Load alleviation on wind turbine blades using variable airfoil geometry

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ABSTRACT
A two-dimensional theoretical study of the aeroelastic behaviour of an airfoil has been performed, whose geometry can be altered using a rear-mounted flap. This device is governed by a controller, whose objective is to reduce the airfoil displacements and, therefore, the stresses present in a real blade. The aerodynamic problem was solved numerically by a panel method using the potential theory, suitable for modelling attached flows. It is therefore mostly applicable for Pitch Regulated Variable Speed (PRVS) wind turbines, which mainly operate under this flow condition.The results show evident reductions in the airfoil displacements by using simple control strategies having the airfoil position and its first and second derivatives as input, especially at the system's eigenfrequency. The use of variable airfoil geometry is an effective means of reducing the vibration magnitudes of an airfoil that represents a section of a wind turbine blade, when subject to stochastic wind signals. The results of this investigation encourage further investigations with 3D aeroelastic models to predict the reduction in loads in real wind turbines.

Keywords: Variable Geometry, Wind Turbine, Load Alleviation, Fatigue Load, Trailing Edge Flap.

NOMENCLATURE

AS	actuator speed limit [º/s]
c	chord length [m]
c_x	edgewise damping logarithmic decrement [–]
c_y	flapwise damping logarithmic decrement [–]
c_t	torsional damping logarithmic decrement [–]
C_l	lift coefficient [–]
C_d	drag coefficient [–]
C_m	pitching moment with respect to the quarter chord point [–]
f	frequency of freestream angle for sinusoidal incoming flow [Hz]
f_{eigenx}	edgewise natural frequency [Hz]
f_{eigeny}	flapwise natural frequency [Hz]
$f_{eigentor}$	torsional natural frequency [Hz]
k	reduced frequency [-]
k_x	edgewise stiffness natural frequency [Hz]
k_y	flapwise stiffness natural frequency [Hz]
k_t	torsional stiffness natural frequency [Hz]

K_{cr}	minimum proportional gain to obtain sustained oscillations [rad/s]
K_d	differential gain [rad.s/m]
K_p	proportional gain [rad/m]
l	flap length [m]
M_{bend}	bending moment due to force acting on section [Nm]
n	number of points describing profile [–]
N	number of panels [–]
N_t	number of time steps [–]
P_t	period of oscillation at Kcr [s]
r	distance from center of coordinates in cylindrical system [m]
r_{sec}	distance from section in consideration to blade root [m]
t	time [s]
t_0	time of occurrence of step change in freestream angle [s]
TI	turbulence intensity [-]
U	freestream velocity x-component [m/s]
v	relative velocity between undisturbed flow and airfoil [m/s]
$V_{freestream}$	freestream velocity [m/s]
V_{mean}	mean freestream velocity in turbulent simulation [m/s]
V_{rot}	tangential velocity due to rotation of the blade [m/s]
W	freestream velocity y-component [m/s]
x	x-coordinate [m]
x_f	distance from leading edge to springs attachment point [m]
x_i	length of ith panel
x	x-coordinate [m]
$\dot{x}$	derivative of x-position [m/s]
$\ddot{x}$	second derivative of x-position [m/s2]
y	y-coordinate [m]
y_{equil}	equilibrium position of the airfoil [m]
$\dot{y}$	derivative of y-position [m/s]
y	second derivative of y-position [m/s2]
α	angle of attack [°]
α_0	angle of attack corresponding to zero lift [°]
ß	flap deflection angle [°]
Δt	time step [s]
$\Delta\theta$	amplitude of freestream angle for sinusoidal inflow [°]
$\Delta\theta_{step}$	step change in freestream angle for step inflow [°]
η	camberline function
γ	airfoil pitch angle [°]
Γ	circulation
Ω	rotational speed of the wind turbine rotor [rad/s]
Φ	potential function
ρ	fluid density [kg /m^3]
t	dimensionless time [–]
θ_0	angle of freestream flow [°]
Θ	angular position in cylindrical coordinate system [–]
ξ	vorticity

