Aerodynamic flow control effected by interactions of surface-mounted synthetic (zero net mass flux) jet actuators with a local cross flow is reviewed. These jets are formed by the advection and interactions of trains of discrete vortical structures that are engendered by actuators integrated in the boundary of a cross flow. A unique feature of synthetic jets is that they are formed entirely from the working fluid of the flow system in which they are deployed, and thus can transfer linear momentum to the flow system without net mass injection across the flow boundary. The fluid that is necessary to form the vortices that synthesize the jet is typically supplied by intermittent suction between consecutive ejections through an orifice in the flow boundary.

Keywords: flow control; synthetic jets; trapped vorticity

1. Synthetic-jet flow control

In recent years, ‘synthetic’ (zero net mass flux) jets have emerged as a versatile actuation technology tool for a broad range of flow-control applications in wall-bounded and free shear flows. The jets are formed by the advection and interactions of trains of discrete vortical structures that are engendered by actuators integrated in the boundary of a cross flow. A unique feature of synthetic jets is that they are formed entirely from the working fluid of the flow system in which they are deployed, and thus can transfer linear momentum to the flow system without net mass injection across the flow boundary. The fluid that is necessary to form the vortices that synthesize the jet is typically supplied by intermittent suction between consecutive ejections through an orifice in the flow boundary.
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boundary, and is driven by the motion of a diaphragm that is built into one of the walls of an otherwise sealed cavity below the surface. The characteristic scale and momentum (magnitude and direction) of the ensuing jets can be designed to match corresponding scales of the cross flow both on and off the flow surface. These attributes of synthetic jets, coupled with the development of actuators that can be integrated into the flow surface without the need for complex piping and fluidic packaging, make them attractive fluidic actuators for a broad range of flow-control applications. In fact, by exploiting inherent instabilities of the base flow, synthetic jets can effect significant global modifications on scales that are one to two orders of magnitude larger than the characteristic length scales of the jets themselves.

The formation and evolution of isolated synthetic jets in the absence of a cross flow have been the subject of a number of experimental and numerical investigations of plane and round jets with emphasis on near-field formation, evolution and advection of the jet vortices and on scaling of the time-averaged flow (examples of experimental investigations: plane jets [1,2], round jets [3,4]; and of numerical investigations: plane jets [5–7]). Several investigators have considered modelling of the jet actuator, including reduced-order models [8] and lumped-element models [9]. It has also been shown that the time-dependent pressure field in the vicinity of the jet orifice can have a profound effect on adjacent flows. These effects were demonstrated by the strong interactions between adjacent plane and round jets [10,11]. Compressibility effects associated with diaphragm-driven low-speed jets were modelled by Tang & Zhong [12]. Crittenden & Glezer [13] investigated the evolution of a high-speed, piston-driven synthetic jet and showed that, as compressibility effects become important, the suction duration increases, and there is a phase shift between pressure extrema at peak piston displacements and the jet speed.

The interaction of a synthetic jet (or jet arrays) with an external cross flow over the surface in which they are mounted has been of significant interest in light of the applications to flow control. Zhong et al. [14] considered the interaction of a round synthetic jet with a flat-plate laminar boundary layer, and the evolution of the jet vortices (stretching and penetration) for various Reynolds numbers, velocity ratios and formation frequencies. In a related investigation, Liddle & Wood [15] considered streamwise symmetric and asymmetric interactions of clusters of round synthetic jets with the boundary layer. Using flow visualization near the onset of separation on a two-dimensional circular cylinder, Jabbal & Zhong [16] concluded that jet-induced hairpin vortices and stretched vortex rings played a key role in delaying separation. More recently, Jabbal & Zhong [17] concluded that trains of stretched vortex rings would be most effective for separation control based on changes in wall shear stress within a laminar boundary layer. Milanovic & Zaman [18] compared the cross-flow evolution of synthetic and continuous jets having the same orifice and velocity ratio, and showed that for several orifice shapes, the global characteristics of the two jets are similar. In an investigation of the interaction between arrays of rectangular jets and a flat-plate turbulent boundary layer, Smith [19] showed that a streamwise array resulted in wake-like flow, while a spanwise array led to the formation of longitudinal, counter-rotating vortex pairs. The interaction of a synthetic jet with a turbulent boundary layer was investigated numerically by Dandois & Garnier [20] using the geometry adopted by the Computational Fluid Dynamics (CFD) Validation...
Workshop of Synthetic Jets [21]. Even though the primary objective was to compare CFD simulations with experimental data, the authors provide detailed information about the alteration of the velocity field within the boundary layer and the structure of the jet in the vicinity of the orifice. Rathnasingham & Breuer [22] used a spanwise array of synthetic-jet actuators for active control of the near-wall region of a turbulent boundary layer and developed transfer functions to predict downstream characteristics of the streamwise velocity fluctuations. They reported up to a 30 per cent reduction in the streamwise velocity fluctuations and a 23 per cent reduction in the bursting frequency within a domain of influence measuring about $50 \times 150$ viscous lengths in the wall-normal and spanwise directions, respectively.

