Simulation of slot and round synthetic jets in the context of boundary-layer separation control

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Synthetic jets—also referred to as mass-less jets—offer the potential of effective, on-demand, fluid-based control of separating boundary layers on highly loaded aerodynamic surfaces, without the need for a mass source. However, the control authority that may optimally be derived from such jets, and any generality of the underlying flow physics are obscured by the wide range of geometric and flow parameters that contribute to their performance characteristics. The present article reviews the state-of-the-art in the area of computational modelling and simulation of synthetic jets, with emphasis placed on key fluid-mechanics phenomena. The review is divided into two principal parts, one focusing on slot jets and the other on round jets. Within the latter part, ongoing research by the authors on the simulation of synthetic jets discharged into a separated boundary layer is highlighted as an example of the current status in this area.

Keywords: synthetic jets; computational prediction; large-eddy simulation; boundary-layer separation

1. Basic features and relevance of synthetic jets

A synthetic jet—strictly a pair—is formed as a consequence of a fluid being pushed and pulled periodically through an orifice. In highly simplified terms, this actuation causes two trains of vortices to be formed, each set merging, in a time-averaged sense, into jet-like entities. In what follows, the term injection should thus be understood as the outcome of the time-dependent actuation that involves consecutive expulsion and suction phases within an actuation period.

The earliest technological realization and exploitation of a synthetic jet appears to be that reported by Ingard [1], in the context of the design of acoustic resonators. A brief discussion by Saffman [2], under the heading dynamics of vorticity, of a periodically ejected train of interacting vortices, visualized experimentally by Glezer [3], is perhaps the earliest account pertinent to the fluid mechanics of a synthetic jet discharged into stagnant surroundings.

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Figure 1. Phase-averaged images of a round synthetic jet actuated upstream of turbulent separation (§4) covering a single cycle; the images show contours of the pressure Laplacian at four different phases during the cycle (red lines indicate local reverse flow): (a) $3\pi/8$, (b) $5\pi/8$, (c) $7\pi/8$ and (d) $9\pi/8$.

In a practical setting, a synthetic jet is most frequently realized by oscillating the wall of a cavity on one side of the orifice, while on the other side, the vortical structures leaving the aperture interact with a boundary layer, as illustrated in figure 1 with reference to two cases, which differs by the geometry of the aperture (slot or round jet). These cases are presented in more details in §§3 and 4. The mass-flow rate through the aperture typically (but not necessarily) follows a near-sinusoidal pattern, so that the net mass-flow rate through the orifice is zero. However, because of the irreversibility of the motion, associated with viscosity and separation from the orifice edge, there is a net expulsion of vorticity from the aperture (figure 1). During the expulsion stage, vorticity flux and associated circulation (the time integral of the former) are ejected into the outer flow and propagate away from the orifice. In the following suction stroke, the fluid ingested originates predominantly from the area close to the wall surrounding the orifice. Hence, this suction does not reingest the circulation ejected, and the result is a net unsteady ejection of vorticity that, if time averaged, gives rise to a jet with broadly similar (far-field) characteristics to those of a continuous jet—albeit weaker in intensity [4]. This process, appropriately configured, allows the character of the cross flow to be influenced—or controlled—without the need for a mass source. A more detailed discussion of the fluid mechanics associated with the images in figure 1 will be given in §§3 and 4.

Practical interest in synthetic jets, in the context of flow control, is rooted in their potential for effecting on-demand attenuation or prevention of separation of boundary layers subjected to adverse pressure gradient. In simple terms, a synthetic jet causes additional mixing by streamwise vorticity and turbulence, without the introduction of solid, fixed, vortex generators. This is particularly attractive in air transportation where specific boundary-layer control may be needed in high-lift operation during landing or in low-momentum junction regions, whereas such control may be disadvantageous in cruise conditions.
While the flow-control potential of synthetic jets should be evident from the above comments, in general terms, the details of this control depend greatly on many parameters, with each set giving rise to different associated fluid-mechanics scenarios. The most important variable is the geometry of the orifice. The behaviour of the ejected vortices and the manner in which they interact with the cross flow are much more complicated in the case of circular jets than slot jets. The interaction is also weaker and more subtle. Other important variables include the angle of injection, the position of the orifice relative to the nominal separation location in the uncontrolled flow, the cavity and orifice-duct shape, the jet-to-outer-flow momentum ratio, the frequency of the injection, the duty cycle, the mean and turbulence properties of the boundary layer in the cross flow, the Reynolds number of the jet and the boundary layer, and the details of the separated flow to be controlled. This complex multi-dimensional parameter space makes it extremely difficult to derive general conclusions and guidelines on the control effectiveness of synthetic jets, as a single category, and the associated fluid mechanics. Hence, past studies provide no more than a (sparse) knowledge base that yields general pointers, rather than quantitative data. In the following review, we focus on some common elements, derived from computational studies only. Attention is restricted to the control of separation on semi-infinite surfaces, while the subject of the interaction of separation with circulation over closed bodies is excluded. Elements of experimental research are reviewed by Glezer [5] in the present issue.

