MODELING OF AERODYNAMIC FLUTTER ON A NACA 4412 AIRFOIL WIND BLADE

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ABSTRACT
Study of aeroelastic phenomena on wind turbines (WT) has become a very important issue when it comes to safety and economical considerations as WT tend towards gigantism and flexibility. At the Wind Energy Research Laboratory (WERL), several studies and papers have been produced, all focusing on computational fluid dynamics (CFD) approaches to model and simulate different aeroleastic phenomena. Despite very interesting obtained results; CFD is very costly and difficult to be directly used for control purposes due to consequent computational time. This paper, hence, describes a complementary lumped system approach to CFD to model flutter phenomenon. This model is based on a described Matlab-Simulink model that integrates turbulence characteristics as well as characteristics aerodynamic physics. From this model, we elaborate on flutter Eigen modes and Eigen values in an aim to apply control strategies and relates ANSYS based CFD modeling to the lumped system.

Keywords: flutter, Computational fluid dynamics, lumped system, Matlab-Simulink, ANSYS

1. INTRODUCTION
As wind turbines become increasingly larger and more flexible, concerns are increasing about their ability to sustain both static and dynamic charges. When it comes to static loads, the calculation is fairly easy and IEC norms adequately set the standards for the manufacturing industry. However, when it comes to dynamic loads, the modeling is far more complex as we need to include the rotational movement, the bending, the wind speed, turbulence and other complex fluid-structure interactions that can generate divergence, dynamic stall or flutter. The main aim of modeling these phenomena is to be able to apply mitigation actions to avoid them as they are extremely damageable for wind turbines. In this article, we will model one of the most destructive aeroelastic phenomena - flutter via Matlab/Simulink and compare our results with ANSYS – CFX based CFD generated results. The aim of the Simulink based modeling is to set up an integrated model that can more easily be incorporated in a control strategy to limit operation in critical vibration conditions. Aerodynamic flutter is a dynamic aeroelastic phenomenon characterised by blade response with respect to changes of the fluid flow such as external atmospheric disturbances and gusts. Flutter is a very dangerous phenomenon resulting from an interaction between elastic, inertial and aerodynamic forces. This takes place when the structural damping is not sufficient to damp the vibration movements introduced by the aerodynamic effects. Flutter can take place for any object in an intense fluid flow and condition of positive retroaction. In other words, the vibratory movement of the object increases an aerodynamic solicitation, which, in turn, amplifies the structural vibration. When the energy developed during the excitation period is larger than the normal system dumping, the vibration level will increase leading to flutter. The latter is characterized by the superposition of two structural modes – the pitch and plunge movement. When wind speed increases, the frequency of these vibration modes coalesce to create the resonance of flutter.

2. NOMENCLATURE

α Angle of attack θ Plunge angle
w_g Centre of gravity   M Aerodynamic moment
ψ_{lo} Longitudinal Speed Turbulence Spectrum
ψ_{la} Lateral Speed Turbulence Spectrum
ψ_v Vertical Speed Turbulence Spectrum

3. FLUTTER PHENOMENON

As previously mentioned, flutter is caused by the superposition of two structural modes – pitch and plunge. The pitch mode is described by a rotational movement about the elastic centre of the airfoil whereas the plunge mode is a vertical up and down motion at the blade tip. Theodorsen [1-3] developed a method to analyze aeroelastic stability. The technique is described by equations (1) and (2). α is the angle of attack (AoA), α_0 is the static AoA, C(k) is the Theodorsen complex valued function, h the plunge height, L is the lift vector positioned at 0.25 of the chord length, M is the pitching moment about the elastic axis, U is the free velocity, ω is the angular velocity and a, b, d1 and d2 are geometrical quantities as shown in figure 1.

