Computational Investigations of Small Deploying Tabs and Flaps for Aerodynamic Load Control

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The cost of wind-generated electricity can be reduced by mitigating fatigue loads acting on the blades of wind turbine rotors. One way to accomplish this is with active aerodynamic load control devices that supplement the load control obtainable with current full-span pitch control. Techniques to actively mitigate blade loads that are being considered include individual blade pitch control, trailing-edge flaps, and other much smaller trailing-edge devices such as microtabs and microflaps. The focus of this paper is on the latter aerodynamic devices, their time-dependent effect on sectional lift, drag, and pitching moment, and their effectiveness in mitigating high frequency loads on the wind turbine. Although these small devices show promise for this application, significant challenges must be overcome before they can be demonstrated to be a viable, cost-effective technology.

1. Introduction

Today, as energy costs remain high and concern regarding the impact of greenhouse emissions continues to climb, wind energy has begun to move into large-scale implementation. With apparently bigger resulting in lower cost of energy, new wind turbines have grown tremendously in size with many modern turbines now having rotor diameters greater than 80 meters. However, with rotor power increasing with the square of the diameter and rotor mass potentially increasing with diameter cubed (square-cube law), design work has focused on undercutting the square-cube relationship by applying lighter structures which have made the new longer blades more flexible. In turn, this has made blade fatigue and tip deflection critical issues in new wind turbine design. Therefore, new technologies are necessary to expand this design envelope to withstand the fatigue cycles and tip deflections experienced during extreme gusts or high wind conditions. Active load control is one of these avenues that researchers have pursued for wind turbine applications [1-10].

With such a need, many devices have been proposed by other researchers to meet these requirements. Although the sensor and control systems have become realistic, much of the work on active load control devices has focused on systems that must still overcome many other technological hurdles and potentially impractical large energy requirements. Some of the proposed devices include: surface blowing, surface suction, wing morphing, electro-discharge, active flaps, and trailing-edge devices.
One of the more promising devices in terms of mechanical simplicity, low energy requirements, and effectiveness is the microtab concept proposed in 2000 by Yen et al [11]. Microtab devices have been proposed as a viable and effective concept for active load control applications. This concept involves small tabs that are placed near the trailing edge of an airfoil and deploy approximately normal to the airfoil surface. These microtabs have a deployment height on the order of the boundary-layer thickness. The presence of the tabs changes the sectional camber and the trailing-edge flow conditions as depicted in Fig. 1, thereby affecting the aerodynamic characteristics of the section. Lower (pressure) surface tabs increase camber and generate additional lift, while upper (suction) surface tabs reduce lift. It has also been shown that the lift augmentation or reduction is almost a constant effect across all pre-stall angles of attack (and, to some extent, the stalled region as well). The engineering viability of these devices can be attributable to their mechanical simplicity and minimal structural intrusiveness.

Yen-Nakafuji et al [11,12] performed much of the initial development work for the microtab concept. She and her co-researchers conducted both computational and wind-tunnel studies on microtabs on the lower surface of the GU25-5(11)8 airfoil [13]. In addition to 2-D (infinite span models) they also looked at microtabs in a 3-D sense with finite widths and gaps. The promise and benefits of microtabs in terms of lift augmentation without significant drag penalties were immediately apparent from her work. Standish [14] continued this work performing very comprehensive 2-D computational studies examining tab height and tab location on the upper and lower surfaces of the S809 [15] and the GU25-5(11)8 airfoils [13]. General findings were along the same lines in terms of behavior as a Gurney flap configuration. Optimal tab height was again found to be on the order of the boundary layer thickness. An optimal location in terms of airfoil lift and drag and volume to retract the device was found to be at approximately 95% of chord. Standish et al [16] also looked at higher Mach numbers for rotorcraft applications and found similar microtab effectiveness. Baker et al [17,18] conducted a series of experimental studies in the wind tunnel validating the results and trends from Standish’s work with microtabs on the S809 airfoil. Mayda et al [19] performed computational investigations into the 3-D effects of microtabs by modeling finite width microtabs on semi-infinite wing, showing the reduced tab effectiveness as gap size increased.