2. Computational challenges

Prior to a discussion of specific studies, grouped under slot jets and circular jets, it is appropriate to highlight some common challenges that arise in efforts to compute the flows in question.

Synthetic-jet scenarios have been computed with both statistical (Reynolds-averaged Navier–Stokes; RANS) models and with scale-resolving approaches (large-eddy simulation (LES) and direct numerical simulation (DNS)). The obvious attraction of RANS lies in its economy: it gives (nominally) a phase-averaged representation of the flow, and thus allows far larger time steps to be used in the computational solution, this time step being scaled with the injection period, rather than with the turbulent motions; it allows (again nominally) statistically spanwise-homogeneous geometries to be computed in a two-dimensional fashion; and it permits a coarser mesh to be used, as the phase-averaged fields of statistical quantities vary much more smoothly than the field of instantaneous turbulent motions. However, there are potentially serious penalties to pay for this economy: RANS models are ill-suited to time-varying flows, especially if the frequency of this variation is of the same order of magnitude as that of the turbulent motion, as is the case in many applications; RANS models are known to often give a poor representation of separated flows, even if statistically steady, owing to insufficient level of turbulence activity predicted in the separated shear layers; and RANS models cannot properly represent spectral resonance between the actuation and natural instability modes in the upstream boundary layer and the separated flow. While there are examples of the RANS method giving reasonable first-order representations of the primary effects of
synthetic jets (e.g. [6,7]), the details of the representation are model dependent. Also, as demonstrated by Dandois et al. [6], for the case of circular-jet injection into an attached boundary layer, the jet structure returned by RANS modelling is very far from that returned by the corresponding high-quality scale-resolving simulation.

On the other hand, scale-resolving simulations pose a number of major challenges, some not encountered in most other flows. Perhaps, the most serious one is the scale disparity between the very small jet orifice and the large body of fluid being controlled by the jet, the linear ratio of dimensions being of the order of 0.01 or less. This is especially so in the case of circular jets, and gives rise, on its own, to a serious grid-resolution problem. Although the orifice need not be very small, in principle, its size is constrained, in practice, by the need for high expulsion velocity, low cavity volume and surface integrity. The need to resolve the viscosity-affected near-wall region of the boundary layer, which is usually extensive in size and at high Reynolds number, substantially aggravates the resource problem. Next, the nature of the expulsion and suction phases, constituting the complete injection cycle, necessitates, in principle, the resolution of the cavity and duct from which the jet issues and into which fluid is being drawn from the boundary layer during the ingestion part of the cycle. This is, again, especially important in circular-jet injection because the jet properties at the orifice, and thus its evolution in the boundary layer, are strongly affected—more so than in slot jets—by the boundary layer and by the state of the flow inside the cavity. In addition, when the working medium is air or another gas, the acoustic characteristics of the cavity are important, and Helmholtz resonance effects may be influential. However, this introduces a time scale that is very much smaller than the injection period and also of the influential turbulent motion in the boundary layer. Yet, a further problem posed by the unsteadiness is that statistically converged time-averaged and, even more so, phase-averaged and stochastic turbulence data are extremely difficult to obtain because this requires many injection cycles to be included in the simulation, and also because there are no homogeneous directions in circular-jet actuation (unlike in slot-jet injection) over which integration can be performed. Finally, the boundary layer approaching the jet cannot be computed from its inception, far upstream, and this necessitates the prescription of turbulent (unsteady) conditions across an inflow plane fairly close to the jet. The last item is, strictly, pertinent only to high-fidelity DNS and LES computations. In contrast, in detached-eddy simulation, the attached flow upstream of injection or separation is computed with a RANS method, and the LES component is activated upon separation being encountered. Examples are the studies of Qin & Xia [8] and Lopez & Moser [9]. Self-evidently, the advantage of this hybrid approach is economy, but the disadvantage is loss of fidelity because the spectral nature of the upstream flow is influential on the jet/boundary-layer interaction.

3. Slot jets

There is a marked predominance in the literature of studies that focus on geometrically two-dimensional (or nearly two-dimensional) slot-jet configurations
relative to circular jets. There are several reasons for this, some fairly obvious, others less so.

— The control authority that can be exercised with a slot jet, or with several high-aspect-ratio rectangular orifices forming a slot, is substantially greater than that with a circular jet having a diameter equivalent to the slot width—unless a dense array of closely spaced circular jets is used. This is mainly owing to the far greater momentum and vorticity flux ejected across the entire spanwise extent of the flow. Hence, the observed sensitivity of the separation to the actuation is substantial.

