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STALL STRIPS CAN CONTROL EDGEWISE VIBRATIONS

by

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Abstract

The influence on blade vibrations from *stall strips* (in Danish *kantlister*) mounted at the leading edge of wind turbine blades has been investigated. Aeroelastic simulations were performed on a 600 kW wind turbine in operation, using airfoil data obtained from wind tunnel measurements on airfoils with and without stall strips, respectively. The investigation shows that the stall strips result in considerable modification of the airfoil characteristics and through that significant improvement of the aerodynamic damping conditions. In the simulation example a single stall strip of length 2 m increases the aerodynamic damping for the blade with 2%, effectively removing the problem with edgewise vibrations.

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Main results

Some stall regulated wind turbines have under specific conditions during operation in stall suffered from problems with edgewise vibrations of the blades. The problems arise, because the total damping of the blades in the edgewise direction becomes negative. The phenomenon is controlled by a series of parameters, among others the airfoil characteristics, the vibration direction of the blades and the natural frequencies of the turbine. On existing wind turbines the majority of these parameters are difficult to change, but on the other hand it is very important to consider their proper choice during any design phase, where changes are possible, especially when dealing with a new design. Yet, the present results demonstrate that rather limited modifications of the airfoils can change the aerodynamic damping of the blades fundamentally. By mounting *stall strips*, which are small lists with triangular cross section, at the leading edge of the blade – extending only few meters radially on a 20 m blade – the airfoil properties can be changed fundamentally, resulting in elimination of the problem with edgewise vibrations.

The method has been developed by Søren Vinther and Peder Enevoldsen from Bonus Energy A/S. They also carried out thorough experimental investigations of the influence of stall strip modifications in cooperation with LM Glasfiber A/S and Risø. Today LM Glasfiber A/S can deliver blades with stall strips mounted as a standard solution, which is based on these investigations. In the present fact sheet our starting point is airfoil data obtained by wind tunnel measurements carried out on airfoil sections with and without stall strips, respectively. We apply these data in aeroelastic simulations. Based on the measured data we have modelled the influence of stall strips in the aeroelastic code HAWC for a 600 kW turbine with LM-19.0 blades (diameter = 41 m). The calculations show that a stall strip extending 2 m radially at the outer part of the blade can increase the aerodynamic damping with approximately 2% for the modelled turbine. Such an increase in aerodynamic damping will for the majority of wind turbines be sufficient to eliminate the edgewise vibration problem. However, the mounting of stall strips will in addition reduce the peak rotor power significantly. This can be compensated for, for instance by mounting of vortex generators along the inner part of the blades and by simultaneous adjustment of the tip pitch setting.

It must be emphasized that the absolute values obtained by the calculations to some extent are approximate due to uncertainties in the wind tunnel measurements and approximations in the models, whereas the relative results express clear tendencies, which are in agreement with the full scale measurements.

What is the origin of aerodynamic damping ?

The physical concept of aerodynamic damping plays a fundamental role in the problem with edgewise vibrations in stall, because the damping can be negative, meaning that energy is supplied to the vibrating blade. Our work is basically concerned with control of this damping towards improved conditions. We therefore start by looking into a simple model for aerodynamic damping on a single blade. This model is capable of explaining the basic physics. The total damping is the sum of structural damping and aerodynamic damping. If the aerodynamic damping is more negative than the structural damping is positive, the conditions for edgewise vibrations are present.

For a blade section at radius r the aerodynamic damping in the edgewise direction can be expressed – simplified to some extent – as a function of the airfoil lift C_L and the airfoil drag C_D:

$$c_k(r) = \frac{1}{2} c \varrho \frac{r\Omega}{W} \left[\left(\frac{2r^2\Omega^2 + V^2}{r\Omega} \right) C_D - V \frac{\mathrm{d}C_D}{\mathrm{d}\alpha} - V C_L + \frac{V^2}{r\Omega} \frac{\mathrm{d}C_L}{\mathrm{d}\alpha} \right] , \tag{1}$$

where c is the section chord length, ϱ is the air density, Ω is the rotor rotational speed, W is the relative wind velocity at the section and V is the free wind velocity. α is the angle of attack, i.e. the angle between the relative velocity and the section chord. C_L and C_D depend on both radius and angle of attack. In this expression it is assumed that the blade vibrates in the rotor plane. In reality, the edgewise mode shape of the blade simultaneously vibrates in a direction perpendicular to the rotor plane, the flapwise direction. This results in an additional contribution to the resulting damping. In the calculations below this effect is included, as the complete expression is applied, and the true edgewise mode shape of the blade is used, which is important to get realistic results.

