Simulation of Synthetic Jets in the context of Controlling Separated Flows

D. Wu , A. Avdis, M.A. Leschziner
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A synthetic jet is formed as a consequence of a periodic – say sinusoidal – expulsion and extraction of fluid through an orifice, so that the time-averaged flow rate through the orifice is zero. Despite the zero mean mass flux, the sequence of injection followed by suction results in net momentum and vorticity being released into the fluid body in which the jet is generated. This is, essentially, a consequence of the 'asymmetry' in the flow induced at the orifice during the injection and suction strokes and hence differences in the properties of the fluid being injected and extracted.

Fig. 1 shows a sequence of snapshots from a large eddy simulations of a synthetic jet being injected into stagnant surroundings through a rounhd orifice. The injection and suction strokes are initiated from a closed cavity below the orifice, at the bottom of which positive and negative mass transpiration is imposed to mimics the movement of a diaphragm or of a piston. In essence, the injection stokes lead to the formation of a train of vortex rings that propagate into the stagnant fluid by self-induced convection and merge to form the jet. During the suction stokes, fluid is withdrawn into the cavity mostly from the region surrounding the orifice above the orifice wall, so that the train of discharged vortex rings remain intact and carry momentum and vorticity into the stagnant body.

From a practical point of view, synthetic jets are of interest as a means of enhancing mixing, on demand, without the need for a supply of fluid to effect this enhancement. This is especially pertinent to aeronautical applications in which it is desirable to 'control' certain portions of the external flows without bleeding fluid from the propulsion system. The desired 'control' is usually the avoidance of separation in highly-loaded aerodynamic surfaces on which the flow is subjected to large adverse pressure gradients – high-lift devices being a case in point. Such control is usually exercised by passive devices – typically, fences, chevrons and pimples. However, these devices are permanently active, even in conditions in which they are not needed, thus generating undesirable drag. Synthetic jets, on the other hand, act much like solid turbulators, but can be switched on and off at will.

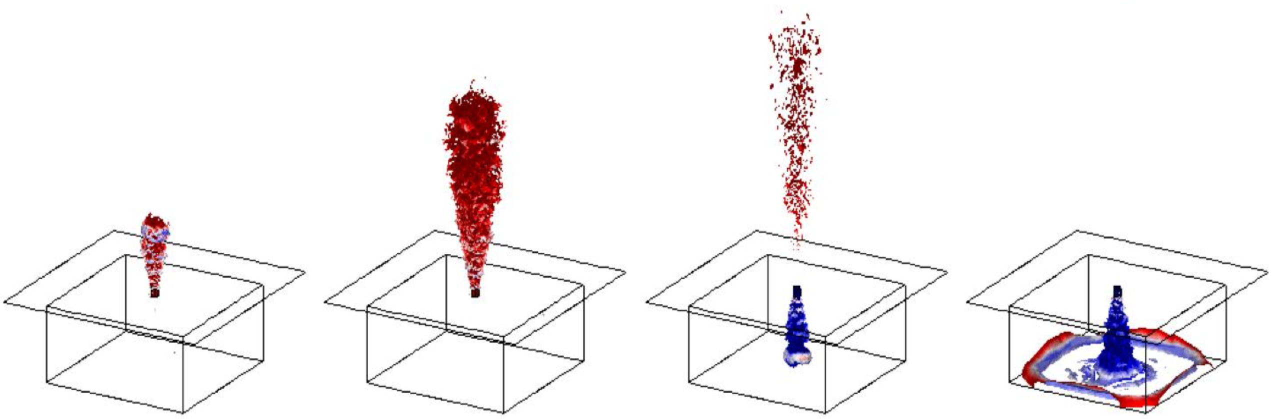


Fig. 1: Synthetic jets in stagnant surroundings – snapshots from large eddy simulations.

At Imperial College, synthetic jets injected into stagnant surroundings as well as into cross-flows have been investigated for several distinctly different configurations, as is shown in Fig. 2, among them two-dimensional slot jets into the separated shear layer andd the injection of square and circular jets into a turbulent boundary layer. An study, by Dejoan and Leschziner (2004), focused on fundamental issues of the injection into a backward-facing-step geometry (first configuration in Fig. 2). Whilst highly relevant to the other configuration, it is not considered further herein. The nature and mechanisms of the interaction between the jet and the cross-flow in the slot-injection and hole-injection configurations differ greatly, and both form distinct areas of research.