— A slot jet offers greater potential for achieving an advantageous spectral resonance with two-dimensional instability modes in the separated shear layer.

— The statistical properties of slot jets can be adequately characterized by the conditions across a single spanwise plane. This is advantageous, in terms of data volume and costs, in both experimental campaigns and computational studies, especially if the latter are undertaken within the RANS framework, in which case, highly economical two-dimensional computations are possible. In the case of scale-resolving simulations (DNS and LES), an advantage arising from the two-dimensionality of slot jets is that their meshing (especially with structured grids) is much easier and that the spanwise mesh density can be kept uniform.

— Because of the strength of the control derived from slot jets, the fidelity of the solution relies less on the inclusion of the discharge duct and the full cavity. Indeed, both are often ignored, with the discharge conditions prescribed explicitly at the jet orifice or slightly into the discharge duct. Moreover, the detailed resolution of the near field around the jet orifice is less important than for a circular jet, and this permits a lower grid density around the slot.

— In basic computational studies in external aerodynamics, attention often focuses on two-dimensional aerofoil sections, rather than on realistic three-dimensional swept wings, principally because of the economy offered by two-dimensional RANS methods in spanwise-homogeneous conditions. This has also motivated related two-dimensional studies of synthetic-jet control with slot jets on aerofoils, within which a range of parametric variations could be explored economically (e.g. [10,11]). Clearly, however, this approach represents a major simplification of reality, with attendant penalties to physical fidelity.

The generic fluid-mechanic processes by which synthetic slot jets effect separation control may be explained with reference to the configuration shown in figure 2, together with the instantaneous flow visualization of figure 1a. This particular flow is, without doubt, the most popular computational test case in its category, because of the availability of extensive experimental data obtained at the National Aeronautics and Space Administration (NASA) by Greenblatt et al. [13,14] for a range of injection and suction conditions, among them synthetic-jet injection. These data formed the basis of two major workshops: one organized by NASA [15] attracting more than 50 computational contributions by 13 participants; and the other, more modest, organized by the European Research Community in Flow, Turbulence and Combustion [16].
Figure 2. Control of separation behind a dune-shaped hump with a synthetic slot jet: results from an LES study by Avdis et al. [12], corresponding to experiments by Greenblatt et al. [14]. (a) Instantaneous realization, (b) time-averaged recirculation with and without actuation and (c) phase-averaged stream traces relative to experimental data.

A boundary layer having a momentum-thickness Reynolds number of about 6000 is made to flow over a dune-shaped hump, separating slightly downstream of its crest and forming a recirculation zone of a length of approximately 0.4 of the bump chord. Stochastic turbulence apart, this zone is essentially steady in so far as it does not display coherent time-dependent motions. The synthetic jet with a close to sinusoidal mass-flux variation is discharged almost horizontally and slightly upstream of the nominal separation line at a maximum velocity of 0.77 times the free-stream velocity $U_\infty$ at a frequency of 138 Hz, corresponding to a Strouhal number $St_L = fL/U_\infty = 0.77$, where $L$ is the length of the separated shear layer in the uncontrolled flow. The significance of this frequency will be discussed later, but it is noted here that values in the range of 0.5–1.5 are often observed to yield maximum reduction in separation, given fixed conditions otherwise. It is also noted here that effective separation control relies on rather high jet-velocity values, with maximum values typically in the range of 0.5–2 times the maximum velocity in the separated shear layer.

Among the many solutions contributed by Rumsey et al. [15], those obtained with RANS yielded recirculation-zone lengths, even for the baseline case, well in excess of that observed experimentally, reflecting a serious underestimation of the turbulence activity within the separated shear layer, especially with more advanced anisotropy-resolving turbulence closures; this is an ubiquitous defect observed in a variety of separated flows, especially when separation occurs on a gently curved surface. In addition, RANS solutions cannot account properly for any spectral resonance between the injection and natural instability modes in the separated shear layer. Scale-resolving solutions for the synthetic-jet conditions were contributed by You et al. [17], Saric et al. [18], Morgan et al. [19] and Avdis et al. [12]. The results in figure 2 are taken from a study by Avdis et al. [12], one that has been found to give particularly close agreement with the experimental data.
Figure 2a shows an instantaneous realization, visualized by iso-surfaces of $V = \pm 0.25 U_\infty$. Although the flow is evidently highly three-dimensional, the spanwise rollers associated with the injection are clearly recognized. Figure 2b shows the injection to result in a substantial reduction in the time-averaged size of the recirculation zone, by a process that will be discussed below. The predicted reduction in length, 30 per cent, is close to that recorded experimentally, at 28 per cent. The most informative view is derived from phase-averaged fields, such as those given in figure 2c, which compares computational with experimental stream traces at four phases. The injection is seen to cause the recirculation zone of the baseline flow (lower plot of figure 2b) to break up into a train of smaller recirculation zones, with stretches of attached flow separating them. On average, there are around 1.5–2 such regions present within the length of the baseline recirculation zone. This can be understood upon noting that $St_L = 0.77$, in combination with a convection velocity of disturbances in the separated shear layer of around $0.5 U_\infty$, suggesting that a distance of about 0.65$L$ separates sequential jet-actuated pulses.