1 INTRODUCTION

Wind turbine blades are subject to fast fluctuating loads during operation, due to turbulence, yawed flow and the effect of the tower, which cause fatigue damage. Several components, including the blades, are dimensioned according to the fatigue damage done by these loads. Therefore, significant benefits could be obtained if the fluctuating nature of these loads could be minimized, and hence the cost of the wind turbines, and therefore the cost of energy generated per kWh, could be reduced. It is known that altering the blade section geometry at the rear of an airfoil, i.e. by using 'trailing edge flaps', affects the forces acting on the blade. This feature can be used to minimize the fluctuating loads on the blades.

The use of trailing edge flaps has been investigated in helicopter rotors (Prechtl 1991, Leishman et al. 2000), to minimize the vibrations, and in airplanes, to reduce gust related loads (Chambers et al. 2000). Furthermore, the use of such control surfaces has been investigated in bridges (Kwon et al. 1999) for suppression of flutter and gust alleviation. Although the flow conditions for wind turbines differ from the previous examples, conclusions from these investigations suggest that the use of active trailing edge flaps can reduce the vibration magnitudes considerably. In order to assess the potential of using trailing edge flaps to reduce the fatigue loads in wind turbines, an appropriate model is needed, where the operating conditions of these particular machines are simulated, regarding both the structure and the flow conditions. This study (Basualdo 2004) focuses on horizontal axis Pitch Regulated Variable Speed (PRVS) wind turbines, in which the flow remains attached to the blades for a large portion of the blade under normal operating conditions. PRVS machines became common among most of the major manufacturers in recent years, and prospects show that they will continue to be so. The required flap actuation frequencies are high compared to conventional pitch systems used nowadays in large wind turbines. However recent research on smart materials shows promising results for such characteristics, where fast actuation speeds at reasonable forces are needed.

This study is initiated by the ADAPWING[1] project being developed at Risø National Laboratory. The present study represents a first stage of investigation, where a first estimation of the potential of the variable geometry system to reduce fatigue loads is sought.

2 METHOD

2.1 Problem statement

A model has been implemented of the aerodynamic forces acting on a variable-geometry wind turbine blade, subject to different types of inflow, and their interaction with the structure. The model includes a control system that governs the variable geometry. A wind turbine blade is analysed as a beam of finite length, with NACA 0015 airfoils as cross sections [Gaunaa 2002; Hansen 2000]. Although three-dimensional aerodynamic effects are involved, a 2D model representing a cross section of the blade, gives appropriate qualitative. The airfoil geometry is variable at its rearmost part, as it can be seen in Figure 1. The movable part is usually referred to as flap and it can rotate around the hinge point, giving different lift characteristics. The airfoil thickness is neglected and the airfoil is represented by its camberline, which is representative of the airfoil lift characteristics. Therefore, a theory based on this assumption, the thin airfoil theory, is applicable and was used in the present model.

The fluid flow being studied is assumed to be irrotational and incompressible, which can be studied using potential theory, where the velocity field in the entire region under study can be derived from a potential function. In order to model the flow around an airfoil, a panel method

[1] The ADAPWING project overview is available at www.risoe.dk/vea.adapwing

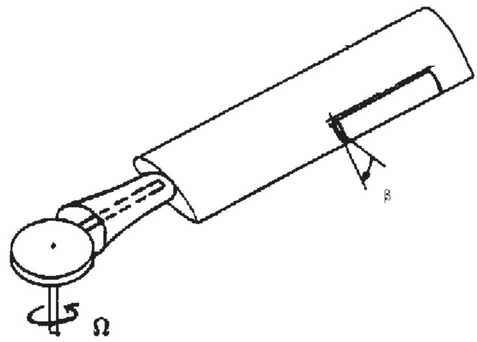

Figure 1: Schematic of blade with trailing edge flap

has been used, which solves the potential flow problem numerically. The airfoil camberline is discretized into a number of segments called panels, on which singularity elements are placed. These elements induce velocities in the entire flow field, and the sum of the contributions of all singularities, give the solution of the velocity field. Once the velocities are known, other quantities are computed, such as pressures and forces acting on the airfoil. Furthermore, the model has been coupled to a structural dynamics model represented by springs and dampers, in order to simulate the elasticity of the blade and its interaction with the aerodynamics.

