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# Microtab Dynamic Modelling for Wind Turbine Blade Load Rejection

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## Abstract

A dynamic model characterising the effect of microtab deployment on the aerodynamics of its base aerofoil is presented. The developed model predicts the transient aerodynamic coefficients consistent with the experimental and computational data reported in the literature. The proposed model is then used to carry out investigation on the effectiveness of microtabs in load alleviation and lifespan increase of wind turbine blades. Simulating a bang-bang controller, different load rejection scenarios are examined and their effect on blade lifespan is investigated. Results indicate that the range of frequencies targeted for rejection can significantly impact the blade fatigue life. Case studies are carried out to compare the predicted load alleviation amount and the blade lifespan using the developed model with those obtained by other researchers using the steady state model. It is shown that the assumption of an instantaneous aerodynamic response as used in the steady state model can lead to inaccurate results.

**Keywords:** wind turbine; microtab; blade load alleviation; blade load rejection; fatigue life; bang-bang control

## 1 Introduction

Fatigue load and flutter, as well as maintaining stiffness and minimizing mass have become of prime concern in design of wind turbine blades as the size of wind turbines increases [1, 2]. Wind turbine blades are now long so that not only does each blade see different incoming wind conditions, the incoming wind conditions vary along each blade itself. At the same time, the dynamic movement of the blade also changes the airflow conditions by dynamic interaction. These two effects create dynamic inputs to the lift and drag loading on the blade, which feed fatigue loads into the blade bending and into the power train; if these turbulence-generated loads can be reduced it will increase the life of wind turbine blades.

At the same time there is a great necessity for the development of computer modelling tools as these dynamic interactions go far beyond the simple assumptions that the long-established blade element momentum theory (BEMT) used to analyse wind turbines dynamic. More advanced models include three dimensional structures and computational fluid dynamics as well as three-dimensionally varying flow fields, however numerical simulation of such models are computationally very expensive. Hence, there is value in the development of much simpler models, extending the BEM approach to enable the potential behaviour of these development ideas to be explored at reasonable computing effort (see [3, 4]).

Within the wind energy industry, effort is being applied to passive and dynamic ways of alleviating these turbulence-generated loads. Several load alleviation/rejection techniques such as individual pitch control, microtabs, morphing aerofoils and trailing edge flaps are currently in practice or under investigation as means of reducing these loads. The individual pitch control system presents a significant capability to reduce load on blades from 1P (rotor rotational frequency) [5, 6] up to 3P [7]. The main advantage of individual pitch control systems is that since no extra sensors are required to be implanted in the blade, the blade structure remains unmodified. On the other hand, compared to other techniques, individual pitch control systems are more expensive, have higher operating energy consumption and have limited impact on load fluctuations with higher frequencies.

Trailing edge flaps are small, efficient and cheap devices acting locally along the blade span. Previous studies by Wilson et al [3] and Castaignet et al [4] have demonstrated, using a structural model combined with a BEMT code, the potential of flaps for rejecting load. Morphing aerofoils are also shown to be promising as active flow controllers. The major challenge remains to manufacture the blade structure flexible enough to morph without losing its capacity to withstand aerodynamic loads. In addition, the study of such structures requires complex aero-elastic models for control purposes [8]. A comprehensive review of the different types of active flow controller is given by Johnson et al [9].

Microtab, proposed in 2000 by Yen et al [10], due to its aerodynamic effectiveness, low energy requirement, low cost, light weight and short actuation time is another promising control surface used for regulating unsteady loads, see Figure 1. The potential of microtabs for load control was first proved numerically and experimentally by Van Dam et al [11]. Baker et al [12] carried out extensive research with microtabs installed on S809 aerofoil, addressing the issue of optimal positioning and sizing for lift generation. Their results suggest that the lower tab height should be close to the boundary layer thickness while being located near the trailing edge as this location provides a good lift/drag ratio and enough volume for the microtab to retract. Nevertheless, optimal sizing and positioning is difficult to achieve due to its dependence on geometric and aerodynamic parameters and will more often result in a trade-off of the lift/drag ratio.