Within a phase-averaged framework, the expulsion phase may be thought of as the periodic injection of two vortex sheets, one on the underside and the other on the upper side of the synthetic jet, which roll up into the vortices sketched in figure 2c. The upper anti-clockwise vortex is carried upward and forward by the combined action of the Magnus force [20] and forward/upward-directed advective motion from the separating shear layer. The lower vortex is trapped in the near-wall layer and enhances the clockwise vorticity in the recirculation zone. The upper train of vortices is to oppose the vorticity in the separated shear layer, accelerate this layer and induces a Coanda-like streaming effect that favours attachment. The intermittent reattachment that results from the injected vortices translates into a substantial increase in time-averaged turbulent shear stress in the separated shear layer and hence early reattachment. The details of the process are likely to be considerably more complicated. In particular, the periodic extra straining can be expected to cause extra production of stochastic turbulence energy and stresses, i.e. components that are entirely different from the periodic (phase-averaged) contributions. This distinction will be pursued in §4, in relation to round jets.

Computational studies that offer reinforcement of some of the arguments given above, as well as providing much additional insight into pertinent fluid-mechanic interactions, are those of Dandois et al. [21], Neumann & Wengle [22] and Dejoan & Leschziner [7]. The third study, in particular, reports LES-derived predictions of a synthetic slot jet injected at 45° into a channel flow that separates from a backward-facing step at a step-height Strouhal number, $St_H = 0.2$, corresponding to $St_L = 1$, where $L \approx 5H$ is the baseline recirculation length. Experimental studies for the same flow by Yoshioka et al. [23] demonstrate a maximum reduction in the baseline separation length of around 30 per cent, well reproduced by the simulation. Phase-averaged vortical patterns reported by Dejoan & Leschziner [7] are remarkably similar to those in figure 2, despite the very different geometry, large differences in flow conditions, especially in the ratio of pre-separation boundary-layer momentum thickness to the length of the separated shear layer, and a factor 30 difference in the respective Reynolds numbers. The LES study reveals, among a number of interactions, that the increase in the time-averaged shear stress, primarily responsible for reducing the separated region, results not
only from the coherent vortical motions induced by the actuation, but also from
an enhancement in mixing provoked by extra generation of stochastic turbulence,
owing to unsteady straining in areas lying roughly midway between consecutive
vortical structures.

A topic that has been the subject of much debate is the role of resonance
between the frequency of the actuation and natural instability modes in the
baseline flow. Discussions around this subject pertain virtually exclusively to
slot jets, as opposed to round jets, because resonance relies on the actuated
disturbances being able to interact with two-dimensional instability modes.
There are at least three instability modes that are assumed to be influential in
reattaching shear layers: the shear-layer, the shedding (or step) and the flapping
modes. A fourth that has been mentioned, albeit rarely, is the bursting frequency
of hairpin vortices in the boundary layer approaching separation, but there is
virtually no evidence that this mode is pertinent. The shear-layer mode is linked
to Kelvin–Helmholtz instabilities in the separated shear layer. Hasan & Khan [24]
show that this is characterized by \( St_\theta = 0.011 \), where \( \theta \) is the momentum thickness
at the location of separation. For turbulent separation from a backward-facing
step, Hasan & Khan [24] also observe, based on controlled-excitation experiments,
that the shedding mode is characterized by \( St_H = 0.185 \), independent from the
state of the separated shear layer. An argument advanced by Hasan & Khan [24],
also stated in Dandois et al. [21], is that the shedding mode is linked to the
shear-layer mode by a sequence of vortex pairing, with the former becoming the
dominant mode as the shear layer evolves. This is the reason why the actuation
frequency for separation control is generally chosen to be around \( St_H = 0.2 \),
regardless of the upstream boundary-layer characteristics. If the length of the
separated shear layer is taken to define the Strouhal number, the above value for
\( St_H \) translates to \( St_L \) in the range of 0.5–1, depending on the flow. Indeed, Dandois
et al. [21] provide a table of around 20 flows for which they list the shedding-mode
Strouhal number (based on separation length) to be mostly in the range of 0.5–0.8.
As the convection velocity in the shear layer is around 0.4 times the free-stream
velocity, the above range suggests the presence of around 1.5 actuation-induced
vortical structures along the separated shear layer, as is seen in figure 2.