The code models variable geometry airfoils, where the rearmost part of the airfoil can rotate around a hinge point and is known as a flap. Deflecting the flap changes the camber of the airfoil and therefore its aerodynamic characteristics.

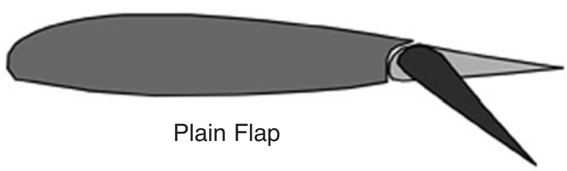

Figure 2: Schematic of airfoil with trailing edge flap

2.2 Assumptions and limitations

2.2.1 Attached flow

The flow is assumed to be attached to the airfoil surface at all times. This is appropriate for this investigation, as it is focused on PRVS wind turbines, in which the airfoils operate mainly in the linear part of the lift curve. Furthermore, this condition is generally satisfied for flap deflections up to 10 to 15 degrees (Abbott et al. 1959; Anderson 1991; Katz 1991).

2.2.2 Variable inflow

In order to investigate the response of the system to different types of wind fields, a varying freestream field has been included in the code. It updates the freestream velocity in the entire field at each time step.

2.2.3 Step change in wind velocity

The time of occurrence t_0 and the step magnitude $\Delta\theta_{step}$ are the parameters defining this velocity signal. A step change in the freestream direction is generated.

$$V_{freestream} = \text{constant}$$

if $t < t_0$ $\quad \begin{cases} U = V_{freestream} \cos(\theta_0) \\ W = V_{freestream} \sin(\theta_0) \end{cases}$

if $t = t_0$ $\quad \begin{cases} U = V_{freestream} \cos(\theta_0 + \Delta\theta_{step}) \\ W = V_{freestream} \sin(\theta_0 + \Delta\theta_{step}) \end{cases}$

2.2.4 Turbulent wind field

In order to simulate the fluctuating wind field seen by a blade section of a horizontal axis wind turbine, a 1-point turbulent wind speed simulation has been implemented. It is created using an inverse Discrete Fourier Transform (DFT), where the Kaimal Power Spectral Density (PSD) function was used as input. This PSD is applicable to the atmospheric boundary layer. It creates a time signal of the wind speed. A complete description of this model is given in (Hansen 2003). It is assumed that the velocity seen by the airfoil, is composed of a velocity due to the rotation of the blade U = Vrot which is kept constant, and a stochastic component due to the wind represented by the component in the y (axial) direction W = Vwind. In reality, the vortex system of a wind turbine induces another axial velocity component that acts against the wind. The latter induced velocity is not included in the present model, since, for the purpose of the present study, it is not necessary.

2.3 Control algorithm

The control algorithm computes the desired flap deflection at each instant, based on the input signals (Bossanyi 2000). The input signals that can be used by the model are

- Position of the airfoil defined by the x and y coordinates and their derivatives $\dot{x}$, $\ddot{x}$, $\dot{y}$ and y
- Freestream flow angle

Simple PD (Proportional and Differential) control strategies have been implemented and tuned to obtain reduction in the fatigue figures. A moving average filter has been implemented on the output signal (the deflection angle) to reduce small fluctuations. Furthermore, a parameter that controls the maximum deflection per unit time (AS) has been incorporated. It limits the rate of change of the deflection

2.4 Strategy

The output signal has three terms. With respect to the plane of the blade, the first is proportional to the airfoil 'vertical' position; the second to the 'vertical' velocity and the third term is proportional to the acceleration of the airfoil, $\ddot{y}$, in the 'vertical' direction. The third term gives a faster response, because the second order term reacts immediately to the forces on the airfoil, whereas the velocities and positions require a finite time to respond.

$$\beta(t) = -K_p(y - y_{equil}) - K_d \frac{\delta y}{\delta t} - K\alpha \frac{\delta^2 y}{\delta t}$$

2.5 Control system tuning

The system has been tuned using Ziegler-Nichols rules (Ogata 1990]), based on the transient characteristics of the system. The simulations were used to obtain the response of the system to step changes in incoming flow angle θ. These rules were developed for PID (Proportional, Integral & Differential) controllers, but can be applied to systems with no integrators.