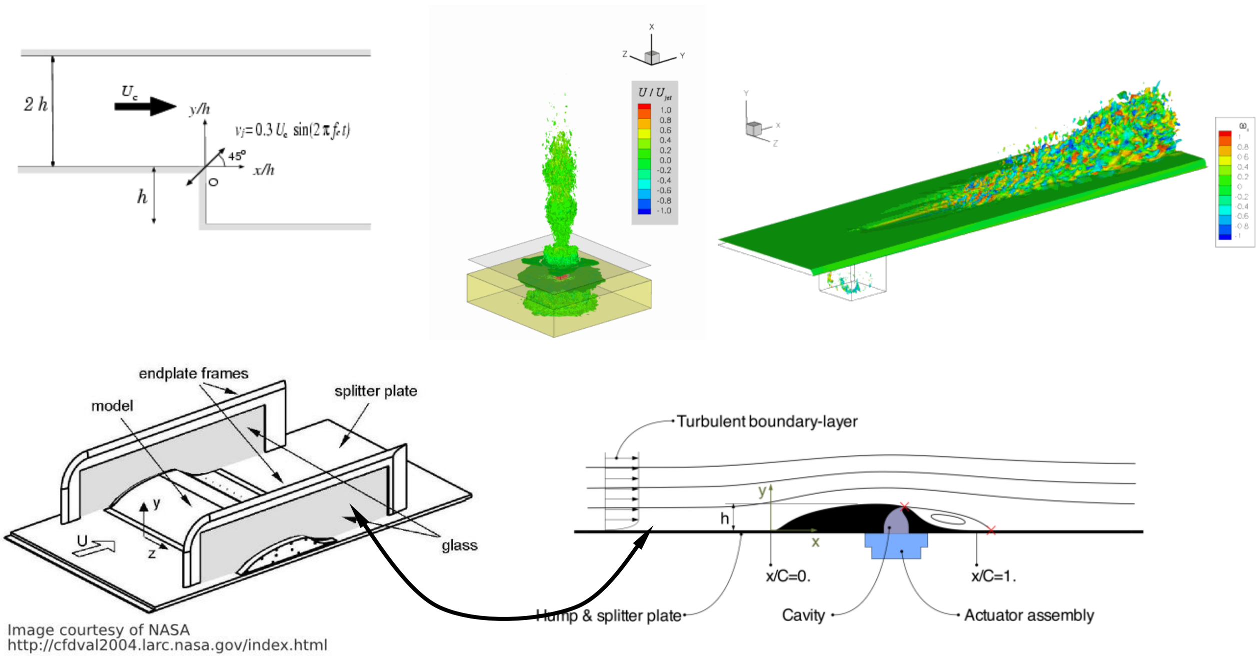


Fig. 2: Major configurations examined

Large eddy simulation is, arguably, the only appropriate computational approach for synthetic jets at practically relevant Reynolds numbers, in contrast to URANS modelling. First, such jets involve injection frequencies which border the frequencies inherent in the turbulent flows to be controlled; hence scale separation, on which statistical (phase-) averaging relies, may be not be present. Second, the unsteady fluctuations and the dynamics associated with them are strong, in which case conventional turbulence models are likely to be inapplicable. Third, turbulence models, even of second-moment variety, are known to display major defects in massively separated flow, one group of flows to be controlled. Fourth, synthetic jets discharged into slow or stagnant flow are often transitional in character, in which case RANS modelling is bound to fail. Finally, only simulation offers the full potential for resolving the interaction between the frequency of injection and instability modes associated with shear-induced turbulence.