It is interesting to observe that the actuation frequency in the case of
figure 2, \( St_H = 0.2 \), translates to \( St_\theta = 0.01 \), while the corresponding value in the
case examined by Dejoan & Leschziner [7] is \( St_\theta = 0.03 \), quite different from
the shear-layer mode given by Hasan & Khan [24]. Yet, Yoshioka et al. [23]
show this actuation frequency to give the maximum reduction in recirculation
length, supporting the supposition that the shear-layer mode is of subordinate
importance to the optimum actuation frequency. Consistently, Neumann &
Wengle [22] also report, based on a range of LES computations for a flow
separating from a curved step, an optimal actuation frequency at \( St_H = 0.2 \), which
corresponds to \( St_L = 0.8 \). In contrast, Dandois et al. [21] argue, for the case of
the curved backward-facing step, that their choice of actuation at \( St_H = 0.14 \),
corresponding to \( St_L = 0.5 \), is the most appropriate, as it is consistent with
the frequency of the first sub-harmonic of the Kelvin–Helmholtz mode in the
separated shear layer, associated with pairing. This frequency suggests that
the optimum actuation is characterized by the presence of a single vortical
perturbation within the separated shear layer at any one time. It is evident,
therefore, that there is some uncertainty and inconsistency in the interpretation
of the links among the shear-layer mode, the shedding mode and the actuation frequency. On the whole, however, the level of disagreement with respect to the choice of actuation frequency is relatively modest, with most studies suggesting that the maximum reduction in recirculation is achieved with actuation in the range of $St_L = 0.5–1$. Finally, the third instability mode, the flapping mode, is associated with a temporally varying imbalance between the entrainment rate into the lower part of the separated shear layer and the amount of fluid returned to the recirculation bubble in the reattachment zone [25]. This mode is characterized by frequencies substantially lower than that of the shedding mode, and is generally regarded as irrelevant to any issues of resonance with the actuation.

A major question mark against the generality of the above observations appears to arise from experimental observations by Amitay et al. [26] and Glezer & Amitay [27], among others, that actuation frequencies are an order of magnitude higher than those considered earlier, i.e. $St_L = 10$ can be highly effective in controlling separation from cylinders and aerofoils. Woo & Glezer [28] also show, by reference to a range of experiments on an aerofoil configuration, that an asymmetric duty cycle—a very short ejection stroke, followed by a relatively long ingestion stroke—is also highly conducive to separation control. Both observations are intriguing. At this high frequency, the actuation is spectrally decoupled from any macro scales of the controlled flow. In fact, this frequency is observed to be within the inertial sub-range of the turbulence spectrum at relatively low Reynolds numbers, and thus cannot be the source of interactions with large energetic scales. The process by which control is effected is then akin to that of a continuous jet that reduces, by streaming, the difference between the actual solid body and the virtual body that is created by displacement and separation. In effect, the synthetic jet increases the Coanda mechanism by accelerating the flow at the edge of the separation region. As to the temporal details of the injection cycle, a short explosive ejection is thought to avoid the formation of trailing vortices, or a trailing vortex sheet, behind a head vortex, due to vorticity saturation in the vortex [29]. Moreover, the weak and prolonged suction stroke avoids a reingestion of ejected vorticity, so that all this vorticity is used in the control process.

4. Round jets

As noted earlier, round synthetic jets pose considerably greater computational challenges than slot jets. Among the most important are those that arise from (i) the need for a much higher local resolution around the jet orifice, (ii) the importance of accounting for the flow in the cavity and jet duct, (iii) associated with (ii), the higher complexity of the geometry, requiring meshes of different topologies to be interfaced (unless the mesh is unstructured), and (iv) the absence of statistically homogeneous directions that aid the derivation of converged statistical information by spanwise averaging. The main argument for including the cavity (or cavities) in the simulation arises from the observation—for example, by Leschziner et al. [30] and Dandois et al. [6]—that the phase-averaged velocity profiles across the orifice are highly asymmetric in space and irregular in time, suggesting a strong interaction between the conditions at the jet exit and the
cavity. An additional, potentially influential, process is the transport of cavity turbulence into the cross flow during the expulsion phase, especially pronounced when the orifice duct is short.

In view of the above comments, it is not surprising that relatively few computational studies have been published on round jets. Of these, most relate either to laminar conditions [31] or to injection into the attached turbulent boundary layers [6,32]. A very recent study of laminar round-jet injection into a separating laminar boundary layer undergoing transition is that of Ozawa et al. [33]. One additional fact that has militated against the emergence of a richer literature on round jets is that a practically effective exploitation of round jets is likely to require several streamwise rows of jets, each consisting of many jets that are separated, typically, by five orifice diameters or less. The simulation of this scenario is clearly a monumental task, and this has encouraged a focus on single or twin jets, the latter assumed to represent a spanwise periodic row.