Wilson et al. [13] have conducted a structural dynamic analysis in which microtabs are shown to achieve a reduction of oscillations of the root flap bending moment from 30% up to 50% for a 600KW wind turbine. Baek et al [14], using a dynamic microtab response, concluded that despite their disadvantages compared to trailing edge flaps, microtabs can still be used for reducing aerodynamic loadings. Baek and Gaunaa [15] used a binned and a proportional controller for load rejection of a five megawatt wind turbine blade once equipped with microtabs and once equipped with flaps. They showed that microtabs can reduce the load about half of the amount of reduction achieved by trailing edge flaps.

While research reported in [10], [11], [12] and [13], have greatly contributed to the proof of the concept of microtabs as effective load controlling devices, these works assume that microtab response is instantaneous leading to a steady state aerodynamic model. On the other hand, the reported studies in [14] and [15] have taken into account the dynamic of microtab response towards a more accurate modelling and analysis. However, their work is limited to the temporal response analysis only.

Due to the stochastic nature of wind, the aerodynamic loads on wind turbine blades have a wide frequency bandwidth. Using active flow control systems aiming at rejecting a specific frequency or a range of frequencies may lead to amplifying loads with other frequencies. A frequency-domain analysis is required in order to avoid cases like this when designing an active load rejection control system. This paper aims at modelling the dynamic response of microtabs to be used in the design of the controller and to analyse the microtab performance in load rejection in the frequency domain. Being focused on implementing microtab dynamic response in the controller design, in this study blades are assumed to be rigid leading to wind turbulence and microtab deployment the only parameters affecting the local flow kinematics.

At a typical microtab station, the local wind speed fluctuation, the amplitude and frequency of the blade vibration at that span location and microtab deployment status affect the local flow kinematics. For accurate evaluation of the performance of active flow control surfaces the effect of blade vibration on the flow kinematics must be taken into account (for example see [15]). However, being focused on developing and implementing microtab dynamic response in the controller design, in this study it is assumed that wind turbulence and microtab deployment are the only parameters affecting the local flow kinematics.

The rest of the paper is structured as follows: In Section 2, the methodology to obtain the microtab dynamic model from experimental/numerical data is developed. In Section 3, the system of equations representing the dynamics of microtabs is developed as to be used in design of the controller. Load rejection, microtab actuation and life increase are investigated through case studies in Sections 4 and compared to the results obtained by steady state model in Section 5. The main results are summarised in Section 6.

# 2 Microtab Dynamic Model

## 2.1 Steady State Aerodynamic Data

A microtab can take any of the three states (i) deployed upward on the suction side of the blade, (ii) deployed downward on the pressure side of the blade and (iii) neutral, where the microtab is inside the blade with no effect on the lift and drag coefficients. The steady data collected from published papers [12] and [14] and two dimensional CFD analysis [16] are used to generate steady state lookup tables. Each table relates the steady state changes in lift $\Delta C_{L,ss}$ and drag coefficients of aerofoils S800 series to the normalised microtab deployment height $\delta$ and the local angle of attack of the blade $\alpha$. Figure 2 shows the effect of microtab deployment on steady state lift coefficient.

In this figure, $h^* = h/c$ denotes the normalised maximum deployment height, $d^* = d/c$ stands for the normalised chord-wise location measured from the leading edge and $c$ is the local chord length. The deployment $0 \le \delta \le 1$ represents the deployment on the suction side (upper surface) of the aerofoil whereas $-1 \le \delta \le 0$ represents the deployment on the pressure side (lower surface) of the aerofoil. The change in steady state lift due to microtab deployment, $\Delta C_{L,ss}$, is a function of the microtab deployment height $\delta$ and the local blade angle of attack $\alpha$. The $\Delta C_{L,ss}(\delta,\alpha)$ lookup tables can be fitted to a surface using Equations 1 to 3.

$$\Delta C_{Lss} = K_1\delta^2 + K_2\delta \tag{1}$$

in which,

$$K_1 = a_1\alpha^2 + a_2\alpha + a_3 \tag{2}$$
$$K_2 = a_4\alpha^2 + a_5\alpha + a_6, \tag{3}$$

and $a_1$ to $a_6$ are constants obtained via curve fitting . The surface given using Equation 1 has a root mean square error of about $4.8\times10^{-3}$ for aerofoil S809.

