Control of vortex shedding on two- and three-dimensional aerofoils

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We review and expand on the control of separated flows over flat plates and aerofoils at low Reynolds numbers associated with micro air vehicles. Experimental observations of the steady-state and transient lift response to actuation, and its dependence on the actuator, aerofoil geometry and flow conditions, are discussed and an attempt is made to unify them in terms of their excitation of periodic and transient vortex shedding. We also examine strategies for closed-loop flow and flight control using actuation of leading-edge vortices.

Keywords: vortex shedding; flow control; micro air vehicles; lift enhancement

1. Introduction

Desirable features of micro air vehicles (MAVs) include low cruising speed, gust resistance, agility and propulsive efficiency. It is as yet unclear whether the required aerodynamic forces for such capabilities can be generated and controlled on a fixed-wing MAV. Two critical gaps in answering this question are, firstly, the dearth of experimental data on three-dimensional effects that dominate the flow fields on low-aspect-ratio (AR) aerofoils (a notable exception is Torres & Mueller [1]), and, secondly, whether active and/or closed-loop flow control techniques may provide sufficient control authority to replace traditional control surfaces or to quicken the response to flight control directives.

In this paper, we review recent work aimed at understanding the underlying flow physics associated with active flow control applied to low-Reynolds number and three-dimensional aerofoils at high angle of attack, and we present new experimental data for a low-AR aerofoil with leading-edge actuation mounted on a pitch–plunge mechanism in the unsteady wind tunnel at the Illinois Institute of Technology (IIT). We focus in particular on unsteady and transient flows produced by leading-edge actuation, in the context of both continuous and short-duration pulse of actuation. Transient effects, in particular, must be understood

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in order to develop closed-loop control strategies. Our scope is restricted to fluid-dynamical and control issues and, for brevity, we must omit many details. Further information is available in several reviews [2–7].

2. Steady-state natural and actuated flows

(a) Separation and vortex shedding

We first consider flow field and forces associated with a flat plate or aerofoil at an angle of attack to an otherwise uniform, steady, stream of speed \( U \), under the action of continuous, but unsteady, forcing from an actuator. The chord length is \( c \), and, unless otherwise mentioned, the planform is rectangular with breadth \( 2b \) and an \( AR = 2b/c \). The relevant Reynolds number is \( Re = Uc/v \). We first discuss the natural (unforced) flow, and, in §2b, actuated (forced) flows.

As the angle of attack, \( \alpha \), is increased, different regions of separated flow appear as a function of the aerofoil shape and Reynolds number. For laminar aerofoils, onset of separation would typically occur near the trailing edge, and progresses upstream as \( \alpha \) is increased. For flat plates and other thin aerofoils, the sharp leading edge promotes separation, and a separation bubble (with typically turbulent reattachment on the suction surface) may precede the fully stalled condition. We are concerned here with completely separated (stalled) flow over the entire suction surface, when the aerofoil behaves as a bluff body with vortex shedding, oscillatory forces and the formation of a Kármán vortex street in the wake. The frequency of vortex shedding, at least for the high-\( AR \) case, follows a Strouhal scaling [8] with \( St = fc \sin \alpha / U \approx 0.15–0.2 \), where \( c \sin \alpha \) is the projected area in the direction of the stream, and the Strouhal number is nearly constant at high \( Re \).

For a strictly two-dimensional flat plate, the onset of vortex shedding occurs, much as it does for a bluff body, as a Hopf bifurcation at a critical value of \( Re \) or \( \alpha \). Ahuja & Rowley [9] found \( \alpha_{crit} = 23^\circ \) at \( Re = 100 \) and Chen et al. [10] found an \( Re_{crit} = 80 \) at a fixed \( \alpha = 30^\circ \). For \( Re > Re_{crit} \), the same variation in shedding frequency with \( Re \) is observed as that on a circular cylinder [11]. Based on the similarity to the flow over a circular cylinder (e.g. [12]), it could be expected that at a higher \( Re \) the two-dimensional vortex shedding would undergo a further bifurcation to three-dimensional flow (even for an infinite plate), but these instabilities are only recently beginning to be studied [13]. For low \( AR \), three-dimensional flat plates at low \( Re \), vortex shedding still occurs, but data are very limited. Taira & Colonius [14] investigated low-\( AR \) flat plates for \( Re = 300 \) and 500 over a range of \( \alpha \) and for rectangular, elliptical, semicircular and delta-shaped planforms. The onset of vortex shedding is delayed to higher \( Re \) and \( \alpha \) as the \( AR \) is decreased, owing to a stabilizing influence of the tip vortices. As the \( AR \) is increased beyond about 3, the initial bifurcation to vortex shedding coincides with the value for strictly two-dimensional flow.