2.6 Computation of fatigue damage

The fatigue of materials occurs due to time varying external loads, when cracks develop causing internal damage. Wind turbines are subject to fluctuating loads, which cause this type of material failure, and the life time of a wind turbine blade depends, among other factors, on the variability of these loads.

The displacements of the airfoil are proportional to the forces acting on it, since it is mounted on springs. Furthermore, the airfoil represents a section of blade and is located at a certain distance from the rotational axis of the wind turbine. The bending moment of the force acting on it with respect to, for example, the blade root, is computed as the force multiplied by the distance from the point where it is applied to the root as $M_{bend} = F \_ r_{sec}$. This means that the airfoil displacements are proportional to the corresponding bending moments, which means that they are directly related to the stresses on the blade, and therefore, the more constant they can be kept, the smaller fatigue damage is caused. The plots showing the displacements as a function of time for the different cases give a clear qualitative picture of the potential benefits of the system.

3 RESULTS

3.1 System Parameters

The parameters in Table 1 have been kept constant for all simulations, unless stated otherwise.

Table 1 General simulation parameters

Variable	Symbol	Value	Units
Flap length	l	10	% of chord
Chord length	c	1	m
Time step	Δt	0.002	s
Number of points describing profile	n	11	-
Number of panels	N	50	-

The time is non-dimensionalized using the following formula

$$\tau = \frac{t \cdot V_{freestream}}{c}$$

Similarly, the reduced frequency is defined as

$$k = \frac{\omega \cdot l}{2 \cdot U_{freestream}}$$

The standard deviation is in all cases normalized to the value that corresponds to the no-control case, and therefore has no units.

The following parameters for the fluid and the structure have been used for all aeroelastic simulations performed under the present study. The structural values were obtained from (Larsen et al. 2002).

The torsional stiffness k_t was equal to 23.16 Hz in the real blade, however in this study, the airfoil was locked in the torsional direction, as $k_t = \bullet$ indicates.

Table 2 System characteristic parameters			
Parameter	**Symbol**	**Value**	**Units**
Flapwise stiffness	k_y	1.636	Hz
Edgewise stiffness	k_x	2.944	Hz
Torsional stiffness	k_t	•	Hz
Flapwise damping	c_y	1.782	%log
Edgewise damping	c_x	3.603	%log
Torsional damping	c_t	•	%log
Fix point	x_f	$0.3 \times c$	m
Fluid density	ρ	1.205	kg/m^3

3.2 Computation of control algorithm gains

Using the Ziegler-Nichols tuning, a first approximation is done. Then, a manual fine tuning is performed in order to obtain the desired response. If the structural characteristics of the system described in Table 2 are changed, the response of the system would be altered and a new tuning would be required.

First, the proportional gain was computed by the procedure described above, having k_α=• . A value of k_{cr} =1.1 gave the system sustained oscillations. The period of the oscillations was $P_{cr} = 0.48$s. Therefore, the suggested proportional gain was set to $K_p = 0.6 \leftrightarrow K_{cr} = 0.7$. Once the first approximation was obtained, the system was tuned to have certain characteristics, with a limited overshoot and fast response, and without requiring actuation speeds to be too fast. This implies determining the differential gain and modifying the initial K_p value if convenient.