Having $\Delta C_{L,ss}$, the dynamic lift coefficient $\Delta C_L$ is calculated using the flow dynamic model detailed in Section 2.2 (see Figure 3).

## 2.2 Flow Dynamic Model

The dynamic characteristics of microtab include deployment time and the microtab deployment speed limit. The aerodynamic response due to microtab actuation can be expressed as a function of the non-dimensional time defined by:

$$T = Vt / c \tag{4}$$

in which, $V$ stands for the local relative velocity (combination of tangential velocity due to blade rotation and wind speed in $m/s$), $c$ is the local chord length ($m$) and $t$ is the real time ($s$). Table 1 shows the temporal response of microtabs with deployment height of $h^* = 1.1\%$, installed on S809 aerofoil, at a free stream Mach number of 0.25, a Reynolds number of 1 million and a local relative velocity of 85m/s [17].

Table 1-Temporal response of microtab [17]

| $T_{deploy}$ | $C_{L,adverse}$ | $\lvert C_{L,adverse} / C_{L,retract} \rvert$ | $T_{delay}$ | $T_{50\%}$ |
|---|---|---|---|---|
| 1 | -0.00978 | 0.0895 | 0.836 | 1.7 |
| 2 | -0.00625 | 0.0572 | 1.304 | 2.34 |
| 4 | -0.00341 | 0.0312 | 2.078 | 3.76 |

According to references [17] and [14], the lift coefficient is subjected to an adverse response as well as a delay due to the formation of a vortex behind the tab whereas the drag coefficient increased significantly over its steady state value. The aerodynamic response of microtab deployment on lift and drag is remarkably rapid, with a significant change occurring during the tab deployment. The drag coefficient increases more than 90% of its steady state value immediately with tab deployment ($T = 1$) before asymptotically approaching the mean steady state value at a noticeably slower rate. The lift rapidly climbs over 50% of its mean steady state value quickly after tab deployment ($T = 1.5$) before rising asymptotically to the mean steady state lift at a much slower rate. Based on the investigation of Chow and van Dam [17], the mean steady state lift, $\Delta C_{L,ss}$ , is assumed to be reached around $30T_{deploy}$ ($T_{ss} \approx 30T_{deploy}$). Additionally, Chow and van Dam [17] demonstrated that the inverse response and the delay observed in microtab dynamic have no significant impact on load rejection due to their short existence.

In view of the above, in developing the dynamic model for the microtab the following assumptions are made. (i) The inverse response and delay are neglected. (ii) The normalised response of microtab is insensitive to variation of high Reynolds numbers (above $1\times10^6$). This assumption is based on the previous work of Baek and Gaunaa [15] and Chow and van Dam [17]. (iii) The dynamics of microtab deploying on the upper and lower surface are assumed to be equivalent.

As explained above, Baek and Gaunaa [15] and Chow and van Dam [17] have already investigated microtab aerodynamic response, however, no mathematical model suitable for control purpose was proposed in their respective works. In this paper, a dynamic model for microtabs is developed based on their results. The non-dimensional deployment time has been taken as $T = 1$ because it will ensure the fastest response and consequently allow the counteraction of higher frequencies. The adverse pressure is neglected as it will be over shortly after the full microtab deployment (fast dynamic) and does not affect slower dynamics. In terms of frequency, the adverse pressure gradient varies at a higher frequency compared to the frequency of the loads to be rejected. Hence, it can be reasonably neglected without loss of accuracy. In a similar manner the delay can be neglected. The second and third assumptions are made mainly due to the lack of experimental data, however, comparing the results of the investigations reported in Baek and Gaunaa [15] and Chow and van Dam [17], one can notice similar normalised aerodynamic response under different Reynolds numbers. This is mainly due to the fact that the aerodynamic coefficients of the modern wind turbine blade aerofoils are less sensitive to the variation of Reynolds number.