Slot-jet injection into a flow separating from a hump

Among several sets of experimental data for separation control with slot-shaped synthetic jets, one that has become especially popular over the past few years as a basis for validating computational schemes is that reported by Greenblatt et al (2006). These data were generated under the aegis of the *NASA Workshop on Synthetic Jets and Turbulent Separation Control,* summarised by Rumsey et al (2004). The configuration, shown in Fig. 2, consists of a wall-mounted ‘Glauert-Goldschmied’-type body, at the crest of which the flow separates, to form a recirculation zone of length 0.45 of the chord of the hump. The Reynolds number, based on the same chord, was 929,000, and the boundary layer thickness just upstream of the hump had a momentum Reynolds number of 6700. The synthetic jet was generated by “voice-coil-actuators” in a cavity deep below the hump and connected through a long contracting channel to a thin slot at the crest of the hump. The peak jet velocity was 0.66 times the freestream velocity, and the Strouhal number, based on hump height, was 0.22 (the frequency being 138 Hz). The latter value is close to that for which the maximum reduction in separation was observed in the previously discussed flow behind a backward-facing step (0.2). Measurements were performed with and without the synthetic jet operating, to identify the effectiveness of the synthetic jet.

Some representative results are shown in Figs. 3 and 4, both for the baseline and the actuated cases. Detailed comparisons with experimental data are given in Avdis (2008) and Avdis & Leschziner (2008). The results obtained demonstrate that the simulations give, with few exceptions, a satisfactory representation of the major flow features – certainly substantially better than obtained with some of the most advanced RANS methods in existence. Interestingly, and in contrast to RANS solutions, the predicted level of turbulence in the separated shear layer is somewhat too high, leading to a slight under-estimation in the length of the recirculation zone. RANS models, on the other hand tend to give far too low a level of turbulence in the separated shear layer, because they do not capture the large-scale turbulence dynamics in the separated shear layer. With the synthetic jet activated, the simulation returns the expected substantial reduction in the size of separation zone, cf. Fig. 3. This reduction, at around 30%, is very similar to that observed in the back-step geometry discussed earlier. The sequence of phase-averaged fields given in Fig. 4 illustrate that the injection results in the formation and propagation of large-scale vertical structures of the same type observed in the previous back-step configuration. Here again, it is these structures – referred to as ‘shear-layer flapping’ – that induced extra strain and hence higher turbulence activity, thus leading to the observed reduction in time-mean recirculation. Comparisons with experimental data can be found in Avdis and Leschziner (2008).

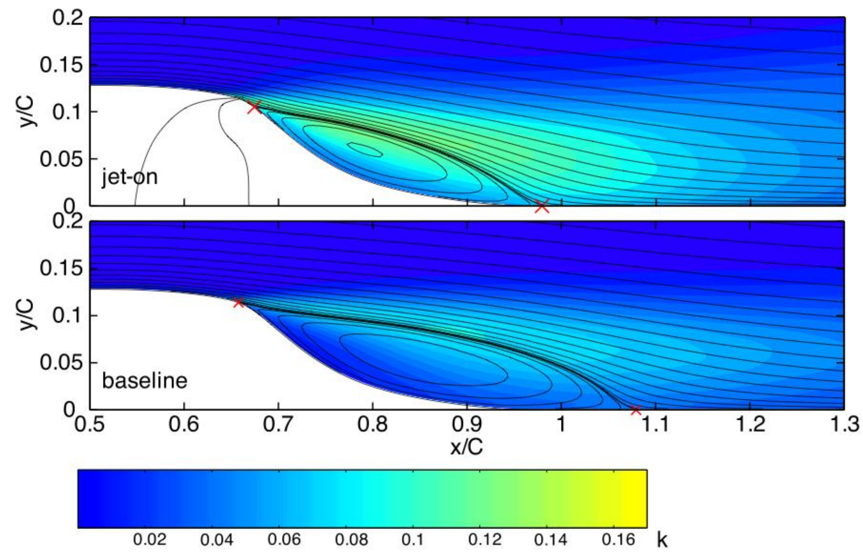


Fig. 3:Time-mean separation zone with (upper) and without (lower) systhetic-jet actuation