Flow-control strategies for external aerodynamic surfaces have mostly focused on mitigation of flow separation, which is typically precipitated by an adverse pressure gradient (e.g. on a lifting surface) or by a sharp discontinuity in the flow boundary (e.g. a cavity or a bluff trailing edge). Attempts to manipulate and ultimately control separation over stalled aerofoils have typically relied on the narrow-band receptivity of the separating flow to external actuation. The separation is simultaneously affected by two instability mechanisms, namely, a local (convective) instability of the separating shear layer, and, more importantly, a near-wake (presumably absolute) instability that ultimately results in the formation and shedding of large-scale vortical structures into the wake (e.g. [23]). Because the nominally time-periodic vortex shedding into the wake is accompanied by global changes in circulation, it strongly affects the evolution of the separating shear layer near the leading edge. In fact, this coupling appears to dominate the rollup of the shear layer, the natural (‘most unstable’) frequency of which is typically higher than the global shedding frequency. Since the characteristic scale of the wake is commensurate with the scale of the separated flow domain, earlier work on separation control over fully or partially stalled aerofoils has emphasized actuation frequencies that are of the order of the shedding frequency. This corresponds to a Strouhal number $St_{\text{act}} = L/U_c T_{\text{act}}$ of $O(1)$ where the actuation period $T_{\text{act}}$ is nominally of the same order as the convective time scale $T_{\text{conv}}$, or time of flight over the separated flow domain ($L$ and $U_c$ are the characteristic advection length and speed, respectively). This approach to control of separation has been used since the early 1980s to restore aerodynamic performance of stalled aerofoils and flaps, and has been applied using different actuation approaches with varying degrees of success (e.g. [24–26]). Seifert et al. [26] used pulsating continuous actuation jets and argued that the actuation is most effective when the ‘reduced frequency’ $F^+$ (which is essentially the actuation Strouhal number $St_{\text{act}}$) is $O(1)$, indicating that the actuation frequency couples to, and in fact drives the shedding in the near wake. Actuation at these frequencies leads to the formation of vortical structures that scale with the length of the separated flow domain, and the ensuing changes in the rate of entrainment result in a deflection of the separating shear layer towards the surface of the stalled aerofoil, as discussed for example by Amitay & Glezer [27,28], Glezer et al. [29] and Greenblatt [30].

It can be argued that the fundamental flow mechanisms of separation control using synthetic-jet actuation at frequencies the period of which is commensurate with the convective time scale of the flow, are probably similar in many respects to the mechanisms associated with ‘conventional’, time periodic (or pulsed) jet

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actuation at the same frequency. Experimental investigations have included those of Greenblatt & Wygnanski [31], who used synthetic-jet actuation to improve stall characteristics. Margalit et al. [32] used low-frequency modulated synthetic-jet actuators to control stall on a delta wing, and reported that modulation at $St_{mod} = O(1)$ yielded the largest increase in the induced normal force. The numerical simulations of Raju et al. [33] considered separation control of a stalled National Advisory Committee for Aeronautics (NACA) 4418 aerofoil. Based on simulations of the baseline flow, the authors identified three characteristic frequencies that, in addition to the separating shear layer and the wake, also include an intermediate frequency associated with a separation bubble that may form if the flow reattaches upstream of the trailing edge and can lead to periodic release of vortices. The simulations suggest that actuation at frequencies that are close to the separation bubble frequency are most effective in diminishing separation, while actuation at frequencies that are commensurate with the separating shear layer tend to enhance separation. You et al. [34] used large-eddy simulation (LES) to investigate turbulent separation over a NACA 0015 aerofoil ($Re_c = 896000$), and showed that when the flow separates around a midchord, the LES agrees well with the measurements of Gilarranz et al. [35], who demonstrated separation delay and a significant increase in the lift by synthetic-jet actuation. However, when the flow separates near the leading edge, the same actuation is only marginally effective. Synthetic-jet actuation at $St_{act} = O(1)$ has also been applied to flaps with emphasis on high-lift systems. Smith et al. [36] used voice-coil actuators to achieve significant lift increments on a super short takeoff and landing (SSTOL) model (0.2 for takeoff and 0.5 for landing at flap deflections of $40^\circ$ and $50^\circ$, respectively), and the addition of a slat could yield up to 40 per cent increase in lift ($Re_c = 7.5 \times 10^5$). The simulations of Shmilovich & Yadlin [37] demonstrated that flow attachment on the flap results in an increase in suction over the main element that also contributes to increased lift. They also showed that staged chordwise actuation can lead to flow attachment through the trailing edge leading to near-inviscid lift levels.

The coupling (or feedback) between the time-periodic shedding of coherent vortices and the separated shear layer in the absence of actuation is intriguing because such feedback between the near-wake instabilities and the separating shear layer is even more pronounced in the presence of actuation. Although the ‘natural’ frequency of the separating shear layer is usually higher than the shedding frequency, the coupling between the two instabilities can result in ‘collective interactions’ during the rollup (as shown in a free shear layer [38] and in vortex formation in the wake of bluff bodies [39]). More importantly (from the standpoint of flow control), actuation at or near the shedding frequencies can amplify the unsteady component of the global aerodynamic forces (as evident in the numerical simulations of Wu et al. [40], and discussed by Amity & Glezer [27,28] and Glezer et al. [29]).