The combination of computational studies and experimental validation has provided confidence in understanding the behavior of microtabs. It has clearly been shown that microtabs provide the aerodynamic effects necessary for an active load control device with no foreseeable technological barriers in the success of a microtab based load control system. In order to implement these devices and to develop a functioning control system, the unsteady behavior and any potential nonlinearities must first be understood. However, until recently, much of the work focused on the steady state behavior of the microtabs. The scope of the current work is to compare the transient behavior of deploying microtabs against that of deploying microflaps on the symmetric NACA 0012 airfoil. This study will use much of the same methodology presented in previously presented studies by Chow et al [20,21].
2. Computational Method

2.1. Flow Solver
OVERFLOW2 is a numerical simulation method that solves the compressible Reynolds-averaged Navier-Stokes equations on structured, overset grids [22]. With its multi- and moving-body capabilities, OVERFLOW2 is particularly well suited for this study. As flow solver, OVERFLOW2 is also very robust and comprehensive, allowing for the selection from a variety of numerical schemes, turbulence models, boundary conditions, and time advancement schemes [23]. Although various numerical methods are available in OVERFLOW2, all calculations are performed with central difference Euler terms and a Beam-Warming pentadiagonal scheme [24]. Several one- and two-equation turbulence models are also available, but this study is limited to Menter’s SST $k-\omega$ model [25]. All solid boundaries are treated as viscous walls, and all calculations are performed fully turbulent. The unsteady calculations are performed with second-order accuracy in time and with dual-time stepping [26,27].

2.2. Computational Meshes
The Chimera overset structured grid scheme is employed to model the computational flow domain. This approach allows geometrically complex multi-body configurations to be constructed from sets of relatively simple overlapping body-fitted grids. The near-body computational grid is generated with Chimera Grid Tools (CGT) 1.9 [28]. The CGT package contains independent grid generation, manipulation, visualization and diagnosis tools that can be run in batch mode under the OVERGRID graphical interface [29]. The Chimera overset scheme is also well suited for moving body applications because body fitted grids need only to be reconnected when the bodies are moved, rather than being regenerated. Regular XML input files are used to specify the prescribed motion of the bodies [30]. As the bodies move in the computational domain, surrounding grids are quickly and efficiently cut using Meakin’s object X-Ray method [31] between each solution frame. Domain connectivity is also performed automatically by OVERFLOW2 using a non-conservative interpolation between overlapping grids. All body-fitted grids are generated with a wall spacing of approximately $y^+\approx0.5$.

Fig. 2  Near-body grid system for airfoil with deploying tab.

2.2.1. Microtab. For this study the dynamic microtab is built on a symmetric NACA 0012 airfoil. The grid topology is described by Chow & van Dam [20]. Figure 2 shows some of the details of the microtab grid system used here. Recently a different meshing methodology was developed for a study of the dynamic tab effect on a cambered airfoil [31]. The latter is more efficient because it allows the tab to grow from the surface of the airfoil as it deploys, thereby eliminating the need to mesh the tab
cavity. The tab cavity does not have any noticeable effect on the flow development about the airfoil and the results with the new meshing technique were nearly identical to those presented here.

2.2.2. **Microflap**. The main airfoil is a modified NACA 0012 with a semi-circular cove truncating the trailing edge. With a fairly blunt trailing edge, a 235×99 O-type grid was used instead of a C-grid. The O-grid extends approximately 1.5c from the airfoil surface. The flap itself is constructed from the aft 1.165%c of the NACA 0012 and a semi-circular arc with diameter 0.330%c. The resulting flap chord length is 1.495%c with a maximum thickness of 0.330%c. A 119×54 O-grid extending approximately 0.20%c away from the surface is also generated for the flap. Again, both airfoil and flap grids used the standard $y^+\approx0.5$ as the normal wall spacing for a chord (c) Reynolds number (Re) of $1\times10^6$. The flap grid in both retracted and fully deployed positions after hole cutting is shown in Fig. 3. As for the tab study, the off-body Cartesian grids are continued until 50c away from the airfoil surface.

![Microflap with body-fitted O-grid in retracted and fully deployed positions](image)

2.3. **Dynamic Motion**

The deploying microtabs are deployed with the following ramp-like motion:

$$h(T) = h_o + \frac{h_{tab}}{2} \left[ 1 - \cos \left( \pi \left( \frac{T - T_o}{T_1 - T_o} \right) \right) \right]$$

where $T=U_{\infty}t/c$ is the nondimensional time, $T_o$ is the deployment onset time, $T_1$ is the deployment completion time, $T_{\text{deploy}}=T_1-T_o$ is the deployment time, $h_{\text{tab}}$ is the fully deployed tab height, and $h_o$ is the initial tab position. This deployment schedule leads to a simple sinusoidal velocity profile for the tab:

$$v(T) = \frac{h_{\text{tab}}}{2} \frac{\pi}{T_1 - T_o} \sin \left( \pi \left( \frac{T - T_o}{T_1 - T_o} \right) \right)$$

