ACTIVE FLOW CONTROL OF SEPARATION ON A WING WITH OSCILLATORY CAMBER

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Active flow control of a wing with a oscillatory camber is discussed. The wing uses an adaptive actuator mounted internally to alter the shape of the suction surface which results in a change in the effective camber by increasing the maximum thickness and moving the location of maximum thickness aft. Since the actuator motion can be altered continuously, this allows the wing shape to be either static or dynamic. Basic control options are discussed for the general case and preliminary results and observations are presented. Dynamic oscillations are used to control the separation over the wing. Experiments in a wind tunnel at low speeds are conducted using PIV and flow visualization. These are compared to results from a numerical investigation.

Aerodynamic Flow Control

The majority of flows of scientific interest or practical use are by nature turbulent and thus have both time dependency and non-linearity. This makes them generally unpredictable (though steady-state approximations can be made which may closely model the flow). The control of the flow field is then a non-trivial problem in all but the simplest of cases. Though flow control may be generally defined to be any method by which the behavior of the flow is modified, in this context we refer to the detailed manipulation of a flow field to achieve a desired change in some flow parameter, such as the control of separation or an increase in turbulent mixing. This can be either passive or active. It is the latter which is of more interest, since it has the ability to respond to changes in the flow field dynamically. However, it also requires the expenditure of energy and usually requires the flow to be monitored.

As a design tool, active flow control is not yet a mature technology, but the lure of its many practical uses makes it a much researched area of fluids engineering. By flow control we mean any method by which the behavior of the flow is modified. We are particularly interested in the detailed manipulation of the flow to control some flow parameter. In our application the parameter of greatest interest is separation. We desire to modify the flow in order to minimize separation, and thus maximize lifting efficiency of a wing.1 Our range of interest is just that range where separation causes the most difficulty. That is, the low-Reynolds-number regime where separation begins in a laminar boundary layer and spreads over a significant portion of the wing. This is illustrated in Figure 1 where a low Reynolds number airfoil, in this case a LNV109A optimized for $Re = 4 \cdot 10^5$, is evaluated in the off-design regime.

While active control methods require an expenditure of energy, their main advantage is that they can respond rapidly to changes in the flow field. Such changes, of course, require monitoring of the flow in order to respond to it, but benefits of aerodynamic tailoring can be exploited if the response of the active system is fast enough.2 Continuous blowing and sucking have long been shown to have pronounced effects. More recently intermittent blowing and sucking in the form of synthetic jets have shown their effectiveness.3–5 These latter methods also suggest “sweet-spots” in the range of frequency inputs, which may translate to other oscillatory inputs.

Dramatic effects can be produced through mechanical momentum transfer as has been shown in various experiments.6,7 Flow fields have been energized using acoustical and mechanical methods as well. Finally, one can control the flow over an airfoil by changing the shape of the foil itself. Such an approach employs an adaptive wing.8

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Fig. 1 Separation over an LNV109A airfoil at low Re.

Adaptive Wings

By an adaptive wing we mean one which can change its shape to adapt to flow conditions. Common examples of wing adaptation include simple flaps, droops, and slats which allow a wing to adapt to the differing demands of differing flight regimes. Such simple adaptations can be thought of as a series of static airfoil shapes a given wing may take on.

The primary motive for altering wing geometry is to improve airfoil efficiency in off-design flight regimes. This concept is a standard implementation in most modern aircraft designs and takes the form of flaps which change the wing area and/or effective camber. A polymorph wing (variable planform) and variable pitch or incidence are also proven methods of wing adaptation. Adaptive concepts have taken many forms and names, including deformable, flexible, and active, in addition to those previously mentioned. In this paper, however, we will use the term adaptive to indicate an airfoil whose actual (as compared to effective) profile can be altered during flight.

The ideal use of an adaptive strategy allows the wing to vary its geometric parameters in flight during encounters in situ of changing flow conditions such as wind speed or direction. As much of the governing principles of the unsteady fluid/structure interactions are unknown, extensive research into the physics is necessary, including the dynamics of series adaptive paneling, the actuation and control of an adaptive wing in flight, and real-time unsteady aerodynamic measurement and analysis. It is the dynamics of the fluid/structure interface that interest us here, primarily the aeroelastic transient coupling of the varying airfoil parameters and the unsteady flow. As the wing changes geometry, the flow will rapidly follow these changes. However, since the flow is a continually evolving structure, the altered flow field can interact with the wing in a nonlinear fashion. To determine the desired singular or periodic variations in wing geometry a priori, it will be necessary to first understand the underlying physics. The number of variables results in an inordinately large parameter space which requires the use of simulations to be used in tandem with any experimental investigation.