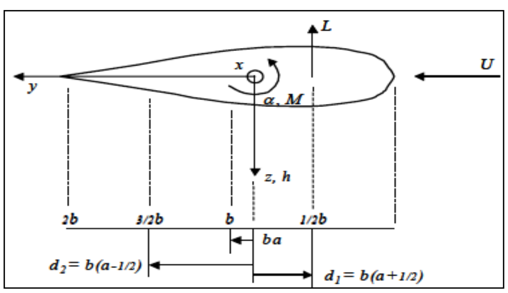

Figure 1: Model defining parameters

$$L = 2\pi\rho U^2 b\left\{\frac{i\omega C(k) h_0}{U} + C(k)\alpha_0 + [1 + C(k)(1-2a)]\frac{i\omega b\alpha_0}{2U} - \frac{\omega^2 b h_0}{2U^2} + \frac{\omega^2 b^2 a\alpha_0}{2U^2}\right\} \quad (1)$$

$$M = 2\pi\rho U^2 b\left\{d_1\left[\frac{i\omega C(k) h_0}{U} + C(k)\alpha_0 + [1 + C(k)(1-2a)]\frac{i\omega b\alpha_0}{2U}\right] + d_2\frac{i\omega b\alpha_0}{2U} - \frac{\omega^2 b^2 a}{2U^2}h_0 + \left(\frac{1}{8} + a^2\right)\frac{\omega^2 b^3 \alpha_0}{2U^2}\right\} \quad (2)$$

The Theodorsen equation can be rewritten in a form that can be entered and analyzed in Matlab Simulink as follows:

$$L = 2\pi\rho U^2 b\left\{\frac{C(k)}{U}\dot{h} + C(k)\alpha + [1 + C(k)(1-2a)]]\frac{b}{2U}\dot{\alpha} + \frac{b}{2U^2}\ddot{h} - \frac{b^2 a}{2U^2}\ddot{\alpha}\right\} \quad (3)$$

$$M = 2\pi\rho U^2 b\left\{d_1\left[\frac{C(k)\,\dot{h}}{U} + C(k)\alpha + \left[1 + C(k)(1-2a)\frac{b}{2U}\dot{\alpha}\right]\right] + d_2\frac{b}{2U}\dot{\alpha} + \frac{ab^2}{2U^2}\ddot{h} - \left(\frac{1}{8} + a^2\right)\frac{b^3\ddot{\alpha}}{2U^2}\right\} \quad (4)$$

4. FLUTTER MOUVEMENT

Flutter can be triggered by a rotation of the profile (t=0 seconds in figure 2). The increase in the force adds to the lift such that the profile tend to undertake a vertical upward movement. Simultaneously, the torsion rigidity of the structure returns the profile to the zero pitch position (t=T/4 in figure 2). The flexion rigidity of the structure tries to return the profile to its neutral position but the profile now adopts a negative angle of attack (t=T/2 in figure 2). Once again, the increase in the aerodynamic force imposes a vertical downwards movement and the torsion rigidity returns the profile to zero angle of attack position. The cycle ends when the profile returns to a neutral position with a positive angle of attack. With time, the vertical movement tends to get damped whereas the rotational movement diverges. If the movement is left to repeat, the rotation induced forces will lead to failure of the structure.

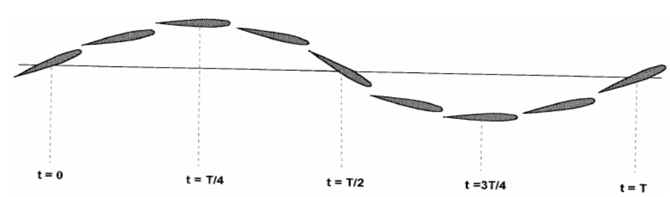

Figure 2: Illustration of the flutter movement

In order to understand this complex phenomenon, we describe flutter as follows: Aerodynamic forces excite the mass – spring system illustrated in figure 3. The plunge spring represents the flexion rigidity of the structure whereas the rotation spring represents the rotation rigidity.

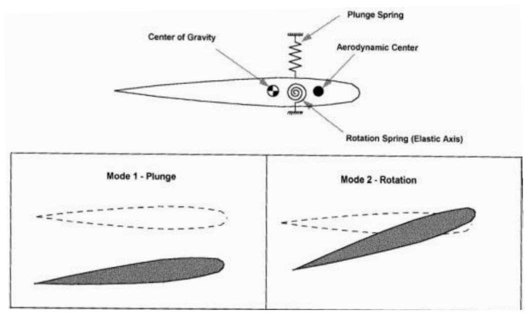

Figure 3: Illustration of both pitch and plunge

5. FLUTTER EQUATIONS

Initially, it is important to find a relationship between the generalized coordinates and the angle of attack of the model. This will be essential in the computation of the aerodynamic forces. From [4], the relationship between the angle of attack and the coordinates can be written as:

$$\alpha(x,y,t) = \theta_T + \theta(t) + \frac{\dot{h}(t)}{U_0} + \frac{l(x)\dot{\theta}(t)}{U_0} - \frac{w_g(x,y,t)}{U_0} \quad (5)$$

From these energy equations, the Lagrangian equations are constructed for the mechanical system. The first one corresponds to the vertical displacement z and the other is subject to the angle of attack α.