3.3 Unsteady flow

Table 3 System response to unit step change in angle of attack at $V_{freestream}$= 50 m/s , with flap actuation speed limited to AS=40°/s			
K_p	K_d	**Overshoot [%]**	**Max AS [º/s]**
0	0	52	40
0.7	0.04	74	40
0.7	50	26	40
1	50	33	40
1	100	1	40

From Table 3 it can be seen that the overshoot values are very similar to no limit on the actuation speed was imposed. This is explained by the fact that the high actuation speeds i AS not limited occur right after the step occurrence, but very shortly after, they decrease to values below 40 °/s. Therefore, its effect on the overshoot is very small.

3.3.1 Tuning using 2 seconds turbulent wind field

Simulations using a stochastic velocity field have been performed with the purpose of fine tuning the control system. The goal was to minimize the standard deviation of the displacements. Summarizing, the steps followed to tune the control system are

1. first approximation by Ziegler-Nichols rules using unit step in incoming flow angle as input to obtain desired overshoot and response time
2. further refinement using unit step input
3. setting of maximum actuation speed

4. fine tuning using turbulent simulations to obtain minimum standard deviation of the oscillation amplitudes

After several simulations performed using different control settings, it was decided to set the proportional gain to $K_p = 1$ and the differential to $K_d = 50$; these result in

- 33% percent overshoot in unit step test.
- fast response
- appropriate actuation speeds best oscillation attenuation in turbulent simulations

Having tuned the system using the first two terms in the algorithm (by setting $K_\alpha = 0$), the third term is now tuned directly with the turbulent wind field as input. The objective was to minimize the amplitude of the oscillations measured by the standard deviation. By increasing K_α, a faster response is obtained. However, due to the limitation imposed by the actuation speed AS, the standard deviation converges to a certain value. No effect is obtained if K_α is increased further. See Figure 3.

Table 4 System response to turbulent field of V_{mean} = 10 m/s , turbulence intensity TI = 20% and flap actuation speed limited to AS=40°/s. 1000 time steps.

k_p	k_d	k_α	Std Dev
0	0	0	1
1	50	1	0.37
1	50	3	0.29
1	50	10	0.26
1	50	20	0.25
1	50	100	0.25

The final settings adopted for the control system are shown in Table 5.

Table 5 Control system settings

Name	Symbol	Value
Proportional	K_p	1
Differential	K_d	50
Differential	K_α	20
Max Actuation Speed	AS	40

3.3 Aeroelastic motion analysis

The results shown in this section are organized according to the type of incoming flow. In this way, a clear picture of the influence of the strategies in the system response is obtained. Emphasis is put on the oscillation amplitudes for each

3.3.1 Unsteady flow case

The results based on inputs where the angle of attack changes in time, give a good idea of the effectiveness of the system to minimize the blade deflections, which in this model are represented by the airfoil displacements. Reducing the displacement fluctuations will reduce the related blade bending moment fluctuations. The ability of the system to achieve this reduction is investigated in this study.

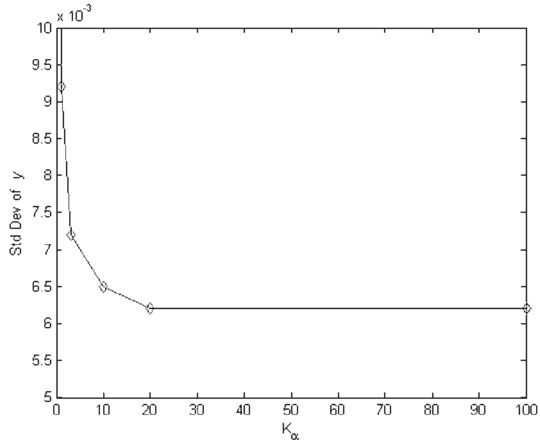

Figure 3: Sensitivity of the system response to K_α measured as standard dev iation of oscillation and AS not limited

3.3.2 Stochastic

Three different time series were generated (2 seconds, 20 seconds and 100 seconds) and they were used for the different simulations. This made the results comparable between same length simulations.

All simulations in this section use a wind speed signal generated by the code, with TI = 20% and V_{mean} = 10 m/s . Only the 100 seconds simulation is described here.