By integration of c_k along the blade span we obtain the aerodynamic damping expressed as logarithmic decrement:

$$\delta = \frac{C_m}{2 f_m M_m} = \frac{\int_0^R c_k(r) \varphi_m^2(r) \mathrm{d}r}{2 f_m \int_0^R m(r) \varphi_m^2(r) \mathrm{d}r} \ , \tag{2}$$

where C_m is the modal damping, f_m is the natural frequency of the edgewise mode shape in Hz, M_m the modal mass, φ_m the mode shape and $m(r)$ is the mass per unit length at radius r. The mode shape is mainly determined by the properties of the blade itself, but the properties of the actual wind turbine nacelle and tower are important as well, as they influence the resulting conditions for the blade vibrations.

From the expression (2) it is immediately observed that the mode shape plays an important role for the total damping, as it is a weighting factor on the local airfoil properties. In other words, the damping properties at the outer part of the blade has a major influence on the total damping. The local damping properties at each blade section depend – as shown in Equation (1) – on four terms: One term depends on C_D, the second on the slope of C_D, the third term depends on C_L and finally the fourth depends on the slope of C_L. This shows that the total damping on the blade can be changed fundamentally, if it is possible to modify these terms along the outer part of the blade. In order to maintain a good power curve it might in addition be important to modify the airfoil properties along the inner part of the blade, which most likely will contribute towards less positive damping. Due to the weighting from the mode shape this can totally result in a change of damping towards more positive values for the whole blade, without significant damage to the power curve.

Significant change of airfoil characteristics

Measurements on airfoil sections in wind tunnel have shown that stall strips change the airfoil characteristics significantly. The stall strip initiates flow-separation from the leading edge, when a certain angle of attack is exceeded. This results in reduced lift and increased drag.

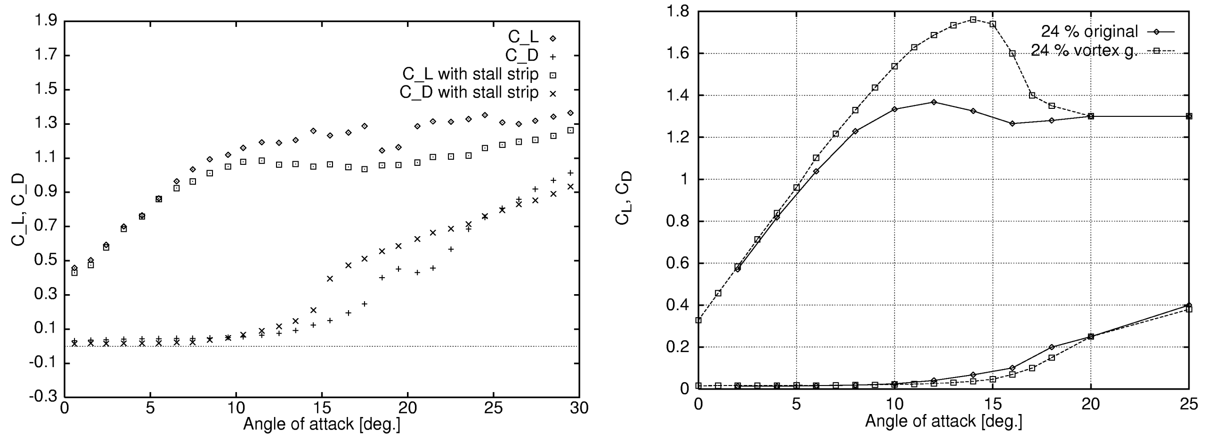

Figure 1: (a) Measured characteristics for a NACA63-215 airfoil with and without stall strip, [3]. (b) Modelled influence from vortex generators on a 24% FFA airfoil.