Some of the basic fluid-mechanic interactions between a round jet and a boundary layer may be discussed with reference to the particular configuration shown in figure 1, which provides images of the phase-averaged structures evolving during the actuation cycle of a turbulent jet injected into a turbulent boundary layer upstream of separation (see §5 for details). However, there is a material dependence of the details of the interaction on the frequency and intensity of the actuation (e.g. jet/boundary-layer velocity ratio), and the generality of the discussion is thus necessarily limited. This is illustrated, for example, by computations of Zhou & Zhong [31], supported by experiments of Jabbal & Zhong [34] for various laminar-flow conditions. A relatively low actuation frequency is observed to give rise to hairpin structures with trailing vortex legs (or tails), while high frequency results in the ejection of essentially isolated, tilted and streamwise-stretched vortex rings, with their head lifted by the Magnus force [20]. Low-frequency injection is associated with large stroke length, \( L^* = L/D = (1/D) \int_0^{T_0} V_{jet} \, dt \), where \( T_0 \) is the expulsion portion of the injection cycle, while high-frequency injection gives rise to short stroke length. The heads of the ejected vortices provoke large periodic disturbances in the outer layer into which they penetrate and in which they propagate, by virtue of the rotational motions they induce, which cause outer boundary-layer fluid to be drawn towards the wall and inner fluid to be pulled upwards. The streamwise vorticity associated with the streamwise-stretched portions of the vortex rings, or the legs of the hairpin vortices, likewise give rise to a convective exchange of near-wall and outer fluid. The motion on the lower side of the vortices, towards the jet centre plane, then induces secondary vortices closer to the wall by a streamwise realignment of initially spanwise vorticity in the boundary layer, combined with the vorticity ejected with the jet from the downstream portion of the orifice edge, which is trapped within the slow near-wall layer. In simplified terms, the transverse field is characterized by a periodic formation of two pairs of counter-rotating vortices, one strong outer pair and a weaker inner pair. Both contribute, although unequally, to the process of separation control, by wall-normal momentum mixing, the contribution of coherent motions to the time-mean stresses and the extra generation of stochastic turbulence by the unsteady straining associated with the periodic actuation. Both Leschziner et al. [30] and Dandois et al. [6] show that, as the Reynolds number increases, the impingement of the boundary layer onto the exiting jet plug results in a multiplicity of vortex

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rings wrapped around the ejected jet fluid. The resolution of these features is poor (or non-existent) when the numerical-grid density is coarse and/or a RANS method is used.

Two major studies have been published on the interaction between round jets and the attached turbulent boundary layer. One, already mentioned, is by Dandois et al. [6], while the other is by Wu & Leschziner [32]. These studies are pertinent to the present account in so far as they quantify the effect of the actuation on the boundary layer downstream of the orifice, but within a region that lies upstream of the separation line, as is the case in the flow discussed in the next section.

The two studies target different configurations, corresponding to two related sets of experimental data, but the principal flow conditions are not dramatically dissimilar: $Re_D = 2380$ and $St_D = 0.069$, where $D$ is the jet diameter, and a ratio of maximum jet velocity to free-stream velocity of 2.0, in the case of Wu & Leschziner’s study, and $Re_D = 4275$, $St_D = 0.019$ and a velocity ratio of 1.45, in the study of Dandois et al. The global mesh size was also similar in both cases (about $9 \times 10^6$ nodes), but the more flexible H–O grid topology in the latter study, relative to a pure H-topology coupled with the immersed boundary method in the former study, allowed a much finer resolution than in the former around the jet orifice—albeit at the penalty of significant local mesh distortions. In both cases, the cavity below the jet was included in the simulations, and the computational inflow conditions included (at least in some simulations) a full representation of the unsteady turbulent state of the boundary layer.

While the studies reveal a wide range of interesting features, the most important common observations may be summarized as follows:

— the lateral domain within which the jet modifies the base flow is narrow, extending to only around one dimension on either side of the jet centre plane,
— two major time-averaged vortex pairs are formed, one in the outer portion of the boundary layer, reflecting the trajectory of the jet, and another counter-rotating close to the wall,
— a modest acceleration of the streamwise flow near the wall occurs, owing to streamwise momentum being transported towards the centre plane by the near-wall vortex pairs,
— substantial distortions are caused in the phase-averaged velocity profiles in the near-orifice field, associated with near-wall flow acceleration and the presence of a distinct velocity maximum in the region in which the head of the ejected vortex induced flow acceleration,
— the control effect of the actuation decays rapidly beyond around $x/D = 5$, following a modest increase of about 30 per cent in the boundary-layer displacement and momentum thicknesses, and
— strong distortions arise in the velocity field across the orifice, as already noted, suggesting that it is imperative to resolve the flow below the orifice.