Table 6 System response to turbulent wind field, at V_{mean} = 10 m/s and TI = 20% during 2 seconds

k_p	k_d	k_α	Std Dev
0	0	0	1
1	50	0	0.85
1	50	20	0.25

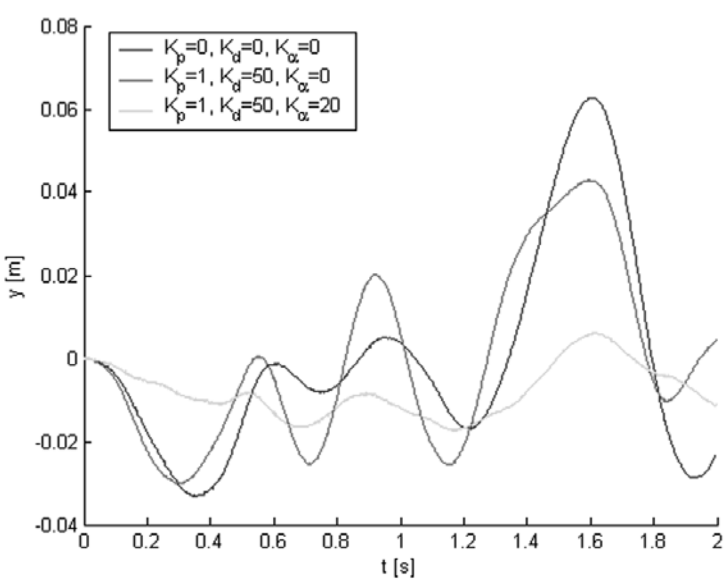

Figure 4: Displacements as function of time for 2 seconds simulation

100 seconds simulations

In these simulations (identified by ID number,, Table 4, it was found out that the standard deviation might not be very representative of the reduction in fluctuations, as the control system is not able to minimize this value. It is increased rather than reduced. However, the graphical results, Figure 5, show how the controlled flap tries to smooth the airfoil displacements. The standard deviation of the wind speed signal used was 1.75.

Table 7 System response to turbulent wind field, at V_{mean} = 10 m/s and TI = 20% during 100 seconds

k_p	k_d	k_α	Std Dev
0	0	0	1
1	50	0	0.97
1	50	3	1.1
1	50	20	1.5

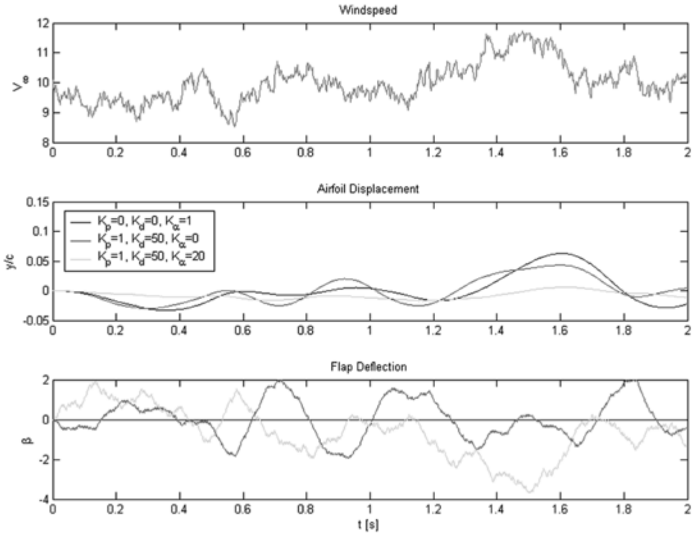

Figure 5: Displacements and flap deflections as function of time, 100 s simulations

For this wind speed signal, the controller strategies applied might not be the most appropriate, as the oscillations were not reduced as well as in the 2 seconds and 20 seconds simulations. Furthermore, the required flap deflections are larger than in those two cases, reaching limits where separation might occur and the model validity breaks down. A different controller tuning might enhance the system response for this simulations, especially for the low frequency oscillations. For example, setting $K_\alpha = 3$ gives smaller displacements.. Furthermore, if the flap system is combined with the pitch system of the wind turbine, better results might be achieved. The pitch system might cancel the low frequency oscillations, whereas the flap system takes care of the high frequency vibrations.