2. Aerodynamic control by virtual surface modification

An alternative flow-control strategy that is based on a quasi-steady modification of the ‘apparent’ aerodynamic shape of the surface can be accomplished by using controlled interactions between a synthetic-jet actuator and the cross
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flow to form localized concentrations of ‘trapped’ vorticity concentrations. The actuation period is selected to be at least an order of magnitude shorter than the relevant local or global time scales of the flow, such that the actuation frequency is effectively decoupled from the global instabilities of the base flow. The control of aerodynamic flows by modifying the apparent shape of aero-surfaces in order to prescribe pressure distribution and therefore influence their aerodynamic performance is not new, and has been addressed in a substantial body of work since the 1940s. Of particular note is the use of trapped vortices to alter the shape of the surface. These vortices scaled with the chord of the aerofoil and were engendered by local separation using passive obstacles or conventional jets (cf. [41]). Perkins & Hazen [42] formed a stationary, trapped vortex using a cusped cavity on the pressure side and a suction slot near the trailing edge to increase lift at zero angle of attack. Trapped vortices were also formed using split flaps [43], and forward-facing cavities [44]. Trapped vorticity concentrations that form naturally, and scale with the boundary layer over bluff bodies, can have substantial effects on the evolution of the global flow. For example, as the Reynolds number of the flow about a two-dimensional circular cylinder is increased, the flow reaches a ‘critical transition’ (around \( \text{Re}_{D_{\text{crit}}} \approx \times 10^5 \)) in which the drag decreases sharply (\( \text{C}_D \approx 0.2 \) in the supercritical regime). This reduction was associated with the formation of a small separation bubble on each side of the cylinder upstream of separation, which enables the separation point to move farther downstream up to about 140° [45,46]. Strong flow asymmetry, which is accompanied by lift (\( \text{C}_L \approx 1 \)), occurs when such a bubble forms on only one side [47]. As noted by Roshko [46], while the Reynolds stress in the boundary layer downstream of the bubble is considerably higher than upstream, boundary-layer transition upstream of separation occurs at higher, post-critical \( \text{Re}_D = O(10^6) \). In fact, natural transition to turbulence first occurs within the separating shear layer, and the onset of transition moves upstream as \( \text{Re}_D \) increases [45]. Following transition, these bubbles disappear and the drag increases as separation moves upstream to 100° [48]. It is also well known that the flow around bluff bodies can be significantly modified by placing a physical obstruction having a characteristic dimension that scales with the boundary-layer thickness upstream of separation. The effects of boundary-layer ‘trip’ on delay of separation were demonstrated by numerous investigators (as early as Prandtl, as noted by Schlichting [49], on a sphere, and by Fage & Wassap [50], on a cylinder), and have been frequently thought to be associated with premature transition to turbulence. Similar to the effects of the natural bubbles, the placement of various small-scale obstructions on the surface of a bluff body can also significantly alter the global aerodynamic forces. On a cylinder, such an obstruction can lead to a reduction in drag, and when positioned asymmetrically, it can also generate lift [51]. Similarly, quasi-steady modifications of the apparent aerodynamic shape of the aero-surfaces can be accomplished using controlled interactions between a synthetic jet and the cross flow where the actuation frequency is high enough so that these interactions are essentially time invariant on a global time scale of the flow (e.g. \( T_{\text{conv}} \)), and therefore the actuation is effectively decoupled from the global instabilities of the base flow (e.g. [29,52,53]). The interaction between a surface-mounted synthetic jet and the local cross flow can lead to the formation of

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a quasi-steady concentration of trapped vorticity having a cross-stream scale that can exceed the local boundary-layer thickness, and a streamwise scale of several actuation wavelengths. Honohan et al. [54] and Honohan [53] demonstrated that the formation of such a (single-sided) domain within the boundary layer of a circular cylinder displaces the local streamlines of the cross flow, and the induced changes in the streamwise pressure gradient lead to a significant delay in separation. The formation and scaling of this recirculation domain within a flat-plate Blasius boundary layer was also investigated numerically by Mittal & Rampunggoon [55].

The utility of this actuation approach for separation control was demonstrated over a broad range of $St_{act}$. In an experimental investigation of the aerodynamic characteristics of an unconventional, thick aerofoil, Amitay et al. [56,57] and Glezer et al. [29] showed that the aerodynamic forces become independent of the actuation frequency as it is increased beyond the unstable frequency band of the base flow, and therefore the induced aerodynamic forces are virtually time invariant. Timor et al. [58], who investigated three-dimensional effects on a cropped NACA 0018 aerofoil, showed that actuation led to a significant increase in lift and in pitch-down moment. In an effort to mitigate vortex breakdown and therefore unsteady dynamic loading over highly swept wings, Watson et al. [59] controlled the separating shear layer using an actuation frequency that was an order of magnitude higher than the band of vortex bursting frequencies, and showed reduction of about 40 per cent in the unsteady pressure fluctuations near the trailing edge. Control effectiveness on a stationary and a pitching NACA 0015 aerofoil ($Re_c = 360000$) was investigated numerically by Rehman & Kontis [60]. For the stationary aerofoil, the lift and drag increased for $10^\circ < \alpha < 20^\circ$ (the drag increment could be reduced if the actuator was placed closer to separation), and while a single synthetic jet did not suppress vortex formation and shedding on the pitching aerofoil, the aerodynamic performance was enhanced.