Hence:

$$J_0\ddot{\alpha} + mdcos(\alpha)\ddot{z} + c(\alpha - \alpha_0) = M_0 \quad (6)$$

and

$$m\ddot{z} + mdcos(\alpha)\ddot{\alpha} - msin(\alpha)\dot{\alpha}^2 + kz \quad (7)$$

In order to enable numerical solving of these equations, we need to express F_z and $M_o$as polynomials of α. Moreover; $F_z(\alpha) = \frac{1}{2}\rho S V^2 C_z(\alpha)$ and $M_o(\alpha) = \frac{1}{2}\rho L S V^2 C_{m0}(\alpha)$ for S being the surface of the blade, C_z, the lift coefficient, C_{m0} being the pitch coefficient, F_z being the lift, M_o, the pitch moment. C_z and C_m values are extracted from NACA 4412. Degree 3 interpolations for C_z and C_m with respect to the AoA are given below:

$$C_z = -0.0000983\,\alpha^3 - 0.0003562\alpha^2 + 0.1312\alpha + 0.4162 \quad (8)$$

$$C_{m0} = -0.00006375\alpha^3 + 0.00149\alpha^2 - 0.001185\,\alpha - 0.9312 \quad (9)$$

6. MATHLAB-SIMULINK AND ANSYS-CFX TOOLS

Reference [5] describes the Matlab included tool Simulink as an environment for multi-domain simulation and Model-Based Design for dynamic and embedded systems. It provides an interactive graphical environment and a customizable set of block libraries that let you design, simulate, implement, and test a variety of time-varying systems. For the flutter modeling project the aerospace blockset of Simulink has been used. The Aerospace Toolbox product provides tools like reference standards, environment models, and aerospace analysis pre-programmed tools as well as aerodynamic coefficient importing options. Among others, the wind library has been used to calculate wind shears and Dryden and Von Karman turbulence. The Von Karman Wind Turbulence model uses the Von Karman spectral representation to add turbulence to the aerospace model through pre-established filters. Turbulence is represented in this blockset as a stochastic process defined by velocity spectra. For a blade in an airspeed V, through a frozen turbulence field, with a spatial frequency of Ω radians per meter, the circular frequency ω is calculated by multiplying V by Ω. For the longitudinal speed, the turbulence spectrum is defined as follows:

$$\psi_{lo} = \frac{\sigma^2{}_{\omega}}{VL_{\omega}} . \frac{0.8(\frac{\pi L_{\omega}}{4b})^{0.3}}{1 + \left(\frac{4b\omega}{\pi V}\right)^2} \quad (10)$$

where $\mathbf{L}_{\omega}$represents the turbulence scale length and $\boldsymbol{\sigma}$ is the turbulence intensity. The corresponding transfer function used in Simulink is expressed as:

$$\psi_{lo} = \frac{\sigma_u \sqrt{\frac{2}{\pi}\frac{L_v}{V}}\left(1 + 0.25\frac{L_v}{V}s\right)}{1 + 1.357\frac{L_v}{V}s + 0.1987\left(\frac{L_v}{V}s\right)^2 s^2} \quad (11)$$

For the lateral speed, the turbulence spectrum is defined as:

$$\psi_{la} = \frac{\mp\left(\frac{\omega}{V}\right)^2}{1 + \left(\frac{3b\omega}{\pi V}\right)^2} . \varphi_v(\omega) \quad (12)$$

and the corresponding transfer function can be expressed as :

$$\boldsymbol{\psi}_{\mathbf{la}} = \frac{\mp\left(\frac{s}{V}\right)^{1}}{1+\left(\frac{3b}{\pi V}s\right)^{1}}.H_v(s) \tag{13}$$