Fig. 2 shows the variation in lift coefficient $C_l$ for two airfoils vs. the angle of attack $\alpha$. For a set profile at a given $Re$ and $M$, the stall angle can be well determined. To increase $C_l$ during such maneuvers as take-off and landing, modern aircraft typically use high-lift devices like leading- and trailing-edge flaps to alter the shape of the wing. This essentially changes the profile of the wing to one which is better optimized at the present free-stream conditions. Figure 2 shows the lift curve slopes for two airfoils, a cambered and symmetric airfoil. The defining difference between these two wing sections is that while the cambered airfoil has a lower stall angle than the symmetric one, the cambered airfoil has a non-zero $C_l$ at zero angle of attack. Thus, the cambered airfoil provides more lift at lower attack angles but stalls sooner than the symmetric wing. An ideal case would be to change the shape of the wing from the cambered airfoil as $\alpha \rightarrow \alpha_{stall}$. If the airfoil can assume an arbitrary profile, then one can continually increase the angle of attack while just staying below $\alpha_{stall}$.

It is worth noting that the angular velocity of the pitching motion, $\frac{d\alpha}{dt}$, has a dramatic effect on flow separation, hence stall. If the motion is oscillatory and at a high frequency, then it is possible to increase $C_l$ above that of the steady $C_{l_{max}}$. The possible use of unsteady aerodynamics in an adaptive application is thus very attractive. This is discussed in some detail below.

The kind of adaptation which interests us in the present paper is that in which the rate of actuation is rapid, and may be able to respond quickly enough to arrest or limit the formation of laminar separation bubbles. Such speeds either require large forces, or
light-weight actuators or both. Different approaches span the range of mechanical actuation techniques. A natural application for MAFC is the μAVs which are small and light, and thus are a natural choice for wings using piezoelectric actuation. There have been several other attempts to influence flow over surfaces using piezoelectric devices. At high Re, the unsteady theory of Theodorsen may be utilized to solve such problems (see Duffy et al. for an example), but at low Re where viscous forces are predominate, there is no rigorous method to predict the unsteady effects of such rapid actuation and how it will alter separation.

**Control Strategy**

The basic flow control algorithm is shown in Fig. 3. The limits of the boundary geometry should be determined for various operating regimes a priori. During operation, sensors measure specific flow conditions, send the information to a control device, and the surface is altered (monotonically or periodically) in the direction of desired control. Feedback is used to monitor response. Due to the complexity of the proposed active device, an artificial neural network (ANN) could be developed to control the aggregate system. Artificial neural networks have been used in a number of applications, most notably flow control and design optimization (see, e.g., Faller and Schreck, Rai and Madavan). In essence, the neural network is necessary to navigate through the function space of the active system. An optimization procedure is required to determine the optimum parametric values for a desired shape.

The control system is responsible for adapting the shape to maximize pre-determined parameters for any given operating condition. The control system will have a hierarchical architecture, consisting of a high level module that determines the optimal overall shape and numerous low level modules that control local surface positions. The high level module will receive flow condition variables as input (e.g., pressure drop, Mach number, Reynolds number) and determine the corresponding optimal shape for the given operating condition. Pressure and shear stress sensors can further be used to refine the shape. A neuro-fuzzy system could be used to learn the complex relationships between flow conditions and optimal surface geometry from simulation data. A neuro-fuzzy system represents input/output relationships in the form of fuzzy rules and uses neural network techniques to learn the rules. Whereas a conventional neural network is essentially a black box containing abstruse connection weights, a neuro-fuzzy system produces human-readable rules that are easy to understand and debug. The optimal surface shape can then be represented by a parameterized curve equation, where the neuro-fuzzy system will learn the mapping from the operating condition parameter values to the curve parameter values.

Conformal mapping techniques are one obvious choice as a method of predicting AFC boundary conditions. This has been shown to work well in the area of low speed airfoil design. This is based on an inverse design method where the shape of the geometry is determined to obtain a prescribed velocity distribution. In essence, the velocity field is prescribed about a fixed reference geometry and various transformations are used to obtain the desired geometry. The transformation is determined by the details of the velocity distribution. This technique has the benefit that a single geometry can be optimized across operating regimes or designed for a single operating point. This allows for variety in the AFC strategy, where a ‘fixed’ geometry can be selected that will operate over a given operating regime or where the geometry can be varied according to changing flow conditions. Thus, the AFC system will not have to continually operate in the active mode.

To help quantify unsteady variations in surface geometry, one can categorize effects as either steady or unsteady and either viscous or inviscid. Thus, a change in surface geometry can alter the flow by any of four possible means: (1) steady potential, (2) unsteady potential, (3) steady viscous, and (4) unsteady viscous. This allows one to separate the analysis into increasing levels of difficulty. The complete behavior is governed by the non-dimensionalized equations of motion.