Unlike actuation at the unstable frequencies of the baseline flow, the use of trapped vorticity for flow control can also be effective when the baseline flow is fully attached, at low angles of attack. Chatlynne et al. [61] and Amitay et al. [56,57] showed that the formation of a stationary trapped vortex above an aerofoil at low angles of attack leads to pressure-drag reduction that is comparable to the magnitude of the pressure drag of the baseline configuration with minimal lift penalty. This approach was expanded by DeSalvo & Glezer [62,63] to manipulate the Kutta condition of an aerofoil by controlled concentrations of trapped vorticity near the trailing edge and near $c/4$ using a miniature $O(0.01c)$ hybrid actuator. The actuation near the trailing edge leads to a substantial reduction in pressure drag with virtually no loss in lift, and an increase in the pitching moment. The authors also demonstrated minimal changes in skin friction drag by trapped vorticity concentrations at $c/4$. More recently, DeSalvo & Glezer [64] reported variable bi-directional changes in the pitching moment at low angles of attack without moving control surfaces using controllable, nominally symmetric trapped vorticity concentrations on both the suction and pressure surfaces near the trailing edge. This control of the pitching moment was adopted by Muse et al. [65] to effect 2 d.f. manoeuvres (pitch and plunge) of a free aerofoil using adaptive, closed-loop control with application to uninhabited aerial vehicles.

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Figure 1. (a) Azimuthal pressure distribution, $Re_D = 75\,000$, $\gamma = 60^\circ$, $C_\mu = 3.8 \times 10^{-3}$, $St_D = 4.0$: baseline (open circle) and actuated (filled circle). The actuator location is indicated by the dashed line. (b) Smoke visualization, $Re_D = O(10^3)$, $St_D = O(10^2)$, $C_\mu = O(10^{-1})$, $\gamma = 60^\circ$.

3. Examples of flow control using trapped vorticity concentrations

Similar to the alteration of the aerodynamic forces on a circular cylinder near $Re_{D_{crit}}$ by the appearance of natural trapped vorticity concentrations, the aerodynamic forces on lifting surfaces can be altered by using vorticity concentrations that are engendered by the interactions of synthetic jets or miniature solid obstructions with the cross flow. Subsections 3a,b discuss the role of these trapped vorticity concentrations in the modification of the aerodynamic forces on a circular cylinder and on an aerofoil, respectively.

(a) Trapped vorticity concentrations induced by synthetic jets and passive obstructions on a bluff body

As noted above, the interaction a surface-embedded synthetic jet and the local cross flow changes the flow curvature and alters the streamwise pressure gradient, which can result in partial or complete suppression of separation. An example of this approach was investigated by the interaction of a rectangular spanwise synthetic jet with the flow over one side of a low aspect ratio (AR = 0.8) circular cylinder [29,53]. The azimuthal jet location relative to the front stagnation point $\gamma$ is varied by rotating the cylinder around its axis and the actuation level is characterized using the momentum coefficient $C_\mu = \bar{I}_j(1/2\rho_0 U_0^2 D)$, where $\bar{I}_j$ is the time-averaged jet momentum per unit length (during the outstroke), and $\rho_w$ and $U_0$ are the free-stream fluid density and speed. The azimuthal pressure distributions for the baseline flow and in the presence of actuation at $\gamma = 60^\circ$ are shown in figure 1 (as noted by Szepessy & Bearman [66], the pressure minimum at $\theta = 180^\circ$ at low AR is associated with increased spanwise coherence of vortex shedding). A low-speed image of smoke visualization [$Re_D = O(10^3)$, $St_D = O(10^2)$, $C_\mu \approx 10^{-1}$] shows the displacement of the cross flow in the vicinity of the orifice and separation delay on the actuated side, leading to an asymmetric flow field with a narrower wake (by comparison to an aerofoil, the separation point on a bluff body is more mobile). At higher $Re_D$, the interaction of the jet with the cross flow ($Re_D = 75\,000$, $St_D = 4$ and $C_\mu = 3.8 \times 10^{-3}$) leads to changes in the azimuthal pressure distribution, as manifested by a significant increase in
the suction peak on the actuated side, along with an extended domain of adverse pressure gradient that indicates flow resilience to separation, which is delayed by as much as 10°. Similar changes in pressure distribution were also reported by Tensi et al. [67] at \( Re_D = 10^5 \) (\( St_D = 0.2 \)) with a ‘tripped’ base flow.

The effects of trapped vorticity induced by the synthetic jet and by a spanwise, surface-mounted passive obstruction are compared at \( \gamma = 60° \). The obstruction is a circular tube, the characteristic scale (diameter \( d \)) of which is selected so that the induced forces (lift and pressure drag) are approximately equal to the forces induced by the jet. The variation of the induced forces with the jet’s \( C_m \) and obstruction’s \( d/D \) are shown in figure 2a (\( Re_D = 75 \, 000 \)). It is remarkable that for \( 0.01 < d/D < 0.16 \), the jet- and obstruction-induced lift and drag reduction are similar, despite the fact that the details of their interactions with the cross flow are different. Furthermore, it is noteworthy that while the jet-induced increase in lift and reduction in drag are reasonably invariant over the range of \( C_m \), the corresponding obstruction-induced changes diminish rapidly for \( d/D > 0.02 \).