Considering the assumptions made above, the lift dynamic is approximated using a second order model expressed in the Laplace transform by:

$$\frac{\Delta C_L}{\Delta C_{Lss}} = \frac{c_1 s + c_2}{1 + \frac{2\xi}{w_n} s + \frac{1}{w_n^2} s^2} \tag{5}$$

The coefficients $c_1$, $c_2$, $w_n$ and $\xi$ as explained later in this section, are calculated such that the model fits the dynamic response of experimental data presented in Table 1. The microtab response features two dynamics, one being much faster than the other. Consequently, one can split the microtab response into two distinct dynamics without loss of accuracy: a fast transient response occurring at the same time and shortly after the deployment of microtabs and a slow response starting soon after the deployment as shown in Figure 4.

In the fast dynamic region, $\Delta C_L$ increases sharply half way to the steady state value whereas in the slow dynamic region it varies with a much slower rate to reach the steady state value. Moreover, since no outreaching or oscillations are observed in the response of $\Delta C_L$, the second order model of Equation 5 can be broken down to the summation of two single orders as in Equation 6.

$$\frac{\Delta C_L}{\Delta C_{Lss}} = \frac{c_1 s + c_2}{1 + b_2 s + b_1 s^2} = \frac{c_3}{1 + \tau_f s} + \frac{c_4}{1 + \tau_s s} \tag{6}$$

where $\tau_f$ and $c_3$ are the parameters representing the fast dynamic and $\tau_s$ and $c_4$ are the parameters for the slow dynamic. It can be seen in Figure 4, both dynamics equally contribute to the total response, hence $c_3 = c_4 = 0.5$. The constant time parameters $\tau_i$ are then calculated based on $T_{deploy}$, the response time of the system from Table 1 and on the fact that the response of a 1st order model reaches 90% of the steady state value around $3\tau$.

The procedure to calculate the dynamic model parameters for slow dynamic region is detailed in Algorithm 1. In this algorithm a pattern search method is used to minimise the difference between the experimental data of Table 1 and the predicted data by the model through identifying the best coefficients. The search stops when the difference between the modelled and reported experimental $\Delta C_L$ data is less than a tolerance $\varepsilon$, $\left|\Delta C_{L,model} - \Delta C_{L,\exp}\right| \le \varepsilon$.

**Algorithm 1**-Dynamic model identification

Given: $T_{deploy}$, the local relative velocity $V$ and the local chord length $c$

Step 1- Use Table 1 to read off $T_{50\%}$.

Step 2- Calculate real times: $t_{50\%} = cT_{50\%} / V$, $t_{ss} = cT_{ss} / V$; ($T_{ss} = 30T_{deploy}$)

Step 3- Assign initial values for $\tau_f$ and $\tau_s$

Step 4- Calculate: $b_1 = \tau_f \tau_s$, $b_2 = \tau_f + \tau_s$, $c_1 = 0.5(\tau_f + \tau_s)$, $c_2 = 1$, and $\Delta C_L = \Delta C_{L,ss} \frac{c_1 s + c_2}{1 + b_2 s + b_1 s^2}$

Step 5- Calculate $\left|\Delta C_{L,\mathrm{model}} - \Delta C_{L,\exp}\right|$; If $\left|\Delta C_{L,\mathrm{model}} - \Delta C_{L,\exp}\right| \le \varepsilon$ End; otherwise: employing pattern search find new values for time constants and go back to Step 4.

It was found that initial values $\tau_f = t_{50\%}/3$ and $\tau_s = (t_{ss} - t_{50\%})/3$ lead to the fastest convergence. In this study a tolerance $\varepsilon = 0.01$ was used.

Figure 5 shows the microtab dynamic response model, obtained by Algorithm 1, compared with the experimental data of [17] where the deployment of microtab is represented by a first order ordinary differential equation such that $T_{deploy} = 1$.