As in bluff bodies, vortex shedding persists at high \( \alpha \) when \( Re \) is increased [15]. Nominally two-dimensional aerofoils, and, in particular, the symmetric National Advisory Committee for Aeronautics (NACA) series, have been studied the most. Huang et al. [16] measured the frequency of vortex shedding in the wake of a NACA0012 over a wide range of post-stall values of \( \alpha \) up to \( Re = O(10^4) \). At sufficiently large \( Re \), the thin shear layer bounding the separation displays a
Kelvin–Helmholtz instability (with St about an order of magnitude higher than vortex shedding), and ultimately becomes turbulent [17]. The dominant shear layer instability frequency shows a power-law dependence on Reynolds number, \( f \sim Re^n \), similar to circular cylinders [18]. Like the circular cylinder, separated aerofoil flows typically show a broad band of frequencies centred around the nominal shedding value in the wake, potentially because of the interaction of the differing time scales and the effects of increasingly complicated and turbulent wakes [18]. The situation is more complicated at values of \( \alpha \) near the onset of fully separated flow, where further increases in \( Re \) can lead to reattachment of the separated region prior to the trailing edge. Finally, we note that, for flexible membrane aerofoils, Rojratsirikul et al. [19] found that the natural vortex shedding at post-stall angles was coupled to the membrane oscillations.

(b) Actuated flows

Following the pioneering work of Prandtl [20], classic separation control techniques [21], such as steady blowing and suction, attempt to energize a boundary layer, thereby delaying or preventing separation. Lately, unsteady blowing, zero-net-mass actuators (synthetic jets), piezoelectric flaps, plasma actuators and other unsteady actuators have been shown to achieve similar performance but with far lower mass, momentum and/or energy fluxes than steady blowing or suction [5,6]. For aerofoils and flaps, the lift and lift-to-drag ratio can be substantially increased, but the underlying mechanisms associated with lift enhancement or drag reduction are still debated. The dominant idea, discussed in detail by Greenblatt & Wygnanski [5], is that excitation of vortical structures in the separated shear layer leads to enhanced entrainment and the attendant suction of the shear layer to the nearby surface, eliminating or reducing the extent of the separated region, and leading to a time-averaged flow field closer to the ideal, potential flow. Entrainment probably plays a role regardless of whether vortical structures are generated as part of a Kelvin–Helmholtz instability in the shear layer, or via a global instability of the wake or separation bubble, but, as discussed in §2a, the frequencies at which these instabilities occur are distinct. Especially for low frequencies and high angles of attack, though, lift enhancement has also been explained in terms of vortex lift (e.g. [22]), through concentration of vortical structures closer to the surface of the plate.

For a specified periodic actuator, aerofoil geometry and angle of attack, any non-dimensional performance metric\(^1\) is at most a function of the Reynolds number, the actuator waveform and non-dimensional parameters expressing its frequency and amplitude. For the frequency, the most common choice is a reduced frequency \( f^+ = fc/U \). For amplitude, the momentum coefficient is often used,

\[
c_\mu = \frac{\rho U^2 J_j/(1/2) \rho U^2 A_j}{A}\text{,}
\]

where \( U_j \) and \( A_j \) characterize the mean and/or fluctuating (r.m.s.) velocity and area, respectively, of injection, and \( A \) is the planform area. For both these quantities, the chord length is sometimes replaced by the length of the (natural, unforced) separation bubble when the flow is not fully separated. Mean and fluctuating values of \( c_\mu \) as low as about \( 10^{-4} \) can be effective [5].