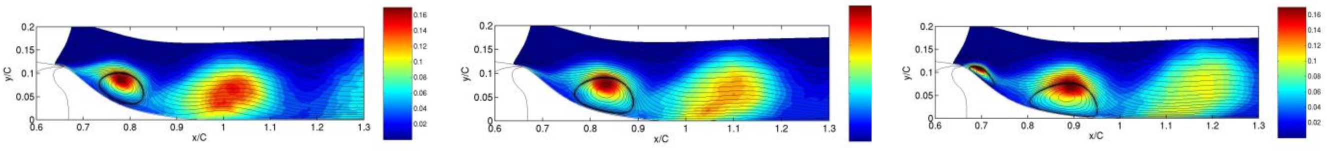


Fig. 4: Sequence of phase-averaged fields, at phases 0^o, 90^o and 180^o of streamfunction and turbulelence energy

Three-dimensional single-jet injection into a boundary layer

As a precursor to simulations for turbulent jets, the injection of a single jet through a square orifice into a stagnant environment was investigated (Wu and Leschziner (2007)) to develop an understanding of how ejected vertical structures behave during the injection process. The jet is injected from a square cavity below the orifice. Its square shape is in accord with the experimental investigation by Garcillan et al (2004). Fig. 5 shows a sequence of phase-averaged fields and associated comparisons with PIV-derived data for the centerline velocity. This flow is essentially laminar, with some evidence of transition (or breakup) observed after consecutive vortex rings merge. In that sense, the practical significance of this case is rather limited, but it does illustrate some interesting pinch and merging phenomena following the injection of the vortex rings. Studies for turbulent jets may be found in Wu and Leschziner (2008).

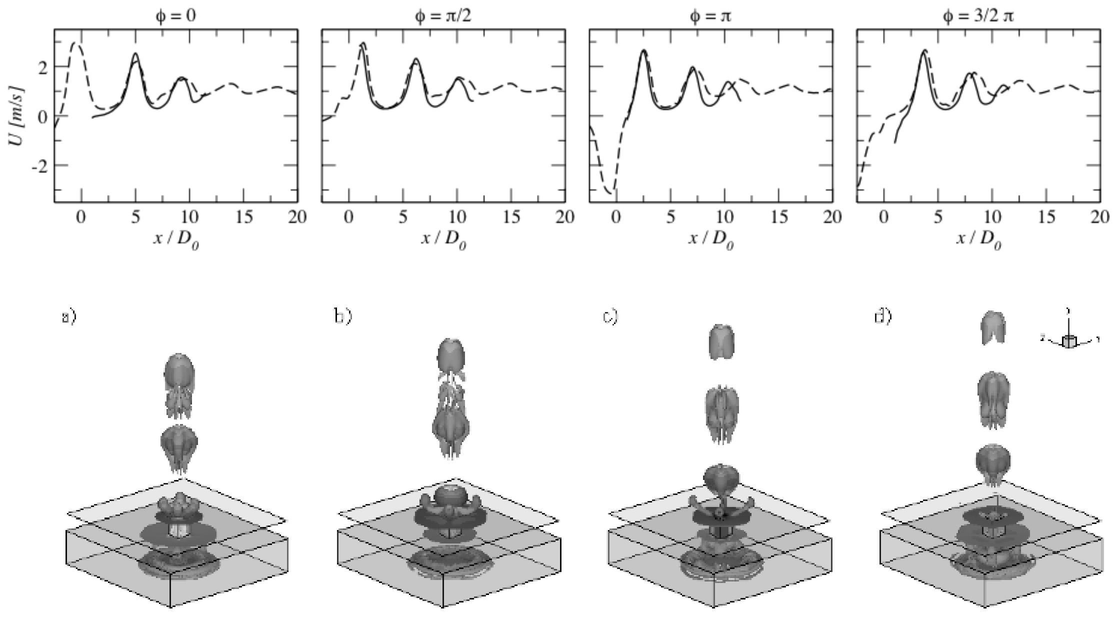
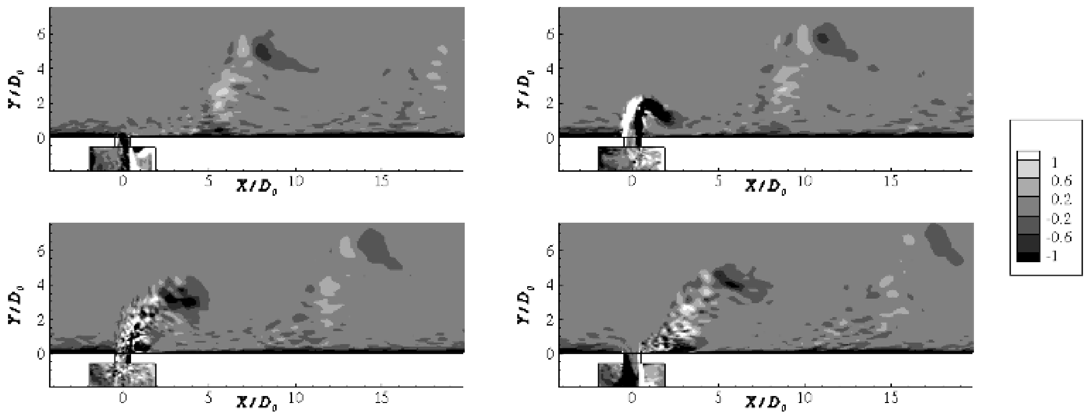
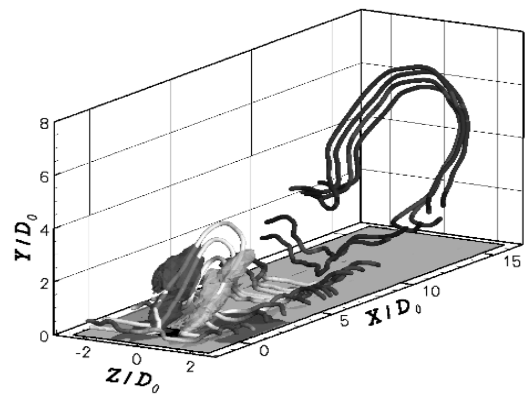