The most important lesson to carry forward from the above observations is that the control authority exercised by an isolated round jet is modest, despite its high momentum. This is simply a consequence of the large-scale disparity between the jet and the flow being controlled. As already noted, this implies the need for large arrays of circular jets if strong control authority is to be exercised.

5. Separation control with round jets

Some of the general arguments presented in the previous section are illustrated and amplified in the present section with reference to ongoing studies pursued by the authors. Specifically, results arising from a particular study are introduced and discussed to convey an impression of the current state of the art and the potential offered by scale-resolving simulations in gaining insight into physical phenomena.

The configuration examined is shown in figure 3: a pair of jets, 10 orifice diameters $D$ apart, injected normally into an attached boundary layer that separates around $8D$, further downstream from a rounded step. The computational geometry and flow conditions adhere closely to those of an experimental study by Zhang & Zhong [35].

The step itself is an extension of one investigated by Song & Eaton [36], without any connection to flow control. The jets are actuated by shaking pistons on the sides of the circular cavities shown in figure 3. The upstream-shifted location of the jets is constrained by the need to accommodate the cavities and the shaking mechanism below the curved wall. The Reynolds number of the boundary layer, based on the free-stream duct velocity, $U_{in}$, and step height, $H$, is 13700, the boundary-layer momentum thickness Reynolds number is 1150, the normalized peak injection velocity, $V_r/U_{in}$, is 1, the jet Reynolds number, based on $D$ and $V_r$ is 2750, and the injection-cycle frequencies investigated are $f = 40$ and 200 Hz. The former value corresponds to a Strouhal number, $St = fU_{in}/H$ of 0.19, equivalent to $St_r = fU_{in}/L_r$ of approximately 0.7, where $L_r$ is the length of the recirculation zone.

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in the unactuated flow. As discussed earlier, values in the range of 0.5–1.0 have been observed in various studies of slot jets to yield a close-to-maximum response to the actuation, and this is related to shedding-mode instability in the separated shear layer forming the outer region of the recirculation zone. It must be pointed out, however, that the instability mode in question is largely two dimensional in character, so that the strongly three-dimensional and local perturbation effected by the circular jets is not expected to have the same significance and impact, in terms of the actuation frequency, as in the case of slot jets.

The solution domain is treated as spanwise-periodic, includes two jets and extends from the lower wall to the upper duct wall of the experimental wind tunnel. The boundary layer on the lower wall is resolved with high fidelity on a fine grid, while the much less important upper-wall boundary layer is resolved on a coarser grid with the aid of a log-law-based wall function. The inlet conditions of both boundary layers are specified by means of a database of 5000 fields extracted from a precursor boundary-layer simulation. The grid used to cover the domain in figure 3 is a multi-block finite-volume ensemble, comprising some 12.8 $\times$ 10$^6$ cells in total. The cavity and orifice are accommodated with the aid of an immersed boundary treatment. The LES formulation advances the velocity field in time by means of a fractional-step method incorporating second-order approximations for the fluxes and a new third-order Gear-like scheme documented by Fishpool & Leschziner [37]. Zero divergence is secured by solving the pressure Poisson equation, which combines the application of an implicit successive over-relaxation (LSOR) method with a multi-grid scheme. Any odd–even oscillations are counteracted by a dynamic total-variation-diminishing-like wiggle-suppression scheme, which introduces a minimal amount of second-order upwind-weighted differencing. Subgrid-scale turbulence is accounted for by way of the Germano–Lilly dynamic model or by a local mixed model (involving no averaging), both giving very close results.

A global view of the effectiveness of the actuation is conveyed in figure 4. This compares, in figure 4a, the separation and reattachment behaviour as derived from the conditions closest to the wall ($y^+ O(1)$); in figure 4b, velocity profiles; and, in figure 4c,d, streamwise turbulence-intensity profiles in both the baseline and actuated flows. The most important observation arising from the comparisons is that the influence of the actuation on the separation is modest, with computation and experiment showing a very similar response. Thus, the recirculation bubble is shortened, but only by 17 per cent. The velocity profiles clearly indicate that injection leads to the elevation of the velocity in the near-wall region, thus delaying separation. Moreover, it is clear that another consequence of the injection is a major perturbation of the velocity in the outer region of the boundary layer, owing to the strong penetration of the head of injected jet across the boundary layer (cf. figure 1). This latter effect is arguably not beneficial in so far as it reflects an input of energy into a region that plays a subordinate role in controlling the structure of the near-wall region. Hence, the implication is that a wall-normal injection at high velocity is not optimal and that other arrangements need to be pursued, for example shallow injection against the boundary layer, an arrangement currently being examined by the authors. Profiles of the streamwise turbulent stress show a pleasing agreement with experiments, and it is especially noteworthy that the near-field behaviour of the jet has been well captured. Interestingly, a close examination shows the
Figure 4. Flow configuration shown in figure 3: (a) separation and reattachment location as a function of the spanwise direction, (b) velocity profiles for different streamwise locations and (c,d) mean streamwise-stress profiles $u'u'^2_{in}/U^2_{in}$. Experimental results are shown with symbols and simulations with lines. Open circles and solid lines, baseline case; filled circles and dashed lines, with synthetic jets at $St_H = 0.2$.