\(^1\)To be fully general, we should also account for the Mach number, and the possibility that the density of injected fluid is not equal to the ambient density, resulting in two additional parameters.
Greenblatt & Wygnanski [5] showed that $c_m$ collapses data obtained with several different actuators, but, in general, it is difficult to compare data from different actuators and waveforms, or with characterizing the actuator performance in terms of a velocity (or mass flux) that can depend on the plumbing for the actuator and whether the performance is measured with or without flow. Most studies observe a lower threshold and upper saturation limit of actuation that define the range of proportional control that can be achieved. In the controls community this is known as the static map and it is an important step in the design of a control system. Reynolds number effects (e.g. [6]) have also been studied. Here the most pressing issue is whether some reports of lift enhancement or drag reduction could be explained by the mechanism of tripping the boundary layer to delay or prevent separation. It is clear, however, that there remains an effect of forcing at $Re$ lower than those for which tripping can lead to a turbulent boundary layer, as well as at high $Re$ when the boundary layer was turbulent even in the absence of tripping [6].

The effect of actuation frequency on performance has also been widely studied, and gains (lift enhancement, drag reduction and other goals) have been realized across a wide range of frequencies. Here we employ the term ‘low frequency’ when the actuation frequency is below and up to the vortex shedding frequency (discussed above), and ‘high frequency’ to refer to everything significantly above the vortex shedding frequency, and in particular to excitation of shear-layer instabilities. As discussed by Raju et al. [23] (hereafter referred to as RMC), a third distinct time scale exists when the (mean) flow forms a closed recirculation bubble on the aerofoil surface. While these three distinct time scales—shear layer, wake (vortex shedding) and (in some cases) separation bubble—can be identified by examining velocity spectra measured at different locations (RMC), the lack of such data makes it difficult to make definitive statements about their values in past experiments. For example, for a turbulent separation, Greenblatt & Wygnanski [5] report an optimal value of $f^+ = 1$ for a deflected flap (with the flap length as the length scale), where ‘optimal’ refers to that frequency at which a minimal actuation amplitude was required for reattachment (in the mean), and they associate this time scale with shear-layer instabilities. Using the simple scaling for the vortex shedding time scale discussed in §2a, $St = 0.15 = f e \sin \delta_f / U$, where $\delta_f$ is the flap deflection angle, we conclude that a typical vortex shedding frequency would have $f^+ > 1$ when $\delta_f > 8^\circ$; one can infer that wake and/or separation bubble instabilities may equally have played a role. Seifert et al. [24] used oscillatory blowing at the leading edge of a NACA0015 aerofoil at $Re = 10^6$, and found lift enhancement and drag reduction over range $0 < f^+ < 2$, with a broad maximum around $f^+ = 0.75$, which, for the range of $16^\circ < \alpha < 22^\circ$ considered, gives $0.2 < St < 0.24$.

For lower Reynolds numbers, Hsiao et al. [25] acoustically forced the flow near the leading edge of a fully separated NACA633-018 aerofoil and observed a strong enhancement of vortex shedding, and the mean lift, but only when excitation was close to the natural vortex shedding frequency. The computational study of RMC showed that, for a NACA4418 at $Re = 40000$ and $\alpha = 18^\circ$, actuation with $f^+ > 6$ was increasingly ineffective; in their case, $f^+ = 12$ was identified as the maximally amplified frequency in the separating shear layer. These results are corroborated by the experimental findings of Cierpka et al. [26], who subjected a NACA0015 ($\alpha = 20^\circ$) and an inclined flat plate ($\alpha = 13^\circ$) to an electromagnetic actuation near
Figure 1. The semicircular aerofoil with leading-edge pulsed-blowing actuators.

the leading edge. For the plate, with $0.5 < f^+ < 3$, the flow was reattached (the lift enhancement was best at $f^+ = 0.7$ ($St \approx 0.24$)), whereas $f^+ > 6$ had little effect on the separation. For their inclined flat plate, they employed a wavelet algorithm to detect large-scale vortices in time-resolved particle image velocimetry (PIV) data, which revealed an interesting coalescence of smaller vortices produced near the actuator into one large coherent vortex advecting down the plate per cycle of actuation, in the case of $f^+ = 1$ ($St = 0.23$), and into two coherent vortices per cycle of actuation when $f^+ = 0.5$, both of which imply vortex shedding at $St = 0.23$. A similar configuration (with a dielectric-barrier discharge actuator) was studied by Greenblatt et al. [27] (flat plate) and Benard et al. [28] (NACA0015).

