3. Parameters for the wing used to analyse stall flutter.

| Span, Chord | Shear centre | Mass centre | Mass per unit length | Polar inertia per unit length, kgm | Bending stiffness Nm² | Torsional stiffness Nm² |
|------------|--------------|-------------|---------------------|-----------------------------------|-----------------------|------------------------|
| m m       | % from leading edge | % from leading edge | kg/m |  |  |  |  |
| 1.016 0.1715 | 35.50 | 46.90 | 4.559 | 0.006630 | 2540.2 | 26.61 |

From the report by Mendelson [3], a model with the same mass and inertia properties was built. The stiffness properties were not supplied in the paper and values were chosen in order to minimise the error between the natural frequencies predicted by the model and those stated in the paper. The resulting parameters used are given in Table 3. The first two natural frequencies of the Bladed model were found to be 11.07 Hz and 17.79 Hz, compared to 12.78 Hz for the bending mode and 13.88 Hz for the torsional mode of the blade section reported in [3]. Additionally, the aerodynamic coefficients used for the blade section are uncertain.

Simulations were run with Bladed to assess the flutter speed of this section with a NACA0012 profile. The simulations in Bladed do not include the lag described by Mendelson directly but this effect is expected to result by the time-domain treatment of the hysteresis of the trailing edge separation, as described in Section 4. The results are presented in Figure 11. While the Bladed results show a higher flutter windspeed than the experiments, this is assumed to be due to the larger separation of structural frequencies. No results are presented beyond 20° due to increasing uncertainty over the aerofoil properties. Despite the differences, the same qualitative behaviour can be seen, with the flutter speed reducing to a minimum more than 50% below the attached flow result.

The results in Figure 11 are for a small wing section, measuring only 10 cm across. It is important to see how the results might change for a typical wind turbine blade. For this analysis, the same blade used in Section 3, with mass axis moved 80% towards the trailing edge, was used, this time with the original aerodynamic twist distribution. The flutter onset wind was assessed by ramping the incoming windspeed for a range of pitch angles between 0° and 30°.
Figure 11. Stall flutter results for a 17cm wing section.

Table 4. Stall flutter results for the NREL blade with 80% mass axis shift.

| Angle of attack, ° | -3.7 | 2.2 | 8.5 | 14.8 | 19.8 | 22.2 | 24.2 | 26.8 |
|-------------------|------|-----|-----|------|------|------|------|------|
| Flutter onset speed, m/s | 80   | 81  | 87.5| 79   | 71.5 | 67   | 71   | 93   |
| % difference from attached flow result | -1   | +1  | +9  | -1   | -11  | -16  | -11  | +16  |

The results are presented in Table 4 and while the reduction in flutter speed is lower than for the small wing section, it is still significant; and in this case sufficient to take the flutter onset to within a possible design load case. As for the small wing section, it is seen that moderate stall angles reduce the flutter onset wind speed, while on entering deeper stall the flutter speed rises again. This is explained by the direction of pitching moment hysteresis loops in Leishman’s book [6].

6. Conclusions
Both a frequency domain and a time domain tools for assessing flutter have been developed. Although the theories behind them differ in their exact formulation and assumptions, the two methods yield similar results for the flutter analysis of a generic multi-megawatt wind turbine blade when the aerodynamics are linear.

The time-domain model has been compared with experimental result of blade stalling with similar behaviour to within model uncertainties. This combined model of attached and stalling behaviour has been used to investigate the stall flutter behaviour of blade sections. In comparisons with published experimental data, qualitatively similar results have been found. In simulations with a modified representative wind turbine blade, aerodynamic stall was shown to decrease the flutter onset speed by more than 15% for some angles of attack. This effect should be considered when assessing the flutter margin using attached flow methods.

Further work is required to build representative models of future, flexible blade designs which may have a flutter boundary closer to the design envelope. As well as assessing the fixed blade, a more thorough investigation of operational cases is necessary; offshore designs are expected
to achieve tip speeds which greatly exceed the highest storm wind speeds and turbulent gusts could drive all or part of the blade into stall. By achieving greater confidence in the models of unstable behaviour, the understanding gained can enable manufacturers to develop innovative blade designs safely.

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