Although the microtab temporal response neglects the short transient dynamic, in view of Figure 5 it can be observed that results show good agreement with previously reported experimental data. Furthermore, the model procedure is flexible and can be easily modified in order to fit new experimental data.

Figure 6 shows a typical microtab deployment in response to wind turbulence and its dynamic response.

Similarities can be observed between the microtab model proposed in this paper and the dynamic model developed by Frederick et al [18] for the actuation of small trailing-edge flaps. However, the microflap model is based on the assumptions of small angle of attack and thin aerofoil, leading to a globally linear model. On the other hand, the microtab model is based on experimental/numerical data where aerofoil thickness and angle of attack are taken into account, leading to a non-linear model (see Eq.1).

## 3 Microtab Control

Combining the curve fitting from the steady data (Eq. 1) with the flow dynamic model (Eq. 6), the response of microtab deployment $\delta$ on the dynamic lift coefficient $\Delta C_L$ can then be written in the form of the nonlinear system of Equations 7 to 10:

$$\dot{x}(t) = fx(t) + gu(t) \tag{7}$$

where,

$$x^T = \begin{bmatrix} C_L & \dot{C}_L - r_1 C_{L\,ss} & \delta \end{bmatrix} \tag{8}$$

$$g^T = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix} \tag{9}$$

$$f = \begin{bmatrix} 0 & 1 & r_1(K_1 x_3 + K_2) \\ -m_2 & -m_1 & \eta(K_1 x_3 + K_2) \\ 0 & 0 & -1/\tau \end{bmatrix} \tag{10}$$

Parameter $x(t)$ denotes the state vector and $u(t)$ is the control vector (a scalar in this case). The parameter $\tau$ denotes the time constant for microtab actuation (Figures 5 and 6). Having the system model identified by using Algorithm 1, constants $c_1, c_2, b_1$ and $b_2$ can be used to find $m_1, m_2, r_1, r_2$ and $\eta$ as follows

$$m_1 = b_2 / b_1 \tag{11}$$

$$m_2 = 1 / b_1 \tag{12}$$

$$r_1 = c_1 / b_1 \tag{13}$$

$$r_2 = c_2 / b_1 \tag{14}$$

$$\eta = -m_1 r_1 + r_2 \tag{15}$$

The system is exponentially stable, controllable, and partially observable since no sensor directly measures the lift coefficient. The non-observed part of the state vector is estimated using the dynamic flow model.

A bang-bang control with the following control law is implemented:

$$U(t) = sign(M_t - M_m) U_{sat} \tag{16}$$

In the above equation $M_t$ denotes the target bending moment at the root of the blade, in which those variations with certain frequencies (targeted to be rejected) are filtered. Parameter $M_m$ is the measured bending moment at the root of the blade and $U_{sat}$ stands for the maximum control value corresponding to the maximum deployment height. An ideal controller ensures the full rejection of loads with targeted frequencies and a bending moment of $M_t$.

The bang-bang control law employed in this study covers cases $u_j = 0$ standing for no actuation ($\delta_j = 0$), $u_j = +U_{sat,j}$ standing for maximum deployment on the upper surface ($\delta_j = +1$) and $u_j = -U_{sat,j}$ standing for maximum deployment on the lower surface of the blade ($\delta_j = -1$).

## 4 Microtab in Practice-Wind Turbine Performance Simulation

The wind turbine aerodynamic performance is obtained using a modified version of WTAero, a blade element momentum theory-based aerodynamic code [20]. In this modified version, the unsteady flow simulation is carried out using the frozen wake model [21]. The dynamic stall is also taken into account based on the work of Larsen [22]. The different unsteady wind fields used for the wind turbine simulation have been generated using TurbSim [23]. For each case study, the controller is designed using the method explained in the previous section, and is implemented into a MATLAB code linked to the modified WTAero. Employing Equations 7 and 16, at each time step ($\Delta t = 0.01s$), the simulated controller calculates the microtab deployment height and accordingly the modified WTAero calculates the aerodynamic performance of wind turbine including the bending moment in the blade.