The oscillations at the eigenfrequency (1.636Hz) of the vertical spring have been reduced. For this purpose, a Fourier Transform on the vertical displacement signal has been performed, for which, the power contained in the oscillations around the eigenfrequency has been reduced.

3.3.3 Flap shape influence

The results, Figure 7, show that a flat flap requires larger deflections for the same control algorithm. This can be explained by doing a steady analysis of the lift for both cases. It shows that for the same flap deflection, i.e. 10°, the lift coefficient is equal to 0.545 for a curved flap and 0.427 for a flat flap. The flat flap is less effective for the flow condition and controller strategy than the curved flap. The larger the increase in lift per angle of flap deflection, the smaller deflection will be needed in the same flow conditions. Therefore, a well designed airfoil and flap with a high lift per angle of deflection rate will be very beneficial in terms of reducing the flap deflection amplitudes.

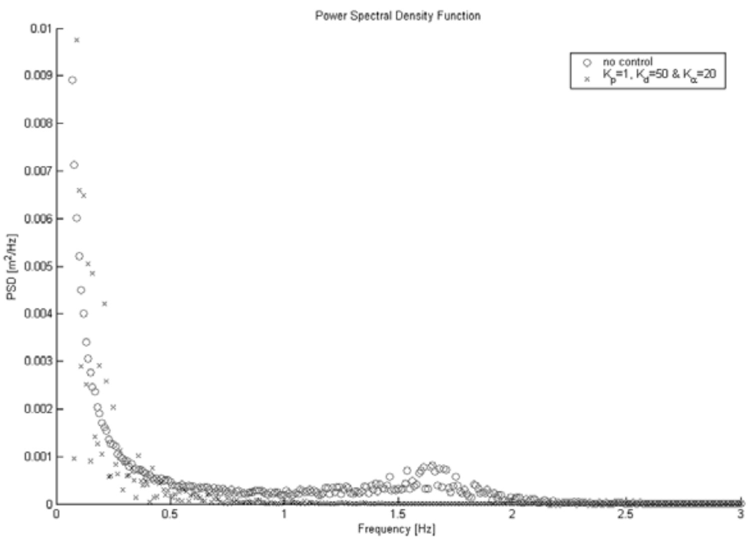

Figure 6: Power spectra density of the displacements as function of frequency for *no control* vs. *controlled*

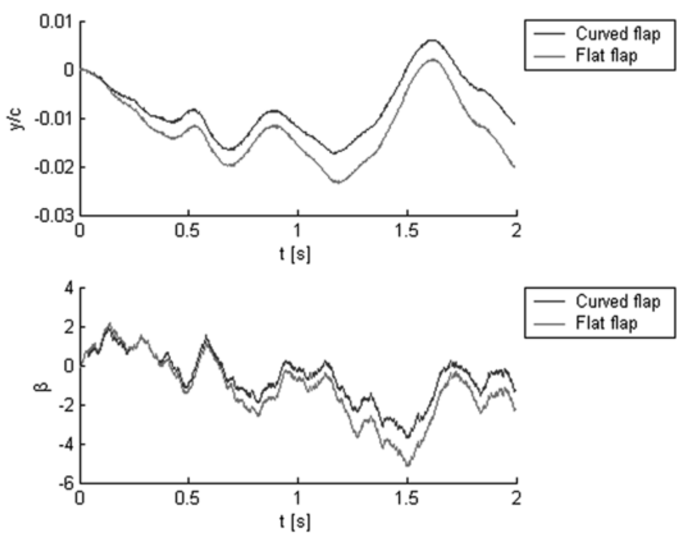

Figure 7: Displacements and flap deflecitons as function of time for curved and flat flap

3.3.4 Actuator speed influence

Actuation speed AS is a very critical characteristic of the system. The nature of the fluctuating inflow requires actuators to react fast enough to achieve the reduction in oscillation amplitudes. Figure 8 shows the results for both simulations.