Finally, the vertical turbulence spectrum is expressed as follows:

$$\boldsymbol{\psi}_{\mathbf{v}} = \frac{\mp\left(\frac{\omega}{V}\right)^{2}}{1+\left(\frac{4b\omega}{\pi V}\right)^{2}}.\varphi_{\omega}(\omega) \tag{14}$$

and the corresponding transfer function is expressed as follows:

$$\boldsymbol{\psi}_{\mathbf{v}} = \frac{\mp\left(\frac{s}{V}\right)^{1}}{1+\left(\frac{4b}{\pi V}s\right)^{1}}.H_{\omega}(s) \tag{15}$$

The Aerodynamic Forces and Moments block computes the aerodynamic forces and moments about the center of gravity. The net rotation from body to wind axes is expressed as:

$$\mathrm{C}_{\omega\leftarrow\mathrm{b}} = \begin{bmatrix} \cos(\alpha)\cos(\beta) & \sin(\beta) & \sin(\alpha)\cos(\beta) \\ -\cos(\alpha)\sin(\beta) & \cos(\beta) & -\sin(\alpha)\sin(\beta) \\ -\sin(\alpha) & 0 & \cos(\alpha) \end{bmatrix} \tag{16}$$

On the other hand, the fluid structure interaction to model aerodynamic flutter was made using ANSYS multi domain (MFX). As we mentioned in the abstract of this paper, the drawback of the ANSYS model is that it is very time and memory consuming. However, it provides a very good option to compare and validate simplified model results and understand the intrinsic theories of flutter modelling. On one hand, the aerodynamics of the application is modelled using the fluid module CFX and on the other side, the dynamic structural part is modelled using ANSYS structural module. An iterative exchange of data between the two modules to simulate the flutter phenomenon is done using the Workbench interface. Details of this modelling are available in [6].

7. EXPERIMENT FOR VALIDATION

Reference [7] makes a literature review of work performed on divergence and flutter. It is clear from there that most work has been performed on the control and mitigation of such phenomena without emphasizing on the modelling. This is mainly because the latter is very complex and the aim is primarily to avoid these phenomena. The aims of the studies conducted in by Heeg [8] were to: 1) to find the divergence or flutter dynamic pressure; 2) to examine the modal characteristics of non-critical modes, both in subcritical and at the divergence condition; 3) to examine the eigenvector behaviour. The test was conducted by setting as close as possible to zero the rigid angle of attack, $\square_0$, for a zero airspeed. The divergence/flutter dynamic pressure was determined by gradually increasing the velocity and measuring the system response until it became unstable. The results of [8] will be compared with our aerospace blockset-based obtained model.

8. RESULTS

We will first present the results obtained by modeling AoA for configuration # 2 in [8] for an initial AoA of 0°. As soon as divergence is triggered, within 1 second the blade oscillates in a very spectacular and dangerous manner. This happens at a dynamic pressure of 5,59 lb/pi^2 (268 N/m^2). Configuration #2 uses, in the airfoil: 20 elements, unity as the normalized element size and unity as the normalized airfoil length. Similarly, the number of elements in the wake is 360 and the corresponding normalized element size is unity and the normalized wake length is equal to 2. The result obtained in [8] is illustrated in figure 2:

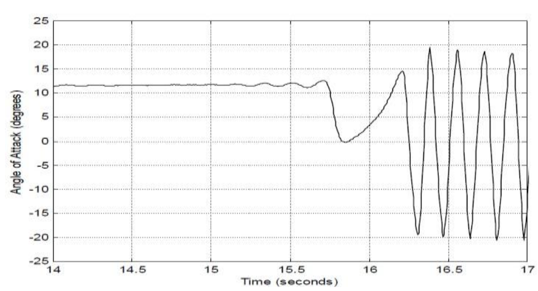

Figure 4: Flutter response- an excerpt from [8]

We can notice that at the beginning there is a non-established instability followed by a recurrent oscillation. The peak to peak distance corresponds to around 2.5 seconds, that is, a frequency of 0.4 Hz. The oscillation can be defined approximately by amplitude of $0^0 \pm 17^0$. The same modelling was performed using the Simulink model and the result for the AoA variation and the plunge displacement is shown below:

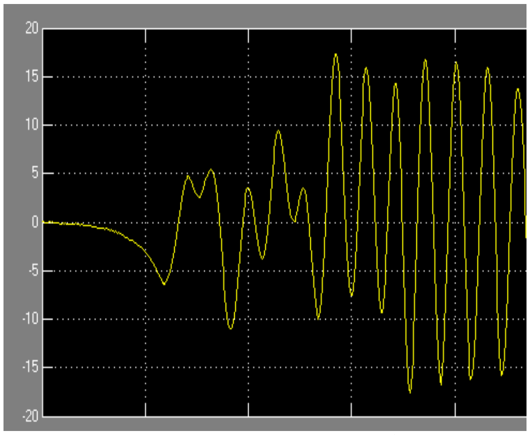

Figure 5: Flutter response obtained from Matlab Aerospace blockset

We can note that for the AoA variation, the aerospace blockset based model provides very similar results with J. Heeg results. The amplitude is, also, around $0^0 \pm 17^0$ and the frequency is 0.45 Hz. Furthermore, we notice that the profile of the variation is very similar. We can conclude that the aerospace model does represent the flutter in a proper manner. It is important to note that this is a special type of flutter. The frequency of the beat is zero and, hence, represents divergence of "zero frequency flutter". Using Simulink, we will vary the angular velocity of the blade until the eigenmode tends to a negative damping coefficient. The damping coefficient, ξ is obtained as: $\xi = \frac{c}{2m\omega}$, ω is measured as the Laplace integral in Simulink, c is the viscous damping and $\omega = \sqrt{\frac{k}{m}}$.

Table 1 below gives a summary of the obtained results of damping coefficient against rotor speed which are plotted in figure 4.

Table 1: Damping coefficient and frequency mode

Rotor Speed (Hz)	Damping Coefficient	Frequency of flutter mode (Hz)
0.1	0.0082	9.4
0.3	0.0731	8.721
0.45	0.1023	8.2532
0.6	0.2013	7.5324
0.65	0.15343	7.01325
0.7	0.08931	6.4351
0.75	-0.09321	6.33
0.8	-0.099315	5.5835

We can note that as the rotation speed increases, the damping becomes negative such that the aerodynamic instability which contributes to an oscillation of the profile is amplified. We also notice that the frequency reduces and becomes nearer to the natural frequency of the system. This explains the reason for which flutter is usually very similar to resonance as it occurs due to a coalescing of dynamic modes close to the natural vibrating mode of the system.