The system of equations represents only one microtab. However, in practice blades are equipped with a string of microtabs distributed over a span of $S_{MT}$ as shown in Figure 7. The string of microtabs is divided into $n$ segments. Microtabs located on the same segment actuate simultaneously acting as a single unit, while each segment of microtabs operates independently.

The wind turbine selected for study is the constant-speed stall-regulated AWT-27, featuring 2 blades spanning a diameter of 27.5m and a rated power of 300KW. In simulation, it is assumed that each blade is equipped with nine sections of microtabs distributed over 2.83m of the blade span from 10 to 12.83m. Microtabs have a maximum deployment height of 1.1% of the local chord and are located at 85% and 95% of the chord from the leading edge on the blade suction and pressure sides respectively. Moreover, microtabs are assumed to be deployable only in on/off positions. Each blade is assumed to be equipped with a conventional five holes Pitot tube located at the centre of the blade span equipped with microtabs. The local wind speed for nearby microtab positions are estimated based on the change in the tangential velocity. The axial velocity is assumed to be equal to the one measured at the Pitot location whereas the tangential velocity varies linearly along the blade span. As the length of the string of microtabs increases multiple Pitot tubes can be used (e.g. see [4]).

### 4.1 Load Rejection-Targeting a Range of Frequencies

In the first case study, the controller is designed to reject loads with frequencies in the range of 2P to 5P, equivalent to 1.777 to 4.4Hz (corresponding to the rotor speed of 53.3 rpm) produced by a 180-second wind flow field with a mean value of 8m/s and a turbulence intensity of type B. Results of simulation are shown in Figure 8. Representing the controlled bending moment at the root of the blade by two components, the mean value $\overline{M}_c$ and the variable part $\hat{M}_c$ ($M_c = \overline{M}_c + \hat{M}_c$), Figure 8.a shows the spectral density of the variable part of the controlled bending moment. In this figure, the peaks correspond to the $nP$ frequencies; $n \in \{0,1,2,3,4,5\}$. Figure 8.b shows the spectral density of the load alleviation achieved when employing microtabs. In Figure 8.b the trend line, shown in yellow, is generated by averaging the fluctuations over 0.1 Hz spans.

It should be noted that the rejection of the 1P frequencies is not due to a filtering issue but because when a given range of frequencies is targeted, the control naturally tends to reduce nearby lower frequencies as well. Quantitative results extract from Figure 8 are given in Table 2.

Table 2-Load alleviation using microtabs targeting 2P-5P (based on trend lines).

| Frequency | 1P | 2P | 3P | 4P | 5P |
|---|---|---|---|---|---|
| Load reduction at V=8m/s (Bang-Bang controller) | 22% | 46% | 38% | 35% | 26% |

In Figure 8.b, it can be observed that both reductions at 1P and 2P frequencies have similar magnitude whereas in terms of the percentage (Table 2), the 2P reduction is twice as the 1P reduction. Results in Table 2 also show that when a large range of frequency is chosen to be rejected, the control effort is focused in the lowest targeted frequency (2P) before progressively reducing until the last values of the range (5P).

Figure 9 shows a typical portion of the time history of $M$ the total bending moment at the root of the blade, microtab deployment and the spectral density of microtabs actuation over 180 seconds of simulation. Figure 9.a shows the blade bending moment when no controller is in place $M_0$, the target load $M_t$ (corresponding to the case of employing an ideal controller leading to perfect filtering of targeted frequencies) and the achieved load $M_c$ as a result of microtab control (using presented dynamic model). Figure 9.b shows a typical microtabs deployment time history. The spectral density of the actuation of the same microtab over 180 seconds is shown in Figure 9.c where the trend line is obtained by averaging the fluctuations over 0.1 Hz spans. This figure shows that microtabs actuation under bang-bang control is subjected to high frequency variation, possibly leading to actuator damage [14]. Results suggest that other microtab controllers should be investigated to avoid high frequency actuation.