The details of the cross-flow interactions with the obstruction and the jet are compared when the \( C_L \) and \( C_D \) are nearly equal (\( C_m = 1.0 \times 10^{-3} \) and \( d/D = 0.014 \)) using time-averaged distributions of spanwise vorticity concentrations obtained from particle image velocimetry measurements in the cross plane (\( x-y \)), as shown in figure 2b(ii) and (iii), respectively (the baseline flow is shown in figure 2b(i)). The azimuthal position of separation (determined from shear-stress distributions at the wall) is nearly identical for both the obstruction and the jet (\( \theta_{sp} = 110° \)). However, the interaction domains are significantly different. The vorticity concentration downstream of the obstruction forms a ‘bubble’ within the domain \( 60° \leq \theta \leq 76° \) \((-0.25 \leq x/D \leq -0.12\)) that displaces and accelerates the cross flow and leads to a sharp suction peak at \( \theta = 65° \) (another bubble forms upstream of the obstruction). By comparison, the interaction domain of the synthetic jet is far more subtle, and its characteristic cross-stream scale is significantly smaller. Downstream from the obstruction’s bubble (\( \theta = 80° \)), the boundary layer is significantly thicker (\( \delta \approx 1.4 \, \text{mm} \)) than in either the baseline (\( \delta \approx 2.2 \, \text{mm} \)) or the jet actuated (\( \delta \approx 0.8 \, \text{mm} \)) flows, and in the presence of the jet, the speed of the outer flow is significantly higher than with the obstruction. As shown by Honohan [53], the reduction in the width of the wake (and in pressure drag) by the synthetic jet and the obstruction is accompanied by suppression of vortex shedding in the near wake and a significant reduction in Reynolds stresses within the boundary layer upstream of separation. In a recent investigation of the flow past a circular cylinder (\( Re_D = 10^4 \)) with a surface-mounted wire (diameter larger than the thickness of the base-flow boundary layer), Ekmekci & Rockwell [68] reported that the near wake can significantly broaden or contract depending on the azimuthal position of the wire. Broadening was associated with bistable oscillations of the separating shear layer (on a time scale that is longer than that of the Kármán vortex shedding), and contraction occurs when the Kármán vortices are suppressed.

In order to demonstrate that the presence and effects of trapped vorticity concentrations are insensitive to whether the boundary layer is laminar or turbulent, the interaction of a synthetic-jet actuator with the cross flow over the cylinder is investigated in a boundary layer that is tripped symmetrically by placing small trip obstructions (\( d/D = 0.02 \)) upstream of separation (at \( \gamma = \pm 34° \)). The tripping results in a ‘turbulent-like’ pressure distribution (figure 3a)
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Figure 2. Effects of actuation by synthetic jet and passive obstruction \( (Re_D = 75000, \gamma = 60^\circ) \): (a) variation of \( C_L \) (filled circle, filled square) and \( \Delta C_D \) (open circle, open square) with actuation magnitude (jet: filled circle, open circle) and (obstruction: filled square, open square) and (b) time-averaged, normalized spanwise vorticity and velocity vectors: (i) baseline, (ii) obstruction, and (iii) synthetic jet. Separation locations are marked by closed triangles.

Figure 3. The interaction of a synthetic jet with a tripped boundary layer \( (Re_D = 75000) \). (a) Azimuthal pressure distribution: baseline (open circle), with trips \( (d/D = 0.020) \) at \( \pm 34^\circ \) (filled circle), and with jet actuation \( (\gamma = 100^\circ, St_D = 4.0, C_m = 3.8 \times 10^{-3}) \) (filled triangle). (b) Displacement thickness: baseline (open circle), tripped (filled circle), actuated (filled triangle). (c) Normalized Reynolds stresses: (i) baseline, (ii) tripped, and (iii) actuated. (Online version in colour.)

with increased suction peaks and greater pressure recovery, as indicated by the increase in the base pressure following separation (the absence of a suction peak at \( \theta = 180^\circ \) indicates partial suppression of vortex shedding). The changes in
the pressure distribution result in a substantial (41%) reduction in pressure drag \((C_D = 0.82\) compared with \(C_D = 1.40\) for base flow). The local decrease in pressure immediately downstream of the trip obstructions is attributed to the acceleration of the cross flow around bubbles downstream of the obstructions. Jet actuation at \(\gamma = 100^\circ\) induces additional changes in pressure, as manifested by the increase and decrease in the magnitude of each suction peak on the actuated and opposite sides, respectively. As shown by Honohan [53], actuation of the tripped flow moves the time-averaged separation point to \(\theta_{sp} = 116^\circ\) and the separated shear layer is deflected towards the wake, as is also evident from pressure decrease and increase over the actuated and opposite surfaces, which yield a net lift of \(\mathcal{C}_L = 0.36\). The increase in base pressure relative to the unforced (tripped) flow contributes to an additional 28 per cent reduction in pressure drag to \(C_D = 0.59\). Azimuthal evolution of the boundary-layer displacement thickness (figure 3b) shows that while at \(\theta = 70^\circ\), the tripped boundary layer is thicker than the baseline layer, by \(\theta = 80^\circ\) the tripped boundary layer is thinner than in the baseline flow, and remains so through separation, resulting in a significantly thinner shear layer. Jet actuation in the tripped flow results in thinning of the boundary layer upstream of the actuator orifice. Further downstream, the boundary layer in the presence of actuation is significantly thinner than in both the baseline and tripped flow fields. In fact, the onset of rapid boundary-layer growth is delayed to \(\theta \approx 100^\circ\), ostensibly as a result of higher velocity above the interaction domain. Finally, cross-stream distributions of the Reynolds stress components \(\overline{u'_r w'_r}\) (figure 3c) show that in the baseline flow (figure 3c(i)), \(\overline{u'_r w'_r}\) increases in magnitude with downstream distance. However, the addition of the upstream trips (figure 3c(ii)) results in a significant reduction in \(\overline{u'_r w'_r}\) across the boundary layer, which also persists in the separated shear layer and is attributed, in part, to diminution (or partial suppression) of vortex shedding. Jet actuation (figure 3c(iii)) leads to significant deflection of the separated shear layer towards the wake and reductions in its cross-stream spreading and in \(\overline{u'_r w'_r}\). These data indicate that the state of the boundary layer does not have a significant effect on the global aerodynamic changes that are induced by the interactions with the cross flow of either the trip obstructions or the jet.