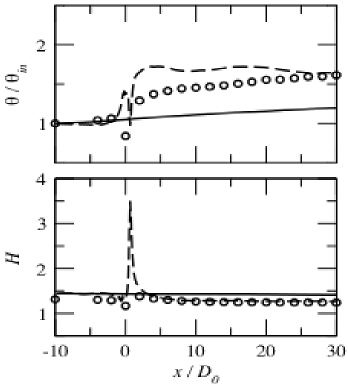
Fig. 5: Isolated synthetic jet ensuing into quiescent surroundings. Above: phase-averaged centre-line velocity, –: PIV data from Garcillan et al. (2004), --: LES. Below: iso-surfaces of constant vorticity magnitude at the respective phases.

Fig. 6 shows results for the injection of a synthetic jet into a flat-plate, zero-pressure-gradient boundary layer at a momentum-thickness Reynolds number $Re_{\theta,in}$ = 920 and maximum jet-to-freestream velocity ratio $u_{jet} / u_\infty = 2$. At the injection position, the ratio of the boundary-layer thickness to the orifice diameter, δ / d_0, is 4 – that is, the boundary layer is relatively thick. The high injection velocity is remarkable, and the choice of this value in the corresponding experiments of Garcillan et al (2005) reflects the general assumption that effective separation control with circular or square jets requires an injection velocity of the same order as the free-stream velocity, so that the jet is allowed to penetrate through the boundary layer into the free stream. In the experiment, the orifice was circular, while in the corresponding computations, the orifice was approximated by a square shape having the same area, because of grid-topology limitations. Computations with a circular orifice, represented by means of the Immersed Boundary Method, are in progress at the time of writing.



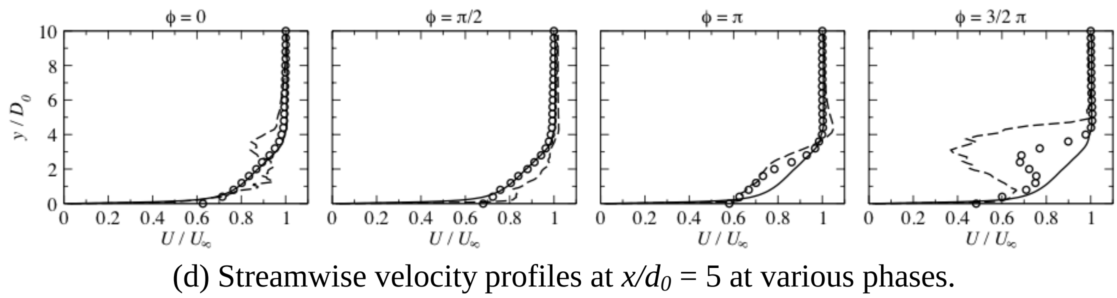
(a) Out-of-plane vorticity in the mid-span plane at various phases





(b) Vorticity lines overlaid with shades of vorticity magnitude returned by POD analysis of the flow field

(c) Streamwise evolution of the momentum thickness and the shape factor in the mid-span plane



(d) Streamwise velocity profiles at x/d_0 = 5 at various phases.