For the flat plate at $a = 20^\circ$, $0.3 < f^+ < 0.6$ provided the best lift enhancement, whereas $f^+ > 3$ was ineffective, and smoke visualization at $f^+ = 0.4$ showed a strong vortex advecting downstream along the chord; $f^+ = 1.5$ was optimal for a NACA0015 at $a = 16^\circ$.

Recent studies have also documented the effect of the waveform on performance. It appears that periodic but pulsatile actuation or modulated high-frequency sinusoidal oscillation can produce performance equal to or greater than sinusoidal actuation at the same frequency [26,27,29–31]. Indeed, it appears that pulses with as low a duty cycle as 5 per cent can be effective [27]. Joe & Colonius [31] employed an adjoint-based approach in a low-Reynolds number direct numerical simulation to find the actuator signal (a body force in this case) that gave the highest lift. Indeed, the optimal signal was a nearly periodic pulsatile forcing at a frequency close to that of the vortex shedding.

All of the above studies have focused on two-dimensional geometries. Recently, pulsed-jet actuation has been implemented on three-dimensional, low-AR aerofoils in the Andrew Fejer Unsteady Wind Tunnel at IIT. Results are presented here for a semicircular flat-plate (6.9% thickness) aerofoil with a rounded leading edge [32]. The chord is 0.2 m and the model is mounted on a pitch–plunge mechanism, and, for the results discussed in this section, operated here at fixed angle of attack and steady freestream speeds of 3–9 m s$^{-1}$ ($Re = 40 000–120 000$). Sixteen microvalve pulsed-blowing actuators were controlled by a pneumatic transducer supplying a plenum inside the aerofoil and positioned radially outward along the leading edge of the aerofoil (figure 1).
Figure 2. (a) Lift versus angle of attack with (open circles) and without (open squares) actuation at \(U = 5\, \text{m s}^{-1}\). (b) Mean lift coefficient increment due to pulsed-jet actuation for \(\alpha = 20^\circ\) with \(U = 5\, \text{m s}^{-1}\) (asterisks), \(U = 7\, \text{m s}^{-1}\) (open circles) and \(U = 9\, \text{m s}^{-1}\) (open squares). For all cases, \(f^+ = 1.16\) and \(U_j/U = 2.0\).

Figure 3. Smoke visualization of the (a) natural and (b) actuated midspan flow over the semi-circular aerofoil at \(\alpha = 20^\circ\). \((U = 5\, \text{m s}^{-1}, f^+ = 1.16, U_j/U = 2.0)\)

**Figure 2** shows that the lift as angle of attack is varied, for the natural flow and with actuation consisting of pulses of duration \(\Delta t^+ = U \Delta t/c = 0.43\), repeated periodically at \(f^+ = 1.16\). The natural flow stalls at \(\alpha = 14^\circ\). Smoke wire visualization for the natural and actuated flows at \(\alpha = 20^\circ\) (figure 3) shows that the actuation concentrates the leading-edge vortex and promotes reattachment near the trailing edge. Experiments with different actuator pressures showed that the lift coefficient scaled well with the coefficient of pressure, \(C_{pj} = \Delta p_j/(1/2) \rho U^2 = 556.0(U_j^2/U^2)\), where the second equality with the actuator jet velocity, \(U_j\), is found by calibrating the actuators using hot-wire measurements of the (maximum) velocity measured near the actuator with the flow off. The lift coefficient increment due to actuation in figure 2 shows a nearly linear increase with \(U_j/U\) up to about 1.6, and then saturates. The small deviation from linearity near the origin is repeatable, but its origin is unclear. Similar to the two-dimensional aerofoil studies, actuation was effective for lift enhancement over a broad range of low frequencies around the vortex shedding frequency, for which lift spectra at \(\alpha = 20^\circ\) for the natural flow showed a peak around \(f^+ = 0.66\) (\(St = 0.23\)).