(b) Aerodynamic control of aerofoils at low angles of attack

As noted in §2, an important attribute of flow control by trapped vorticity is that it is also effective at low angles of attack when the baseline flow is fully attached. DeSalvo & Glezer [63,64,69] leveraged a hybrid actuation approach to control low-angle-of-attack aerodynamic characteristics of a swept aerofoil. The model had a fixed cross section based on a commercial aircraft configuration, a sweep angle of 27.1° and a 500 mm streamwise chord. A hybrid actuator comprised a synthetic jet (\(St_{act} = 44\) at \(Re_c = 6.7 \times 10^5\)), integrated with a miniature \([O(0.01c)]\) high], surface-mounted passive obstruction was used to regulate the scale of trapped vorticity concentrations, and requires significantly reduced actuation power compared with the use of the jet alone.

When the actuator is mounted on the pressure side of the aerofoil near its leading edge (the jet orifice is placed at \(x/c = 0.21\), figure 4a,b) the trapped vorticity induces flow acceleration upstream and pressure recovery immediately downstream of the actuator, which can lead to significant reduction in pressure

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drag (assessed from circumferential pressure distributions). The variation of the fractional drag increment (relative to the baseline aerofoil) $\hat{C}_{Dp} = \Delta C_{Dp}/C_{Dp\text{ smooth}}$ with actuation momentum coefficient $C_m$ is shown in figure 4a ($\alpha = 4^\circ$) for $Re_c = 6.7 \times 10^5$, $1.0 \times 10^6$ and $1.3 \times 10^6$. The maximum value of $C_m$ (which is limited by the actuator design) results in reduction in pressure drag of up to 55 per cent relative to the baseline configuration, and these data suggest that the performance improves with increasing $Re_c$. In fact, at $Re_c = 1.3 \times 10^6$, the reduction in pressure drag is 45 per cent, even though the maximum available $C_m$ is 0.05 per cent. Note that at low $C_m$, actuation results in a small increase in pressure drag relative to the baseline and to the aerofoil with the inactive hybrid actuator ostensibly owing to an increase in the extent of the recirculating flow domain downstream of the actuator. The corresponding variation of $C_{Dp}$ with $\alpha$, figure 4b, shows that there is a minimal change in pressure drag owing to the presence of the inactive hybrid.

Figure 4. The effects of hybrid actuators. Actuator on the pressure side at $x/c = 0.21$: (a) variation of $C_{Dp}$ with $C_m$ for $Re_c = 6.7 \times 10^5$ (filled inverted triangle), $1.0 \times 10^6$ (filled square) and $1.3 \times 10^6$ (open square) and (b) variation of $C_{Dp}$ with $\alpha$. Dual, trailing-edge actuator configuration at $x/c_s = 0.95$: (c) bi-directional variation of $C_M$ with $\alpha$: unactuated (filled circle), pressure-side actuator (filled triangle), suction-side actuator (filled inverted triangle), both actuators (open diamond) and baseline (dashed black line). (Online version in colour.)
actuator. However, operating the actuator ($C_m = 0.2\%$) reduces $C_{D_p}$ substantially ($\Delta C_{D_p} \approx 0.07$) and uniformly over the entire range of $\alpha$. Of particular note are the (small) negative values of $C_{D_p}$ for $-2^\circ < \alpha < 3^\circ$, indicating that the reduction in pressure drag can further offset the friction drag provided it is unaffected by the presence of the hybrid actuator. DeSalvo & Glezer [69] showed that the integrated friction drag coefficients $C_{D_f}$ for the baseline aerofoil and the aerofoil with the inactive and active hybrid actuator were 0.0058, 0.0081 and 0.0076, respectively. These small increases in $C_{D_f}$ (which would be smaller for a tripped baseline boundary layer) are clearly smaller than the reduction in $C_{D_p}$.