**Fig. 2** Lift coefficient vs. α for a cambered and symmetric airfoil.

**Fig. 3** Control functional block diagram. The purpose of the neuro-fuzzy controller is to determine if and what changes should be made from normal sensor input. This will require extensive training of any AFC system.
motion in an incompressible flow which take the form
\[ \nabla \cdot \mathbf{u} = 0 \]
and
\[ St \frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \frac{1}{Re} \nabla^2 \mathbf{u} \]
for mass and momentum conservation, respectively. Standard boundary layer theory allows us to reduce the complexity of the equations, but solutions are still non-trivial except for specific geometries. For the steady inviscid formulation, we can reduce this to determine a solution for the pressure field by using the complex velocity \( w(z) \) as related to the pressure coefficient \( C_p \) such that
\[ C_p = 1 - \left| \frac{w(z)}{U_\infty} \right|^2 \]
where the complex velocity is related to the complex potential \( \phi \) by
\[ w(z) = \frac{d\phi}{dz} \]
These can be used to determine the pressure field on a conformal surface. Static flow control requires that each surface must be optimized within its possible geometric parameter space for a given set of significant flow conditions. A parameterization of the geometry defined in key length scales \( \eta \) can be defined by a summation of sinusoidal basis functions \( g_k \) which perturb the boundary normal to the surface by a distance \( \Delta l \). \[^{31}\]

The mode parameters \( G_k \) are used as the optimized design parameters such that
\[ \Delta l = \sum_{k=1}^{K} G_k g_k(\eta) \]
where
\[ g_k(\eta) = \frac{1}{k} \sin(k \pi \eta) \]
Specific geometry bases must be determined for a given problem and the actual optimization is dependent upon the number and type of parameters involved. In addition, dynamic flow control increases the complexity of the problem through the addition of a time-dependent geometry whose frequency of shape variation can be used to control a steady surrounding flow field or adapt to a changing flow field. Each case must be examined separately.

Power requirements for active flow control are an important concern, since energy consumption makes an important determination in selection of flow control technologies. For piezoelectric actuators, for example, the required input power is linearly proportional to the effective capacitance, output frequency, and square of the input voltage. \[^{32}\] Since many MEMS are designed using piezoelectric materials, this allows a direct comparison between MEMS flow control and AFC technology. Since MEMS devices are often designed to continually perturb the flow at some frequency, this makes AFC competitive even though their initial input voltage may be higher since only a stepwise change is required to achieve the same flow control goal.

**Experimental Portion**

The adaptive wing design is based upon a test article constructed by Pinkerton and Moses as a feasibility test for drag reduction. \[^{23}\] A molded airfoil section is constructed with a recess cut in the upper surface to receive a Thunder (Face Corp, Norfolk, VA.) piezoelectric actuator. The actuator is mounted in such a way that it is even with the un-recessed airfoil section when it is at its smallest effective radius (when it is most curved). A thin plastic sheet is then placed over the actuator to smooth the profile, and then the entire assembly is wrapped in a latex membrane to hold it together and provide a seamless outer surface. When the actuator is at its smallest effective radius, the assembly has the same cross-section as the base airfoil; and we expect the flows and the coefficients of lift and drag to be the same as the base airfoil. When the actuator is shifted to its greatest effective radius (closest to being flat) it protrudes through the upper cross-section. The plastic sheet and latex membrane smoothes the upper surface and the effective camber of the upper surface is increased and the point of maximum thickness is moved aft.

Five identical modular wing sections were constructed. These can be placed end-to-end along with wing-tip caps to construct a single wing with up to 5 separately controlled actuators. Each modular wing section has a chord of 8 inches and a width of 3.25 inches, giving the completed wing an approximate maximum span of 17 inches with wing-tips. Shorter wings can be built from fewer modules to test the effects of aspect ratio.

Flow visualization and PIV are used in the tunnel to obtain information regarding the separation region. The smoke wire technique as described in Batill and Mueller is used. \[^{33}\] The flow speed is limited by the wire \( Re_d \) which must be kept low to prevent vortex shedding; typically \( Re_d < 50 \). Displacement of the actuators was measured *in situ* with a Keyence LK-501 laser displacement sensor. These measurements are accurate to within ±5% at all frequencies.