To summarize, many studies of both two- and three-dimensional aerofoils show that a strong vortex shedding response is excited when the actuation frequency is close to the frequency of natural vortex shedding, and this results in significant
enhancement of the lift, typically optimal over the range of frequencies that have been investigated. However, we note that relatively few studies have reported unsteady flow metrics associated with fluctuating forces as a function of the actuation frequency. As pointed out by Amitay & Glezer [29], enhancement of vortex shedding by forcing near its natural frequency also increases the fluctuating lift and drag compared with the baseline. Aside from being potentially detrimental in application, such unsteady effects are essential to understand whether closed-loop control approaches are to be successful. This is discussed in greater detail in the next sections.

3. Transients

(a) Leading-edge vortex

When a flat plate at high angle of attack is impulsively started, the separating vortex sheets at the leading and trailing edges roll up into coherent leading- and trailing-edge vortices (LEV/TEV). The TEV (start-up vortex) is rapidly shed into the wake, while the LEV continues to grow for about a chord-length of travel, where the lift and drag reach their maximal values (without regard to the additional added mass force during the acceleration). Once the LEV begins to shed, the lift decreases to a minimum that occurs after four to five chord-lengths of travel, which appears to be only weakly dependent on the Reynolds number or acceleration rate [10]. This time scale is consistent with the so-called universal time scale of vortex formation that is observed in a variety of flows (e.g. [33]). Rotational forces on flapping wings, on the other hand, appear to prolong (stabilize) the LEV structure [34]. For a translating wing, after the initial LEV is shed, alternating TEV and LEV of diminishing amplitude are shed until periodic or quasi-periodic vortex shedding is attained. The ‘extra’ lift force of the initial LEV has been measured to be as much as 80 per cent above the steady-state (time-averaged) value [35]. The LEV and its associated lift increment are similar to the dynamic stall vortex that is produced and shed during rapid pitch up to high angles of attack (e.g. [36]).

(b) Transient response to actuation

As discussed above, understanding the transient response to initiation, termination or other changes to actuation parameters is essential to the development of closed-loop flow and/or flight control strategies. Relatively few experimental and computational studies have addressed this issue. Amitay & Glezer [29,37] examined the response of a symmetric NACA aerofoil at $Re = 3 \times 10^6$ and $\alpha = 17.5^\circ$ to a burst of high-frequency synthetic jet actuation. The response of the actuator consists of several ejection/suction phases of the actuator ($f^+ = 10$) with rapidly diminishing amplitude. The phase-average circulation flux in the wake was considerable despite the low actuation amplitude $c_\mu \approx 10^{-3}$, and consisted of an initial negative contribution to the circulation, followed by a large positive vortex being shed into the wake, and additional oscillations of diminishing amplitude. The total duration of the transient response was long when compared with the actuation, lasting several hundred actuation cycles, or about 10 convective time units ($t^+ = tU/c = 10$). The response to step changes
in actuation has also been studied [29,38,39] and shows similarly long transient times when toggling between fully separated and controlled flow states. Similar to the burst of actuation, the forced reattachment first results in a negative vortex followed by the shedding of large, positive vortices. Darabi & Wygnanski [39] studied flow over a deflected flap, and showed that the response scales well with convective time; at a minimum, when the actuation amplitude is sufficiently large, the controlled state is reached after about $t^+ = 20$. At lower Reynolds number, the response is more oscillatory, and seems to consist of consecutive shedding of large-scale vortices from the flap. Toggling off control results in transients of similar duration, but the early response includes the formation of a large (positive) vortex which Darabi & Wygnanski [39] liken to the dynamic stall vortex.