Concentrations of trapped vorticity controlled by hybrid actuation can be staged at multiple locations around the aerofoil with cumulative or different effects. For example, DeSalvo & Glezer [69] showed that simultaneous actuation on the pressure side near the leading and trailing edges of the aerofoil results in increased pressure on the pressure surface between the actuators and a comparable decrease in pressure across the suction surface, and consequently in a small increase in lift and pressure drag, similar to the effects of a leading-edge slat and a trailing-edge flap. Actuation of the upstream or downstream actuator decreases the pressure drag to or below the level of the baseline aerofoil, and the drag reduction is larger when both actuators are operational, resulting in up to a 2.6-fold increase in $L/D_p$ (at $\alpha = 6^\circ$). Bi-directional variation in the pitching moment can be effected using controlled trapped vorticity concentrations on the suction and pressure surfaces to alter the Kutta condition near the aerofoil's trailing edge [64]. The variation of $C_M$ with angle of attack when the hybrid actuators (similar to Gurney flaps) are mounted near $x/c = 0.95$ is shown in figure 4c for the baseline aerofoil and in the presence of the inactive and active actuators. When the actuator on either side of the aerofoil is active, a significant moment increment (which varies with angle of attack) is induced relative to the aerofoil with the inactive actuators: pitch-up by the pressure-side actuator, and pitch-down by the suction-side actuator. These data show that the pressure-side actuation is more effective as $\alpha$ increases owing to the thickening of the boundary layer on the suction side.

Trapped vorticity actuation near the trailing edge was used to achieve closed-loop control in wind-tunnel experiments of pitch and plunge of a ‘free’ (NACA 4415) aerofoil in 2 d.f. [65,70]. The effects of the actuation near the trailing edge of the stationary aerofoil are assessed from time-averaged raster plots of distributions of the spanwise vorticity $\omega_{cv} U_0$ and sample streamlines, as shown in figure 5 ($\alpha = 3^\circ$, $0.85 < x/c < 1.14$ and $-0.05 < y/c < 0.08$, where the field of view includes the exit planes of the suction and pressure side actuator jets). In the absence of actuation (figure 5b), the baseline flow separates locally over the downstream edge of each of the actuators and forms a trapped vortex within the closed recirculation domains between each actuator and the trailing edge. Each of these trapped vortices has the same vorticity sense (clockwise, CW or counter-clockwise, CCW) as in the upstream boundary layer. Although the flow near the surface of the aerofoil upstream of the trailing edge is not fully resolved, it is possible to identify CCW and CW vorticity layers near the suction and pressure surfaces, respectively, that are induced by the upstream flow. By regulating the size and strength of these trapped vortices, it is possible to alter the pitching moments on the aerofoil (cf. figure 4). Activation of the suction-side actuators (figure 5a) reduces the thickness of the vorticity layer and minimizes
the trapped vortex, resulting in tilting of the flow downstream of the actuator towards the surface and in a reduction in the cross-stream width of the near wake. As shown by Muse et al. [65], this downwash is accompanied by an increase in circulation and lift and in nose-down pitching moment. Activation of the pressure-side actuators (figure 5c) causes the CCW trapped vorticity layer on the pressure side to become somewhat thinner and leads to an upwash of the near wake that is associated with a reduction in the lift and a nose-up pitching moment (relative to the unactuated aerofoil). It is noteworthy that pressure-side actuation results in significant changes in the trapped vortex upstream of the trailing edge on the suction side of the aerofoil and in migration of the stagnation point. The variation of the pitching moment (about \(c/4\)) with the amplitude of the actuation waveform \(u_t\) (normalized by the maximum actuation amplitude) over a range of angles of attack is shown in figure 5d \((-2^\circ < \alpha < 10^\circ)\). While \(\Delta C_M\) increases almost monotonically with \(u_t\) for pressure-side actuation \((u_t < 0)\), suction-side actuation \((u_t > 0)\) exhibits some latency for \(u_t < 0.2\), indicating a possible threshold in effectiveness that is presumably associated with the thicker boundary layer on the suction surface. As noted above, the effectiveness of the actuation on the suction side decreases with increasing \(\alpha\) and the magnitude of the maximum nose-down moment increment is about 60 per cent of the corresponding nose-up moment on the pressure side. The co-dependence of the induced lift and pitching moment increments \(\Delta C_L\) and \(\Delta C_{M,c/4}\) is shown in figure 5e for the entire dataset (about 3000 points) within the range \(-2^\circ < \alpha < 10^\circ\), \(-1 < u_t < 1\), and for several streamwise positions of the actuators \(x_{PS}\) and \(x_{SS}\). It is remarkable that the entire dataset collapses on a single linear distribution with a slope of \(\partial \Delta C_L / \partial \Delta C_{M,c/4} = -3.2\) (for a thin aerofoil \(\partial C_L / \partial C_{M,0} = -4\)). The collapse of

**Figure 5.** Time-averaged vorticity field in the near wake with overlaid sample streamlines at \(\alpha = 3^\circ\) for (a) suction-side actuation, (b) no actuation and (c) pressure-side actuation. (d) The variation of the induced pitching moment increment \(\Delta C_M\) with (normalized) actuation level \(u_t\) (pressure side, filled inverted triangle; suction side, filled triangle) at \(\alpha = -2^\circ, 3^\circ\) and \(10^\circ\). (e) The variation of the induced increments in lift \((\Delta C_L)\) and pitching moments \((\Delta C_M)\) for a 3000 point dataset over a range of \(u_t, \alpha, x_{PS}\) and \(x_{SS}\).
Figure 6. Transition from inactive actuators to full suction-side actuation: the phase-averaged vorticity field in the near wake at (a) $t/T_{\text{conv}} = 0$, (b) 0.2, (c) 0.4, (d) 0.6 and (e) 0.8. (f) An $x-t$ diagram of the (cross-stream) vorticity flux into the wake (downstream of the trailing edge) following the transition and (g) the time history of circulation increment from integrated vorticity flux.