The influence from stall strips mounted on a NACA 63-215 airfoil has been investigated experimentally in wind tunnel. This has been done both by FFA and Risø. FFA measured under 2D conditions [2] and Risø measured on a full scale LM-8.5 m blade in the Velux wind tunnel, [3]. The result from the Velux measurements are shown in Figure 1(a). It is observed from the figure that the airfoil with stall strip has almost the same properties as the original airfoil in the linear range, while the properties have been changed significantly for angles of attack above approximately 8°. The stall strip initiates leading edge stall for angles of attack in the range 8–10°, limiting the maximum lift (C_L) to 1.0–1.1. At the same time the drag C_D is increased significantly. It is expected that the airfoil characteristics for a stall strip only to a limited extent depend on the actual airfoil shape. This means that the observed changes of the airfoil characteristics due to the stall strip, with good approximation can be transferred to other airfoil types. Even for airfoil types with lower maximum lift it appears that the stall strip has significant influence, especially on C_D. Based on the two mentioned wind tunnel measurements a set of airfoil data has been generated for an airfoil (14–18%) with stall strip. This set of data is applied in the aeroelastic calculations on the LM-19.0 blade reported below.

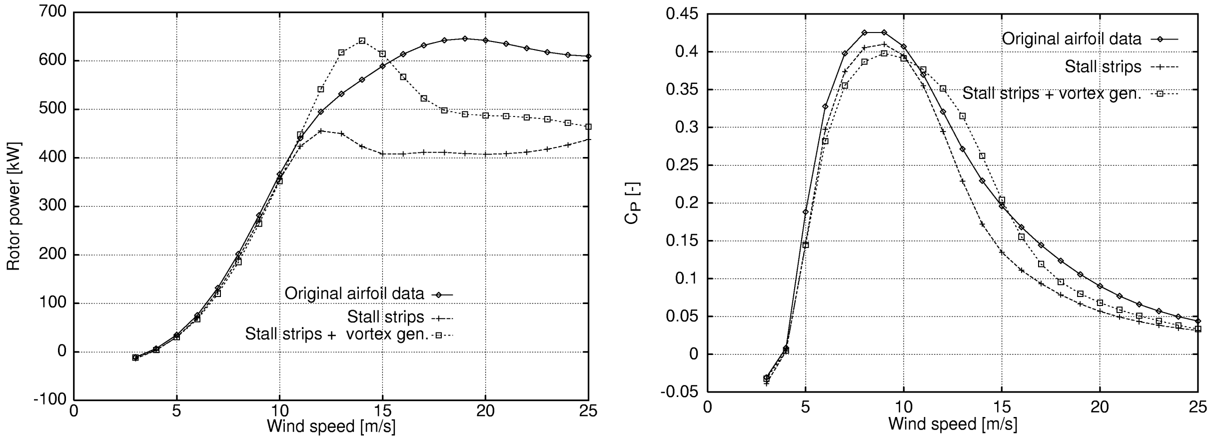

Figure 2: (a) Calculated rotor power curves corresponding to original and modified airfoil characteristics, respectively. For the configuration with vortex generators the tip pitch setting is changed (+ 1.5°). (b) Corresponding rotor efficiency characteristics, C_P.

Due to the changed airfoil characteristics the rotor power curve is changed as well. Often, this can be compensated for by changing airfoil characteristics along the inner part of the blade. One possibility is to mount vortex generators and change the tip pitch setting simultaneously. The result of this solution is illustrated in Figure 1(b), where the estimated influence from vortex generators on a 24% airfoil is shown. In Figure 2 the influence on the rotor power curve is illustrated. On the configuration with stall strips, the strips cover 2 m radially from the airbrake bearing (r = 18.5 m) and inwards. The third configuration has in addition vortex generators mounted along the inner part of the blades (r = 3–14 m), and the tip pitch setting is changed 1.5° in positive direction.