In order to maintain similarity with the baseline microtab deployment, the same sinusoidal ramp function was used to deploy the microflap. The resulting flap velocity profile is:

$$\omega(T) = \frac{\theta_{\text{deploy}}}{2} \frac{\pi}{T_1 - T_o} \sin \left( \pi \left( \frac{T - T_o}{T_1 - T_o} \right) \right)$$

where $\omega$ is the angular velocity, $\theta_{\text{deploy}}$ is the maximum deployment angle (90°), with the deployment time being $T_{\text{deploy}}=T_1-T_o$. The flap hinge point is selected to be at 0.98835c on the symmetric chord line. Fully deployed, this results in an flap height measured from the airfoil surface that is identical to that of the tab (1.0%c).

2.4. **Validation**

Time accurate experimental data for airfoils with fast control surfaces are difficult to come by, with the data set acquired by Yeung et al [33] for an airfoil with a rapidly deploying spoiler being one of
the few available. This data set was used to validate OVERFLOW2 for the deploying tab and flap study. Chow [20,21] presents the comparison of the computed and measured aerodynamic response to a deploying upper surface spoiler (10%c with hinge-point at 0.70c) on a NACA 0012 airfoil at a chord Reynolds number of 350,000. The spoiler was deployed in $T_{\text{deploy}}=4.4$ and the results show generally good agreement between the computed and measured lift, drag, and pitching moment results. More detailed validation results including spatial and temporal convergence histories are presented in [20,21].

3. Results

3.1. Comparison of Transient Aerodynamic Characteristics

The transient aerodynamic response of the microtab and the microflap are compared in Fig. 4. Flow visualization in the form of pressure contours and instantaneous streamlines during deployment are shown for the flap in Fig. 5. The initial lift and pitching moment response for the flap differs from the tab. As the flap deploys, airfoil lift almost immediately begins to increase. Similarly, airfoil pitching moment drops, also without any adverse behavior. However, as the tab deploys, the lift and pitching moment show a slightly delayed adverse response. This is no surprise, since from the microtab study [20,21] the initial delay in lift and moment response is due to the rapid build up and growth of the vortex downstream of the tab. For a trailing-edge device such as the flap, the Kutta condition is altered immediately as the device is deployed (Fig. 5i). The drag response for the flap case is very similarly to the tab drag development since the increase is primarily a function of pressure drag on the tab/flap.

From the comparison of the response histories it is also clear that the faster response for the flap is only present during the initial deployment phase. Post deployment, the qualitative temporal responses of the two devices are essentially identical. In terms of the aerodynamic coefficients, the two devices behave very similarly as well. The lift, drag, and pitching moment coefficients for the airfoil with flap all exhibit larger harmonic shedding oscillations at a higher frequency which is consistent with the behavior of the static geometry comparisons. Because of the more aft location, the increments in lift, drag, and pitching moment for the microflap are slightly larger than the microtab. This matches earlier wind-tunnel based observations for static tabs [17].

Again, the slow asymptotic change of the lift towards the steady state can be approximated closely by the Wagner indicial lift function [34,35]. This shows that the global response is not governed by near-body behavior; once the deployment of the flap or tab is completed, the mean solution development becomes a convection driven process.

3.2 Flap Deployment Time Study

The transient aerodynamic responses for various flap deployment times are shown in Fig. 6. The initial transient lift response is clearly accelerated by the short deployment times of $T_{\text{deploy}}=0.25$ and 0.50 compared to the baseline deployment time of unity. Again, this rate increase is only present during the flap deployment phase. After the deployment completion, at $T=2$, the resulting lift rise-time is only shifted by an interval equal to the deployment time differences. However, for the fastest deployment time examined here ($T_{\text{deploy}}=0.25$) a slight overshoot in both the moment and drag can be observed as the flap is fully deployed.