Similar experiments for $Re = 10^4–10^5$ have been conducted in the semicircular aerofoil in the IIT wind tunnel with leading-edge pulsed-jet or synthetic jet actuators, and they reveal strikingly similar transients to the two-dimensional aerofoils and flaps previously studied. Figure 4 shows the transient lift response to a single pulse of the jets as well as the scaling of the maximum lift increment achieved at $\alpha = 20^\circ$, for a range of free stream speed of 2.5–8 m s$^{-1}$, pulse duration (valve time on), $\Delta t$, from 0.005 to 0.06 s (or 0.06 < $\Delta t^+$ < 2), and actuator supply pressure, $\Delta p_j$, from 3.45 to 34.5 kPa. Dimensional analysis suggests that, for a fixed actuator design, $\Delta C_{l_{\text{max}}} = \text{fun}(\alpha, U_j/U, \Delta t^+, Re)$. As is seen in the plot, a reasonable collapse of the data is achieved by neglecting the variation with $\Delta t^+$ and Reynolds number. The scatter is generally within the uncertainty in the force measurements. The lack of dependence on $\Delta t^+$ is indicative of the short (impulsive) actuation. The maximum lift increment is also quite similar to the time-averaged value when actuators are operated continuously at $f^+ = 1.16$, shown in figure 2. The duration of the pulse, $t^+ \approx 10$, scales well with convective time units, and is similar to that measured by Amitay & Glezer [37] and Siauw et al. [40] with different actuators. In figure 4, we have superposed the lift response from a companion experiment in which synthetic jet actuators were used, as well as results from Woo et al. [30], who used a NACA4415 at $\alpha = 20^\circ$ with $Re = 570\,000$ and a burst from a pulse combustion actuator. The ordinate is scaled by the maximum value in order to compare the shape and time scale of response.
for different actuators (with different amplitudes), and because Woo et al. [30] reported the change in circulation flux in the wake rather than the lift. The time axis was also shifted slightly to align the maxima of the curves owing to slightly different time delays in the different actuation system.

The apparent invariance of the response with respect to the details of the actuator again tends to indicate that these experiments are revealing the (fluid mechanical) impulse response of the aerofoil to a small perturbation near the leading edge. For a linear system, at least, the response can be used as a kernel to predict the lift response to arbitrary input signals. Such an approach is discussed below. Phase-locked PIV (not shown) along the aerofoil midspan reveals a process similar to that documented and described on a two-dimensional aerofoil by Woo et al. [30]. During and just after the pulse a negative (counterclockwise) vortex is formed as the actuator jet pushes into the separated region, and begins a process where the entire separated region is detached and advected downstream. Following this, a fresh LEV begins to form and is eventually shed, in a process that appears similar to that which occurs following the initial separation on an impulsively started aerofoil and the dynamic stall process during rapid pitch up. We note that Siauw et al. [40] report being able to capture the dynamics of the transient process with a four-state dynamical system using a proper orthogonal decomposition (POD)/Galerkin projection approach.

The single-pulse response was used as a kernel [41] to predict the time-varying lift signals that would be obtained from more complicated actuator inputs. Sequences of multiple pulse (3, 5 and 10 pulse) and low-frequency square-wave modulation of continuous pulsation were used as inputs to the linear convolution function. The convolution was able to reproduce the general features observed in the experimentally measured time-varying lift response. For modulated continuous pulsation, the approach captured the shift in the average lift coefficient and the phase of the lift fluctuations, and explains the connection between the static map and impulse response of lift increments (figures 2b and 4, respectively).

4. Closed-loop control

While open-loop actuation is capable of enhancing post-stall lift under steady flight conditions, two goals of controlling actuation with sensor-based feedback can be distinguished. The first, and more ambitious, goal is to alter the dynamics of the flow in ways inaccessible to open-loop actuation. For example, is it possible to eliminate vortex shedding? The second, more modest, goal is to improve flight performance in unsteady flight, especially in regimes where conventional control surfaces may not be effective. Obviously the distinction between these becomes blurred as the time scales of imposed unsteadiness approach the intrinsic fluid dynamic time scales associated with either vortex shedding or shear layer instabilities.