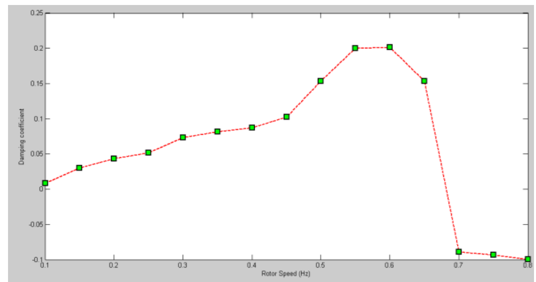

Figure 6: Damping coefficient against rotational speed

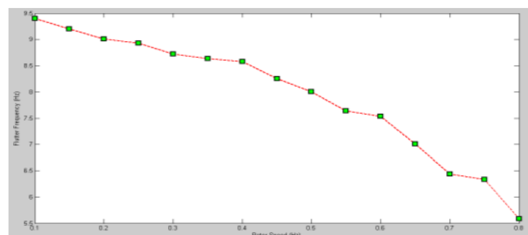

Figure 7: Flutter frequency against rotor speed

We, now present the results obtained for the same case study using ANSYS – CFX. We notice that the frequency of the movement using Matlab is 6.5 Hz that using the ANSYS-CFX model, 6.325 Hz and that obtained from Jennifer Heeg experiments 7.1Hz. Furthermore, the amplitudes of vibration are very close as well as the trend of the oscillations. For points noted 1, 2 and 3 on the flutter illustration, we exemplify the relevant flow over the profile. The maximum air speed at moment noted 1 is 26.95 m/s. we note such a velocity difference over the airfoil that an anticlockwise moment will be created which will cause an increase in the angle of attack. Since the velocity, hence, pressure difference, is very large, we note from the flutter curve, that we have an overshoot. The velocity profile at moment 2, i.e., at 1.88822 s shows a similar velocity disparity, but of lower intensity. This is visible as a reduction in the gradient of the flutter curve as the moment on the airfoil is reduced. Finally at moment 3, we note that the velocity profile is, more or less, symmetric over the airfoil such that the moment is momentarily zero. This corresponds to a maximum stationary point on the flutter curve. After this point, the velocity disparity will change position such that angle of attack will again increase and the flutter oscillation trend maintained, but in oposite direction. This cyclic condition repeats and intensifies as we have previously proved that the damping coefficient tends to a negative value.

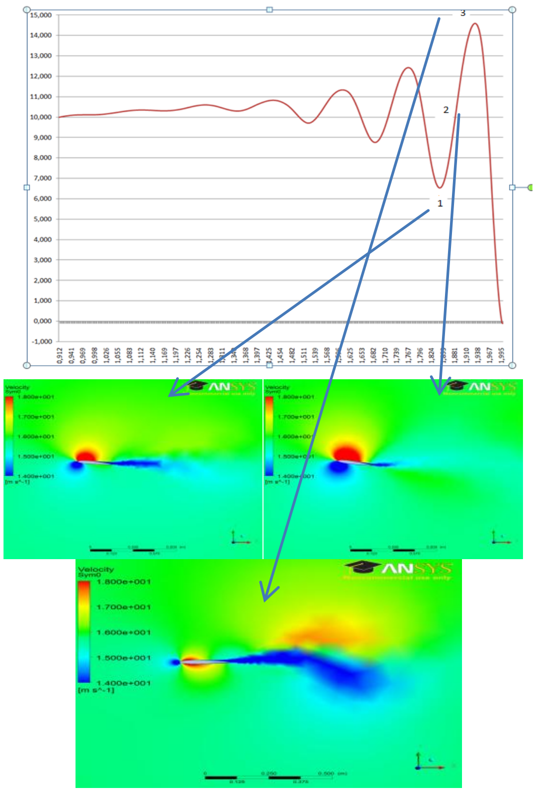

Figure 7: Flutter simulation with ANSYS-CFX at 1) 1.8449 s, 2) 1.88822 s and 1.93154s

9. DISCUSSION AND FUTURE OF THE PROJECT

In this article, we have detailed the aims and steps of modeling flutter using Simulink. The obtained results are very close to those obtained by Heeg [8]. The model furthermore enables monitoring of the damping with respect to rotational speed. Coupled with the eigenvalues and eigen frequencies analysis, the model enables a satisfactory representation of the phenomenon and a very conducive form for incorporation in a control strategy. However, this model needs to be further tried and refined to include other aspects such as rapid change in the wind speed (gusts), the flexibility of the model to adapt to different airfoils, etc. In future studies, the model will be used on different airfoils and for various wind regimes. Furthermore, additional variables will be entered in the model such as thermal variability. Once, the model is enough optimized to approach experimental results, control strategies will be applied to damp the vibrations. In an initial phase, classic control strategies such as the “Proportional Integration Differentiator Filter” models, cascade models, internal models, and Smith predictive models will be used. In a second phase, if required, a neural network control will be tried on the model.

10. CONCLUSION

In this article we modeled the very complex and dangerous flutter phenomenon. In an initial phase, we described the phenomenon and the equations characterizing it analytically. This was done by emphasizing on the required fluid-structure interaction. The article then ponders on the Matlab and ANSYS models used to simulate the phenomena as well as the experimental work used to validate our results. Both ANSYS and Matlab have given very interesting results. However, it can be noted that Matlab can only propose the aerodynamics coefficient curves while ANSYS can provide both the aerodynamic characteristics of the response and visualisation of the different flow fields along the airf oil at all time. It must be emphasized that the use of one model or the other must be based on several criteria. ANSYS requires very large computational capacity whereas the Matlab model is very less demanding. For academic and research needs, the ANSYS model proves to be very interesting as the generated flow fields help to understand the intrinsic phenomena that causes flutter. On the other hand, the Matlab model is better suited for industrial applications, as the model can be directly integrated in a control strategy and the flutter phenomenon avoided.

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