The lift response characteristics are summarized and compared in Table 1. In this table the effect of deployment time on peak adverse lift ($C_{L,\text{adverse}}$), delay time ($T_{\text{delay}}$), and rise time ($T_{90\%}$) is presented for the two configurations. Here $C_{L,\text{adverse}}$ defines the maximum adverse lift coefficient (i.e., lift opposite to the desired effect) and $T_{\text{delay}}$ defines the corresponding nondimensional time. The rise time, $T_{90\%}$, defines the nondimensional time to 50% of the asymptotic mean lift coefficient ($C_{L,\infty}/2$) where $C_{L,\infty}=0.208$ for the tab and $C_{L,\infty}=0.232$ for the flap configuration. As expected the shorter tab deployment times generate a larger adverse response in lift than longer deployment times [20]. Although $T_{\text{delay}}$ and $T_{90\%}$ occur earlier with faster tab deployment, when normalized by deployment...
time, the trend is reversed. With tab deployment times of $T_{\text{deploy}}=2.0$, the adverse response is nearly negligible. However the most interesting finding from this study is that even with all the different transient effects during tab/flap deployment, at $T=2$ all the cases reach approximately the same aerodynamic state in terms of lift, drag, and pitching moment. For a wind turbine blade with a chord length of 0.35 m in the tip region and an airspeed of 70 m/s, $T_{\text{deploy}}=2.0$ corresponds to $t_{\text{deploy}}=0.01$ sec.

Table 1 Effect of deployment time on peak adverse lift, delay time, and rise time for microtab and microflap configuration

| $T_{\text{deploy}}$ | Configuration | $C_{L,\text{adverse}}$ | $T_{\text{delay}}$ | $T_{\text{delay}}/T_{\text{deploy}}$ | $T_{50}$ | $T_{50}/T_{\text{deploy}}$ |
|---------------------|---------------|------------------------|-------------------|-----------------------------------|---------|--------------------------|
| 0.25                | Tab           | -0.0164                | 0.303             | 1.212                             | 0.647   | 2.589                    |
| 0.25                | Flap          | 0                      | 0                 | 0                                 | 0.362   | 1.448                    |
| 0.50                | Tab           | -0.0156                | 0.412             | 0.824                             | 0.724   | 1.447                    |
| 0.50                | Flap          | 0                      | 0                 | 0                                 | 0.497   | 0.994                    |
| 1.00                | Tab           | -0.0126                | 0.593             | 0.593                             | 0.946   | 0.946                    |
| 1.00                | Flap          | 0                      | 0                 | 0                                 | 0.928   | 0.928                    |
| 1.50                | Tab           | -0.0076                | 0.716             | 0.477                             | 1.329   | 0.886                    |
| 2.00                | Tab           | -0.0047                | 0.836             | 0.418                             | 1.697   | 0.848                    |

4. Conclusions
Active aerodynamic load control devices have the potential to reduce the aerodynamic-fatigue loads on wind turbine blades. Techniques to actively mitigate blade loads include traditional trailing-edge flaps ($\approx 10\%c$) and small tab and flap trailing-edge devices ($\approx 1\%c$). The transient response of airfoils with small fast-acting trailing-edge tabs and flaps is the focus of the present study. The microtab slides in and out of the surface and, hence, must be located just ahead of the trailing edge whereas the rotating microflap can be located at the trailing edge. The goal of the study is to compare the transient aerodynamic characteristics of the microtab and microflap, to determine the deployment time requirements for these devices, and to assess the occurrence of any nonlinear aerodynamic phenomena during their deployment. Given the difficulty and cost of time-accurate experiments involving small fast-acting devices, the study is limited to numerical simulations using an unsteady Reynolds-averaged Navier-Stokes method. This method has been extensively validated against benchmark wind tunnel experiments involving a fast-acting spoiler and demonstrated to accurately capture the governing aerodynamic phenomena.

The overall transient behavior of the microflap is very similar to that of the microtab, with a slightly faster initial response time and larger lift effectiveness due to the trailing-edge location of the former. The trailing-edge location also results in an increased magnitude of bluff-body vortex shedding. From an overall perspective, this study reiterates some of the conclusions derived from a previously published microtab study in that the deployment transients dissipate within one convective time unit ($=c/U_\infty$) post deployment followed by an asymptotic rise, similar to the Wagner function, towards a steady-state response.

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Fig. 4 Airfoil aerodynamic response due to deployment of microflap and microtab. NACA 0012, T\(_{\text{deploy}}\)=1.0, \(\alpha=0^\circ\), fully turbulent flow, Re=1.0 million, M\(_\infty\)=0.25.
Fig. 5  Airfoil pressure contours (left) and instantaneous streamlines (right) due to deployment of microflap. NACA 0012, $T_{deploy}=1.0$, $\alpha=0^\circ$, fully turbulent flow, $Re=1.0$ million, $M_\infty=0.25$. 


Fig. 6  Effect of flap deployment time on airfoil transient aerodynamic response. NACA 0012, $\alpha=0^\circ$, fully turbulent flow, Re=1.0 million, $M_*=0.25$. 