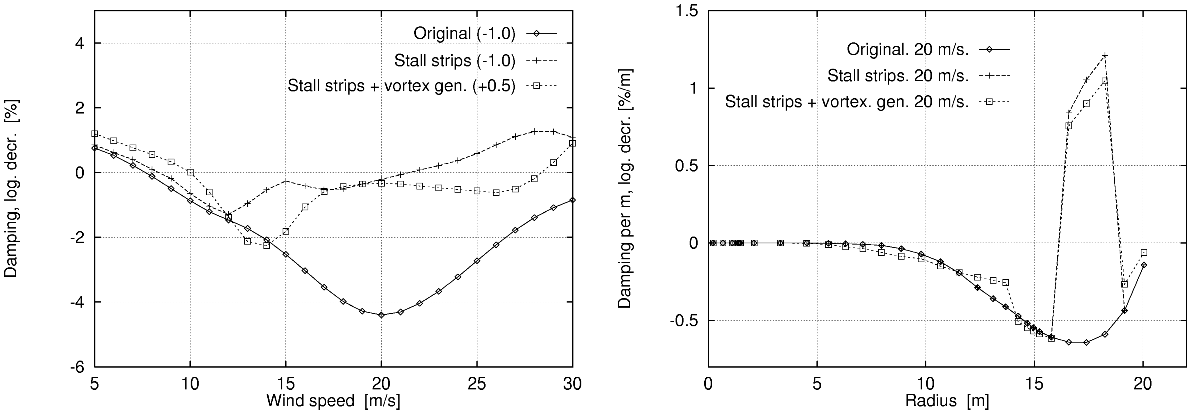

Figure 3: (a) Calculated aerodynamic damping in edgewise direction as function of the free wind speed and (b) the damping per unit length at 20 m/s. The calculations are quasi steady.

Changes of blade damping

The presented changes of the profile characteristics have significant influence on the aerodynamic damping. In Figure 3 the aerodynamic damping in edgewise direction is shown with the original data and the modified airfoil data, respectively. The calculations cover the same configurations as referred to in Figure 2(a).

From Figure 3(a) it is observed that the total damping is changed from a minimum value of approximately -4% to a value of approximately -2%. At the same time the critical operational wind speed is changed from 20 m/s to 14 m/s, which is caused primarily by the influence from the vortex generators. From Figure 3(b) it is observed that the damping is negative along the whole blade for the original configuration at 20 m/s wind speed. For the configurations with stall strips the influence from these is a local increase of the damping in the area with stall strips of approximately 1.5–2.0%/m.

The changed damping can be illustrated in another way, as demonstrated in Figure 4. This figure shows a time trace of the edgewise root bending moment at 20 m/s for a turbine with original and modified airfoil data, respectively. As mentioned previously the application of stall strips will be a balance between increased aerodynamic damping and reduced power production. This indicates that practical applications can take advantage of thorough optimization of the spanwise distribution of the devices used for modification of the airfoil characteristics, in the present case the stall strips and the vortex generators.

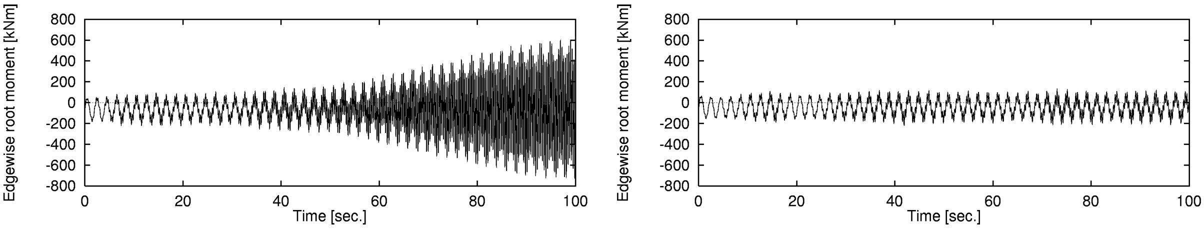

Figure 4: Time trace examples of edgewise root bending moment for (a) original airfoil data and (b) modified airfoil data (vortex generators + stall strips). The free wind speed is 20 m/s and the structural damping is 3% (log. decrement) in edgewise direction.

Other parameters than the airfoil characteristics are important for the vibration phenomenon, for instance the actual mode shape (size and direction of the deflection, controlled by the structural properties of the blade), the dynamic coupling to the nacelle and the tower (especially the 2^{nd} tilt- and yaw-frequencies [1]) and the blade planform.

Based on the work with the vibration phenomenon it is presently considered a practical possibility to take into account the influence of these important parameters during the design phase and in this way to design wind turbine blades with very limited risk for edgewise vibrations. One possibility is to apply airfoils, where the desired properties are integrated in the airfoil shape – thus eliminating the need for subsequent modifications.

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