### 4.2 Load Rejection-Targeting a Specific Frequency

Flutter delay techniques normally target a specific frequency (e.g. first natural frequency) and attempt to reject loads with that frequency to avoid dynamic aeroelastic instability. However, it is well-known that targeting a specific frequency may have adverse effect on adjacent frequencies. To investigate the performance of microtabs in targeting a specific frequency, loads with frequencies of 2P are selected for rejection and the results are compared with the case of load rejection when targeting frequencies in the range of 2P-5P.

Figure 10 compares the efficiency of load rejection depending on the range of frequency chosen to be rejected. Figures 10.a and 10.b show load alleviation spectral density when targeting 2P and 2P-5P frequencies respectively whereas Figure 10.c compares the performance of microtab when targeting different ranges of frequencies. Figure 10.c shows $\Delta A$, the difference between the amount of load alleviation when targeting 2P frequencies $A_{2P}$ , and $A_{2P-5P}$ the amount of load alleviation when targeting 2P-5P frequencies ( $\Delta A = A_{2P} - A_{2P-5P}$ ).With reference to this figure, it can be observed that targeting a specific frequency (2P) has adverse effect on the adjacent higher frequencies. On the other hand, when targeting larger ranges (2P-5P) the rejection is efficient over the entire range. In both cases rejection of 2P frequency loads are more or less similar whereas the case of 2P-5P shows significantly better results for 3P-5P.

In this figure and the subsequent figure all trend lines are based on the averaged values over 0.1 Hz spans.

Table 3 summarises the results of similar simulations carried out for various targeted ranges at different mean wind speeds.

Table 3- Effects of the range of targeted frequencies on the results

| | | Range of targeted frequencies | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1P-2P | 1P-3P | 1P-5P | 2P-5P | 3P-5P | 1P | 2P |
| Wind speed mean value (m/s) | 15 | M | M | L | L | L | H | H |
| | 12 | M | M | L | L | L | H | H |
| | 10 | M | M | L | L | L | H | H |
| | 8 | M | M | M | L | L | H | H |
| | 5 | M | M | M | M | M | H | H |

H: High adverse effect on adjacent higher frequencies
M: Medium adverse effect on adjacent higher frequencies
L: Low adverse effect on adjacent higher frequencies

It can be observed that as the range of the targeted frequencies decreases, the impact on the adjacent higher frequencies increases. When targeting a particular frequency, the controller simply loses its ability to reject other frequencies. One can also notice the dependency of the effect of load rejection on adjacent higher frequencies to the mean wind speed that can be explained as follows. The effect of a deployed microtab on lift and drag coefficients reduces drastically at high attack angles. Recalling that the simulated wind turbine is stall regulated, as the wind speed increases the outer parts of the blade start entering the stall regime and consequently more microtabs will be operating with minimal effect on the aerodynamic forces.

## 4.3 Lifespan Calculation

This section aims at demonstration of the efficiency of microtabs in increasing the life of wind turbine blades. The effect of load alleviation on the fatigue life of blades are estimated and compared for two different targeted frequencies. The software tool Mlife [24] based on IEC 61400 standards [25] is used to estimate the blade lifespan. Load data are broken down into individual cycles using the rainflow counting technique and the fatigue damage is assumed to be accumulated linearly according to Palmgren-Miner’s rule:

$$D = \sum_k \frac{n_k}{N_k\left(L_k^{RF}\right)} \tag{17}$$

where $N_k$ represents the number of cycles to failure, $n_k$ is the cycle count of the k-th frequency and $L_k^{RF}$ stands for the k-th cycle load range about a fixed mean value. The damage accumulated over time causes failure when $D \geq 1$. According to Mlife, to construct the S-N curve an ultimate load, calculated by simulation of an extreme turbulent event occurring during normal operating conditions is required. This ultimate load represents the $10^0 = 1$ cycle load on the curve. The extreme turbulent event selected is a gust with a return of 50-years at a mean wind speed of 25m/s (cut out wind speed). According to IEC standards, a safety factor of 1.35 is then applied to obtain the ultimate design load. Eleven load samples from 5 to 25m/s with increments of 2 m/s and a Rayleigh probability density function for wind distribution are then used to estimate blades lifespan. Life estimation results are presented in Table 4.