For relatively slow changes in operating conditions, one may schedule operating parameters in a way that is not fundamentally different from open-loop actuation, though there remain challenges such as the hysteresis associated with toggling between separated and attached flow (e.g. [38]). For example, Magill et al. [42] used pressure fed back to a dynamic stall model to detect imminent separation.
during cyclic pitching of an aerofoil, and applied pulsed-vortex generator jets only over a portion of the pitch cycle and achieved similar lift increases to continual operation. Pinier et al. [43] controlled incipient separation with a proportional feedback signal based on the first global mode obtained using POD. Benard et al. [44] exploited hysteresis in the separation/reattachment process by detecting the signature of incipient separation with a pressure sensor, and then lowering the actuator voltage when the flow is already attached.

The next level of complication is to optimize performance as a function of input parameters. Benard et al. [45] used the measured lift to adjust the voltage to a dielectric-barrier discharge actuator on a NACA0015 aerofoil to autonomously reattach the flow at different speeds, and for step changes to the operating conditions. Becker et al. [46] implemented multiple-input, multiple-output, extremum-seeking control for spanwise distributed actuation and (pressure) sensing for pulsed-jet actuators on a flap, and were able to achieve higher lift than open-loop actuation, including lower angles of attack where the flow was not fully separated and where open-loop control showed little effect. Taira et al. [47] also used extremum seeking to optimize actuation frequency in numerical simulations of three-dimensional aerofoils at low $Re$.

For sufficiently fast changes in operating conditions there are bandwidth limitations for a particular architecture, i.e. the controller and the dynamic response of actuators, sensors and the inherent response of flow fluctuations to actuation and to changes in operating conditions. As shown in §3, the lift response to actuation in the separated regime is governed by the convective time scale and reaches a peak transient lift at $t^+ \approx 3$. For MAVs, this implies a full-scale frequency of the order of 1–100 Hz, and this is likely to be considerably lower than bandwidth limitations associated with the actuation and sensing. The pertinent question is whether this transient response to actuation can be shortened with feedback?

To examine this question and the underlying bandwidth limitations of the response to actuation, a series of controllers were designed to suppress lift fluctuations on the semicircular aerofoil discussed in §§2 and 3 when the freestream speed was allowed to vary by up to 10 per cent, either randomly or sinusoidally up to $f^+ \approx 0.12$. The model was held fixed with $\alpha = 20^\circ$, with a resulting (unforced) vortex shedding frequency of $f^+ = 0.66$. The lift force and freestream speed (measured with a hot wire upstream of the model) were used as inputs to the controller. The output was a signal to the pressure regulator (bandwidth $f^+ \approx 0.08$) that controlled the amplitude of the pulsed-blowing.

The first controller was based on a quasi-steady approach, which suppressed lift fluctuations at the freestream frequency and its harmonic, but the bandwidth was limited to $f^+ = 0.008$, indicating the importance of compensating for not only the unsteady aerodynamics but also the time lag due to actuation. The second controller increased the bandwidth by tuning the time delay associated with the lift response to actuation. It suppressed relatively higher frequency (up to $f^+ = 0.03$) disturbances, but only worked with sinusoidal disturbances of the specified frequency. For the third controller, Kerstens et al. [49] used modern system identification methods to obtain linear black-box models for the unsteady aerodynamics and the transient response to actuation. The architecture
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is shown in figure 5; the unsteady aerodynamic model is $G_d(s)$, and was inverted to produce the feedforward controller, $K_d(s)$. The dynamics of the lift response to actuation are modelled in the plant, $G_p(s)$. The measured lift feeds back and is subtracted from the reference lift to form an error signal, which is the input to a $H_\infty$ controller, $K(s)$. A first-order model with a time delay provided a good representation of the response of the separated flow to unsteady actuation. In combination with a linear model of the unsteady aerodynamics, a closed-loop controller was designed that demonstrated the ability to suppress random gusts with a bandwidth from DC to $f^+ = 0.036$. An example of the controller’s ability to suppress lift fluctuations in a randomized velocity is shown in figure 5. The good agreement between the measured and predicted lift demonstrates the efficacy of the unsteady aerodynamic model. The controlled cases show a significant reduction in lift oscillation.