For the PIV, the laser sheet was generated by a 50 mJ double-pulsed Nd:YAG laser with a maximum repetition rate of 15 Hz. Pulse separations varied from 100 µs to 1 ms based upon the tunnel velocity. A 10 bit CCD camera with a 1008×1018 pixel array was used to capture images over the upper surface of the airfoil in the range of \( x/c = 0.3 - 0.7 \). Uniform seeding was accomplished using 1 micron oil droplets. A predictor-corrector algorithm with an interrogation area of 32×32 was used to generate displacement ve-
Fig. 4 Smoke-wire flow visualization at $Re = 2.5 \cdot 10^4$ for static and actuated cases.

tors and velocity gradients. For each PIV run, at least 100 images were recorded for processing resulting in a minimum of 50 vector and vorticity fields from which to generate ensemble averages and related statistics.

Results

Flow visualization measurements at a chord-based Reynolds number of $2.5 \cdot 10^4$ show that the size of the separated flow is generally reduced with increasing frequency up to the point where normalization is lost. The measurements at $\alpha = 0^\circ$ show a broad minimum around $f^+ = 5$. The measurement at $\alpha = 3^\circ$ may also indicate a minimum before normalization is lost. At higher angles of attack, though, where the decrease in separation is more significant, the improvement in performance appears to continue up to the point of loss of normalization. Past this point, where the amplitude of the actuator oscillation diminishes, the performance of the foil degrades at all angles of attack.

Fig. 5 shows the minimum observed separation for each combination of $\alpha$ and $Re$. It can be seen from this plot that the application of an oscillatory input holds the size of the separated flow to $4 - 6\%$ of chord. This is, of course, more significant for the cases of higher angle of attack and for lower Reynolds number, where the non-actuated flow has a larger separated region. It remains to be seen if increasing amplitude will further improve performance.

PIV measurements are made at 3 speeds, $Re = 2.5 \cdot 10^4$, $5 \cdot 10^4$, and $1 \cdot 10^5$, and two angles of attack, $\alpha = 0^\circ$ and $9^\circ$, across a range of 3 values of $f$, 0, 10, and 25 Hz, providing 2 unique non-zero values of $f^+$ for each $Re$. Results are shown in Fig. 6 through 17. Figures 6, 7, and 8 include velocity, vorticity and FFP plots while the remaining plots display FFP only. Here, FFP (forward flow probability) is determined by examining the percentage of time a vector is facing downstream. For $FFP = 0$, the vector is facing upstream regardless of the value of the vertical velocity component and for $RFP = 1$, the vector is facing downstream 100% of the time. Mathematically, this can be written for a single point as

$$FFP = \frac{1}{N} \sum_{1}^{N} \frac{u}{|u|}$$

where $N$ is the total number of realized images. This is useful in determining both separation and reattachment as well as the unsteadiness of the flow.

It is clear from the figures that increasing $f^+$, even in the small range from 0.5 to 3, significantly decreases the amount of reversed, or separated, flow. Specifically one can observe that the higher $f^+$ values have nearly zero reversed flow, indicating the flow is staying fully attached to the surface. While the flow is still separated in the $f = 10$ Hz cases for both $Re = 2.5 \cdot 10^4$ and $Re = 5.0 \cdot 10^4$ (Figures 13 and 16, respectively),
Numerical Portion

In addition to the experimental investigation, observations are being compared to and guided by results from a computational investigation as well. This includes both an oscillatory wall motion as used in the experiments as well as a synthetic (zero-mass flux) jet for comparison. The code is 2nd order accurate in time uses a 3rd order QUICK scheme with variable grid spacing dependent upon local gradients. Results are shown in Figures 18 and 19. The former figure is the cropped computational domain detailing the Chimera grid structure while the latter is a sample vorticity plot at a single point in time for $Re = 25,000, \alpha = 0^\circ$, and $f^+ = 0$ (no actuation). The area of separated flow is similar to that seen in the experiments and periodic shedding is observed from the surface. Simulations with an oscillating surface are currently being exam-
Acknowledgements

The authors wish to thank the Kentucky Space Grant Consortium for their support of this research.

References


Fig. 13  FFP for $Re = 2.5 \cdot 10^4$, $\alpha = 9^\circ$, $f^+ = 1.2$.

Fig. 14  FFP for $Re = 2.5 \cdot 10^4$, $\alpha = 9^\circ$, $f^+ = 3.0$.

Fig. 15  FFP for $Re = 5.0 \cdot 10^4$, $\alpha = 9^\circ$, $f^+ = 0$.

Fig. 16  FFP for $Re = 5.0 \cdot 10^4$, $\alpha = 9^\circ$, $f^+ = 0.6$.

Fig. 17  FFP for $Re = 5.0 \cdot 10^4$, $\alpha = 9^\circ$, $f^+ = 1.5$.

Fig. 18  Grid for static airfoil case (boundaries have been cropped to show grid detail).

Fig. 19  Simulation for $Re = 25,000$, $\alpha = 0^\circ$, $f^+ = 0$; vorticity contours.