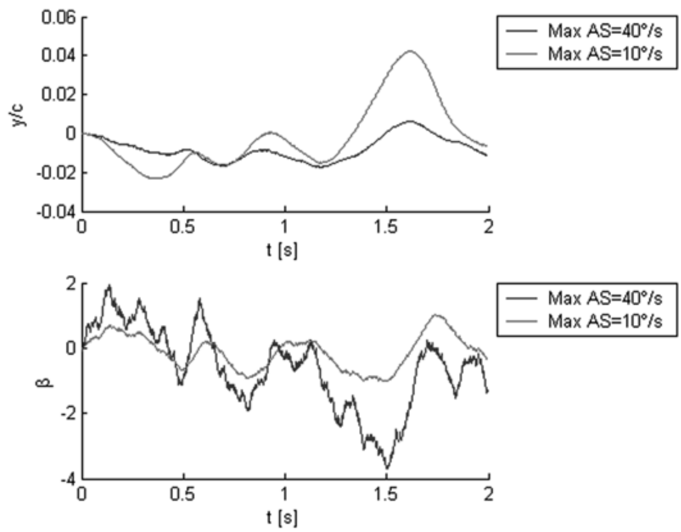

Figure 8: Displacements and flap deflections as function of time for two different maximum actuation speeds

3.3.5 Suggestions for further work

The following developments would be appropriate for further research:

1. Add an integrator to the control function.
2. Analyze the system with 3 degrees of freedom.
3. Use feedforward control techniques, by measuring the disturbances to cancel their effects on the output. In this case the disturbance can be measured through the inflow angle at some distance in front of the leading edge.
4. Use of more advanced multivariable control techniques.
5. Consider the use of pitch control in combination with flap control, where the former compensates for low frequency vibrations and the latter for high frequencies.
6. Consider the effects of noise in the signals from the sensors and study their effect on the system effectiveness.

4 CONCLUSIONS

The results show that the use of variable geometry airfoils in wind turbine blades can lead to load alleviation. The magnitude of the attenuation is measured by the airfoil displacement fluctuations, which are effectively reduced by using an active control system to govern the airfoil geometry. The reduction in fluctuation of the airfoil displacements confirms the potential benefits of this system. A 2D aeroelastic model for variable geometry airfoils has been developed, validated and used for the study of load alleviation in wind turbine blades. The simulations with a step change in angle of inflow show very clearly that the system is able to attenuate the airfoil oscillations. The turbulent '100 seconds' simulations show attenuation of the oscillation amplitudes, although not so effectively as in the step change case. However, the Fourier analysis on the displacements signal gives a very clear picture of the ability of the system to minimize the oscillations around the eigenfrequency of the system.

While more advanced control strategies may lead to smoother airfoil displacements, the simple PD strategies used are successful in reducing the vibratory magnitudes. However, a proportional strategy is not enough, the derivative terms are vital. If the appropriate sensors, actuators and signal conditioning are in place, a reduction of the fatigue loads on the blades can be achieved. The results are very dependent on the control system parameters.

Simulations using actuation speeds of 10 s have been shown to reduce the airfoil displacements, although larger actuation speeds i.e. 40 s give faster response and smaller oscillation amplitudes.

Curved flaps have shown to be more aerodynamically effective than flat flaps. The former require less flap deflection angles and obtain a higher degree of displacement reduction for the same control strategy. Efforts in designing an airfoil and flap with high increase in lift per unit flap deflection can affect the results favourably by reducing the required flap actuation amplitudes.

ACKNOWLEDGMENTS

The author is grateful for the support of his MSc supervisors at DTU Jens Nørkær Sørensen and Martin O.L. Hansen and for technical assistance provided by Mac Gaunaa, Christian Bak and Thomas Buhl of Risø National Laboratory.

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