The characteristic time scale associated with response of the flow to actuation is a crucial parameter for the implementation of real-time control and is investigated using step transitions between pressure-side and suction-side actuations. Figure 6a–e are a sequence of phase-averaged spanwise vorticity maps following the onset of suction-side actuation from a previously unforced state (inactive hybrid actuators) within the domain $0.16 \times 0.16c$ downstream of the trailing edge. In the unactuated state (figure 6a), the CW and CCW vorticity layers from the suction and pressure surfaces merge and mix within the near wake. Following the onset of suction-side actuation, the vortex sheet is severed (figure 6c, $t = 0.4T_{\text{conv}}$, $T_{\text{conv}}$ is the convective time scale of the flow over the aerofoil) and forms a single ‘isolated’ CW vortex that is advected with the flow and leads to the pinching of a CCW vortex from the vorticity layer of the pressure side (figure 6d). The flow begins to relax to the new ‘forced’ state in figure 6e ($t = 0.8T_{\text{conv}}$). The time scale associated with the flow response to this transitory (step) actuation is computed from the phase-averaged vorticity flux integrated in the cross-stream direction at each streamwise ($x$) position within the measurement domain downstream of the trailing edge (an $x-t$ diagram of the flux is shown in figure 6f). The shed CW vortex is disconnected from the trailing edge at $0.25T_{\text{conv}}$, advected downstream with celerity of 0.7 $U_0$, and exits the measurement domain at $0.5T_{\text{conv}}$. The $x-t$ diagram also shows evidence of alternate shedding of weaker CW and CCW vorticity concentrations for the duration of the phase-averaged measurements. It is noteworthy that the shedding frequency has a Strouhal number of 3.8, which corresponds to shedding on June 28, 2017
frequency of the unactuated aerofoil. The vorticity flux at a streamwise station immediately downstream of the trailing edge is integrated forward in time to obtain the time history of the change in circulation about the aerofoil during the transition process (figure 6g). The initial shedding of CW vorticity concentration is associated with an initial reduction in circulation (at about 0.5 $T_{\text{conv}}$), which is followed by shedding of CCW vorticity concentrations that are accompanied by a circulation buildup about the aerofoil ($t > 0.5 T_{\text{conv}}$) until and settling at a new steady level. Perhaps the most salient feature of the circulation time history is the indication that the entire flow over the aerofoil readjusts within about 1.5 $T_{\text{conv}}$. This illustrates that flow-control actuation can be typically effected on time scales that are commensurate with the flow’s convective time scale, and that maneuver response of an aerodynamic platform is limited by the platform’s inertia.

4. Concluding remarks

The potential of synthetic-jet actuation for versatile aerodynamic flow control in a broad range of applications has been demonstrated in numerous experimental and numerical investigations. Two control strategies that differ substantially in terms of the coupling mechanisms between the control input and the embedding flow have emerged. The first approach focuses on mitigation of separation where the characteristic actuation period is commensurate with the convective time scale over the separated flow domain, and emphasizes actuation frequencies that are of the order of the vortex shedding frequency from the separated shear layer. In this approach, the actuation frequency couples to and in fact drives vortex shedding, and leads to the deflection of these vortical structures towards the surface of the stalled aerofoil with significant recovery of (albeit somewhat unsteady) lift. The second control approach is based on a quasi-steady modification of the apparent aerodynamic shape of the surface by using controlled interactions between synthetic-jet actuators and the cross flow to form localized concentrations of trapped vorticity that can exceed the local boundary-layer thickness. The actuation period is selected to be at least an order of magnitude shorter than the relevant global time scale of the base flow, and the actuation frequency is high enough to render the interactions between the actuator and the cross flow effectively time invariant and decoupled from the global instabilities. The utility of trapped vorticity for flow control has been demonstrated not only for separation control, but has also been effective for controlling the aerodynamic forces in fully attached flows (e.g. at low angles of attack).

The role of controlled trapped vorticity concentrations in the modification of the aerodynamic forces has been investigated in some detail in the flow over a circular cylinder. Active modification of the apparent shape of the surface can enable the tailoring of the adverse pressure gradient to overcome local separation, leading to significant changes in the near wake and in the lift and drag that appear to be insensitive to the state of the boundary layer. It was demonstrated that trapped vorticity concentrations engendered by either a miniature passive obstruction or a synthetic jet can yield similar changes in lift and drag, even though the topologies of these concentrations are significantly different. Trapped vorticity concentrations were also used for inducing controlled changes in global aerodynamic forces on aerofoils at low angles of attack. Controlled concentrations

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of trapped vorticity near the trailing edge and elsewhere on the aerofoil can lead to a substantial reduction in pressure drag with minimal changes in skin friction or loss in lift. Furthermore, nominally symmetric vorticity concentrations on both surfaces near the trailing edge result in variable, bi-directional changes in the pitching moment without moving control surfaces. These changes in the aerodynamic forces and moments are effected on time scales that are commensurate with the flow’s convective time scale, indicating that flow-control actuation can be typically applied much faster than with conventional control surfaces and can be exploited for rapid manoeuvring.

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