level of streamwise stress (and also shear stress) in the separated region of the actuated case to be somewhat lower than in the baseline flow. This reflects the weaker recirculation, the weak contribution of the periodic component to the $u\bar{v}$ correlation beyond $x/H = 2$ (see below) and the delayed separation caused by the actuation.

One especially interesting aspect of a periodic jet injection is the relative contribution of the periodic and stochastic turbulence component to the total turbulence quantities. The effect of actuation itself can be separated from the background stochastic motion by performing a triple decomposition of the flow field based on the period of actuation $T$, i.e. any quantity $f(x,t)$, can be written as $f(x,t) = \bar{f}(x) + \tilde{f}(x,t/T) + f'(x,t)$, where $\bar{f}$, $\tilde{f}$ and $f'$ are the mean, periodic and stochastic components of $f$.

Profiles of the periodic, stochastic and total streamwise normal stress at two streamwise locations are shown in figure 5. Close to the injection location ($x/H = 0$ corresponds to $7D$ downstream of the injection), the periodic component...
is much higher than the stochastic component. However, the former decays rapidly further downstream and the total stress is dominated by the stochastic component. Results also exist for the phase-averaged variation of the periodic and stochastic components, but these cannot be included herein.

6. Conclusions

While there is ample evidence that slot jets, if properly configured, can be very effective in controlling separation, such evidence is far weaker in the case of round jets, mainly because of the highly localized transverse region of influence of the latter. Both experiments and simulations for ducted laboratory configurations demonstrate that sinusoidally actuated slot jets can reduce the length of massive separation zones by 30 per cent and above, and can altogether eliminate or prevent weak, incipient or intermittent separation over gently curving surfaces. Simulations show that the injection slot-jet sheet, initially close to being two dimensional, very quickly disintegrates into a vigorous three-dimensional motion, with proper orthogonal decomposition (POD) suggesting the presence of high-energy streamwise vortices. Experimental evidence also suggests that explosive expulsions over a short proportion of the actuation cycle, at a frequency much higher than that associated with the shedding instability can be very effective in eliminating stall on aerofoils. While there is some support for the often stated assumption that resonance of the injection frequency with the shedding-mode instability (represented by $St_H = 0.2$) is especially beneficial, the evidence is not compelling, this support being derived from a few observations in especially simple flow configurations at low Reynolds numbers. POD studies for high Reynolds number slot jets indicate that the periodic injection close to the
shedding frequency favours a structural reorganization, in which the proportion of the energy associated with unsteadiness is shifted towards low-order modes, thus giving more weight to coherent motions. However, the dependence of this process on the actuation frequency is not clear.

There are several reasons why round jets are less effective. First and foremost is the fact that an isolated row of widely spaced round jets is simply too weak to induce large-scale modifications in massive separation because the lateral spread of the control is very limited. Second, the placement of the jet orifices well upstream of the separation region militates against the strength of the control. Third, round jets offer less opportunity for resonance between the actuation frequency and two-dimensional instability modes in the separated shear layer. In fact, the present authors have not observed, albeit based on a small set of simulations, any measurable benefits from changing the injection frequency or the symmetry of the injection cycle. Fourth, simulations, as well as measurements, provide clear evidence that wall-normal injection at high injection velocity leads to strong perturbations of the flow in the outer portion of the boundary layer to be controlled, which does not aid the separation control process. Fifth, the periodic component of the actuated jet decays rapidly within a few jet diameters, so that the bulk of the separation zone is not directly affected by the jet, beyond the interaction of the jet and the boundary layer close to the separation line. Finally, while the unsteady kinetic energy is substantially elevated downstream of the injection location, there is no commensurate elevation of the cross correlation (total shear stress), which is the most important quantity in relation to momentum mixing and hence separation control. This is, again, because the major periodic perturbation arises in the outer portion of the boundary layer.

Computational studies by the authors, to be reported elsewhere, show that injection in opposition to the oncoming boundary layer produced blooming, and hence gave rise to a substantial extension of the lateral control. There is thus now an urgent need to examine a wide parametric space of configurations, including injection angle, inter-jet separation and the benefit arising from several jet rows in tandem. However, such studies are bound to be very costly.

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