Fig. 6: Synthetic jet injected into a turbulent boundary layer at $Re_{\theta,in}$ = 920, u_{jet} / u_∞ = 2, δ / d_0 = 4.

The sequence of plots in Fig. 6(a) shows the injected structures punching through the boundary layer and penetrating deep into the free stream. Fig. 6(b) visualizes, at one particular phase, the deformation of the vortex lines, identified by constant vorticity magnitude, that are induced by the injection process. Fig. 6(c) and (d) compare, respectively, computational results with experiments for the momentum thickness and shape factor in the injection mid-plane, and profiles of phase-averaged velocity on the same plane. In these figures, the symbols represent experimental data, the solid and dashed lines indicate computed velocity profiles in the uncontrolled and controlled flow, respectively. Attention must here be drawn to the fact that phase-averaging is based on a small number of realisations covering only 5 cycles. Moreover, unlike in the previous cases of slot-jet injection, spanwise averaging is not possible to perform in this case. This is the main reason for the lack of smoothness in the phase-averaged profiles in Fig. 6. Simulations over many cycles are, unfortunately, extremely costly. Fig. 6(c) and (d) show that the simulations give a fair representation of the injection process. The injection results in a steep increase in the displacement thickness, with the simulation indicating a stronger effect. The most important consequence is the deformation illustrated in Fig. 6(d), which are accompanied by strong transverse motions around the jet, leading to increased mixing.

REFERENCES

Avdis, A. (2008), Large Eddy Simulation of synthetic jets in the context of flow control, PhD Thesis, Imperial College London.

Avdis, A. and Leschziner, M.A. (2008), Large Eddy Simulation of Separated Flow over a Glauert-Goldschmied Wall-Mounted Hump with and without Control by Means of a Synthetic Jet, Proc. ETTM7, Cyprus, June 2008, pp. 436-442. (to appear in Flow, Turbulence and Combustion, 2008).

Dejoan, A. and Leschziner, M.A. (2004), Large eddy simulation of periodically perturbed separated flow over a backward-facing step, Int. J. Heat and Fluid Flow, 25, pp. 581-592.

Garcillan, L., Little, S., Zhong, S., Pokusevski, Z. and Wood, N.J. (2005), Time evolution of the interaction of synthetic jets with a turbulent boundary layer, CEAS/KATnet Conference on Key Aerodynamic Technologies, Bremen, Germany.

Greenblatt, D., Paschal, K.B., Keith, B., Yao, C.S. and Harris, J. (2006), A separation control CFD validation test case. Part 2: zero efflux oscillatory blowing baseline, AIAA Journal, 44, pp. 2831-2845.

Rumsey, C.L., Gatski, T. B., Sellers, W.L., Vatsa, V.N. and Viken, S.A. (2004), Summary of the 2004 CFD Validation Workshop on Synthetic Jets, AIAA Journal, 44, pp. 194-207.

Wu, D. and Leschziner, M.A. (2007), Large eddy simulation of synthetic jets in stagnant ambient and turbulent cross-flow, Proc. IUTAM Symposium on Flow Control and MEMS, Sept. 2006 (to appear).

Wu, D. (2008), Large Eddy Simulations of Three-Dimensional Synthetic Jets in Quiescent Surroundings and in Turbulent Cross-Flow, Ph.D. Thesis, Imperial College London.

Wu, D. and Leschziner, M.A. (2008), Large-Eddy Simulations of Three-Dimensional Turbulent Synthetic Jets in Stagnant Ambient Conditions and in Turbulent Cross-Flow, Proc. ETMM7, Cyprus, June 2008, pp. 346-351 (to appear in Int. J. Heat and Fluid Flow, 2008).