Table 4- Fatigue Lifespan Estimation

| | No Control | Targeted Frequency 2P | Targeted Frequency range 2P-5P |
|---|---|---|---|
| Estimated lifespan (Years) | 24.8 | 29.92 | 33.48 |
| Lifespan increase (%) | - | 20.6 | 35 |

Life estimation results indicate that the choice of the targeted range of frequencies can significantly impact the fatigue life and that targeting larger range of frequencies is more effective.

# 5 The Performance of the Presented Dynamic Model versus Steady State Model

Using the developed dynamic model and the steady state model based on instantaneous response assumption used by other researchers [3,13], the amount of achieved load alleviation are obtained and compared together. In calculations, employing TurbSim, two 180-second wind speed variations with mean values of 8 and 12m/s with turbulence intensity of type B are used. Figure 11 shows the spectral density of $\Delta A$, the difference between the amount of load alleviation when using the developed dynamic model $A_D$, and $A_{SS}$ the amount of load alleviation when using the simplified steady state model ($\Delta A = A_D - A_{SS}$), where both controllers target 2P-5P frequencies for rejection.

Evidently, assuming an instantaneous response in the simplified steady state model leads to inaccurate results within the targeted range (2P-5P) as well as adjacent frequencies (1P). Table 5 shows the error in load alleviation prediction when using the simplified steady state model. In this table negative values stand for over prediction of the amount of load alleviation when using steady state model.

Table 5- Error in prediction of load alleviation when assuming an instantaneous response in steady state model (Based on trend lines)-Targeted frequencies: 2P-5P

| | 1P | 2P | 3P | 4P | 5P |
|---|---|---|---|---|---|
| V= 8m/s | 2.58% | -0.79 % | -4.36% | -7.95 % | -9.71 % |

| | | | | | |
|---|---|---|---|---|---|
| V= 12m/s | 2.69 % | -1.32 % | -4.44 % | -9.94 % | -11.90 % |

The lifespan is also estimated using the two models and the results are shown in Table 6.

Table 6- Blade lifespan estimation-Targeted frequencies: 2P-5P

| | No Control | Present Dynamic Control Model | Steady State Control Model |
|---|---|---|---|
| Estimated life (Years) | 24.8 | 33.48 | 28.4 |
| Lifespan increase (%) | - | 35 | 14.5 |

Results of Table 6 show that using simplified steady state model also leads to inaccurate results with an error of about 20.5% in estimating the lifespan. This under-prediction is partly due to under prediction of alleviated loads with 1P frequency and partly due to under-prediction of alleviated loads with high frequencies (above about 25P), as shown in Figure 12. In this figure the trend line shows the values averaged over 0.4 Hz spans.

## 6 Summary and Concluding Remarks

Several research works have been published reporting the potential and capability of microtabs in blade load alleviation. Those focused on numerical simulation of wind turbine aerodynamic performance in response to the microtab actuations are based on a steady state flow model (e.g. see [3] and [13]). Moreover, the frequency response of blade loadings due to microtab control was not investigated. In the present study, the experimental results published recently are used to develop a dynamic flow model in response to microtab actuation, which is also suitable for control purposes. This dynamic model is used to design a bang-bang controller to reject loads with various ranges of frequencies.

Using the dynamic model developed in this paper, the capability of microtabs in rejecting various ranges of loads and blade lifespan increase was confirmed. Lifespan estimation results also indicate that the choice of the targeted range of frequencies can impact the fatigue life significantly and that targeting larger range of frequencies is more effective.

It was also shown that using simplified steady state flow model can lead to inaccurate results in the form of under- and over-prediction.

The bang-bang controller was shown to be capable of rejecting loads with frequencies up to 5P (4.4Hz for this case study). However, actuators are subjected to high frequency variations making this type of controller unsuitable for real life applications, where the reliability and lifespan are as important as the performance. Further investigation is required to examine the performance and capabilities of other types of controllers such as linear-quadratic and sliding mode in controlling microtabs.

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