An important result of this study was the recognition that the time delay associated with the LEV formation and shedding was responsible for limiting the bandwidth. It may be possible to design faster controllers, but they will not come from faster actuators. The controllers will have to interact directly with, and use information from, the vortex formation process. This is a difficult task, but some progress has been made in numerical investigations of two-dimensional flows at much lower $Re$. Ahuja & Rowley [9] were able to design a linear-quadratic regulator capable of eliminating vortex shedding on an inclined flat plate at $Re = 100$. Control design was based on a reduced-order model formed using balanced POD for the stable subspace of the linearized system combined with the exact description of the conjugate pair of unstable eigenvectors leading to vortex shedding. The actuator was a body force placed near the trailing edge, and two velocity sensors were placed in the near wake. The controller was effective at suppressing vortex shedding in the full nonlinear simulations. For higher $Re$, where vortex shedding becomes less regular, Joe & Colonius [50] showed that a phase-lock loop compensator could be used to restore phase locking between the lift fluctuations and a small body force placed near the leading or trailing edge, and reproduce high-lift limit cycles that were achieved at lower $Re$ and/or lower angles of attack. The compensator used a short-time Fourier transform and Kalman filter in order to estimate the instantaneous phase and frequency of vortex shedding (from the lift) and make slight adjustments to the forcing. In both of these studies, actuation at the leading and trailing edges was effective. Numerical simulations of the adjoint linearized equations were used in both studies and indicated strong regions of receptivity to actuation in both regions, but, in terms of controller performance, trailing-edge actuation was superior. A similar conclusion was found for three-dimensional separated flow on a low-AR, low-$Re$ flat plate [51], but the extent to which trailing-edge actuation remains superior as $Re$ is increased is not clear.

5. Summary

Sustained pulsatile or sinusoidal leading-edge actuation on two- and three-dimensional aerofoils at low to moderate $Re$ provokes a strong vortex shedding when the frequency of actuation is close to the vortex shedding frequency,
$St \approx 0.2$. This implies, for $\alpha \approx 20^\circ$, a reduced frequency of around $f^+ = 0.6$, with most studies showing a fairly flat mean lift enhancement over a range of frequencies for $0.3 < f^+ < 3$. For both continuous actuation and a single-pulse actuation, the steady-state and peak-transient lift coefficients, respectively, scale well with the actuator velocity ratio, with an approximately linear dependence up to saturation. The transient response to a single pulse of actuation produces a similar lift increment over a convective time scale of about $t^+ = 10$, provided the pulse duration is short when compared with the convective time scale. The single pulse first produces a decrease in lift as the separated region is lifted and cleared from the aerofoil, allowing a new leading-edge vortex to grow and shed. The transient lift recorded during this process is remarkable both for its strength, which is similar in magnitude to the lift increment under continuous actuation, and for its similar signature for flows on different geometries and with different actuators.

Closed-loop control has been successfully implemented to maintain steady lift under sinusoidally varying freestream speed, a model problem for gust alleviation on MAVs. However, there has been an upper bound of $f^+ < 0.03$ beyond which these controllers are ineffective. It appears that the system performance is limited by the fluid dynamic (vortex shedding) response to a pulse of actuation, rather than bandwidth limitations associated with the actuator or with other aspects of the hardware and dynamics. Faster controllers will have to interact directly with, and better use information from, the vortex formation process during actuation. Numerical studies of two-dimensional flows at lower Reynolds numbers have, in fact, demonstrated feasibility of both eliminating vortex shedding entirely and synchronizing pulsation to achieve high-lift limit cycles that are unstable in the absence of feedback. These and future studies will provide important clues about how to develop faster controllers in the laboratory. Finally, to provide more data and insights into the fundamental flow physics, future studies, especially of three-dimensional geometries relevant to MAVs, should also focus on unsteady effects associated with transient and continuous actuation.

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