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EDITORIAL

Supersonic flow control

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1 Introduction

Shock wave-induced boundary layer interactions are unavoidable in high-speed flows. The strong adverse pressure gradient imposed by the shock on the incoming undisturbed boundary layer may result in flow separation that is associated with low-frequency oscillations of the separation shock (see Figs. 1, 2, 3). The separation phenomenon therefore leads to undesirable effects such as wall pressure loading, high local wall heating, increased drag coefficient, reduced mass flow ingestion, lower-pressure recovery and inlet unstart conditions. On the other hand, shock wave/boundary layer interaction (SWBLI) is also responsible for unsteady vortex shedding and shock/vortex interaction, which are major causes of broadband noise [1–5]. For instance, the prediction of pressure fluctuations in the transonic regime is particularly important in the vibro-acoustic design of launch vehicles. Indeed, vibrations induced in the interior of the vehicle may exceed design specifications, and cause payload damage, as well as structural damage due to fatigue problems. Similarly, in rocket propulsion systems these effects are also a matter of concern in supersonic propellant nozzles [7–9]. Therefore, a fundamental understanding of the complex physical phenomena involved in such interactions is extremely important for the development of improved engineering models and to attempt controlling their detrimental effects.

Several studies on SWBLI were conducted in the past [3,4]. Much of the early work was focused on understanding the dynamics of physical mechanisms driving the flow unsteadiness and the underlying causes. Although the mechanisms associated with SWBLI are quite complex and not very well understood, the studies did suggest that the low-frequency oscillations exhibit a wide range of spatial and temporal scale frequencies lower than the temporal scales of the incoming flow [3,5]. The latter seems to be encouraging and opens up various avenues for flow control.

Recently, studies were channelized to apply flow control techniques in order to alleviate or diminish the detrimental effects of flow separation. Various aspects of transonic/supersonic and hypersonic flows with different control strategies (e.g., vanes, micro-ramps, micro-jets, synthetic jets, energy deposition, plasma discharge, actuators, ramp cavity, etc.) were attempted. The topic has received considerable attention and has become an active subject of research in the recent years. The capability to model and control the complex physical phenomena typical of such flows is a key to meet the requirement of enhanced performance, reduction of sound emission (turbulence and flow separation being the main source of airplane noise) and fuel consumption constraints of next generation air transport systems and launchers, etc. Also, a fundamental understanding of the complex physical phenomena involved in such flows is extremely important. Therefore, the present thematic issue focuses on the experimental results based on the study of supersonic flow control methodologies that will help providing a basis for future work in this area.

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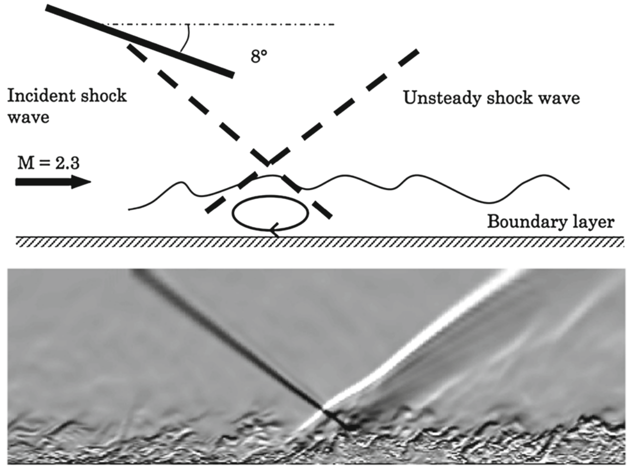


Fig. 1 Schematic representation of an oblique shock impinging on a turbulent boundary layer at $M_\infty = 2.3$ and $Re_\theta \simeq 5350$. The incoming boundary layer has a thickness of $\delta = 10.83$ mm, with an incident-shock angle $\beta = 32.41°$ and a wedge deflection $\theta = 8°$. The *bottom picture* is based on the instantaneous density-gradient field, extracted from an LES computation performed by the authors

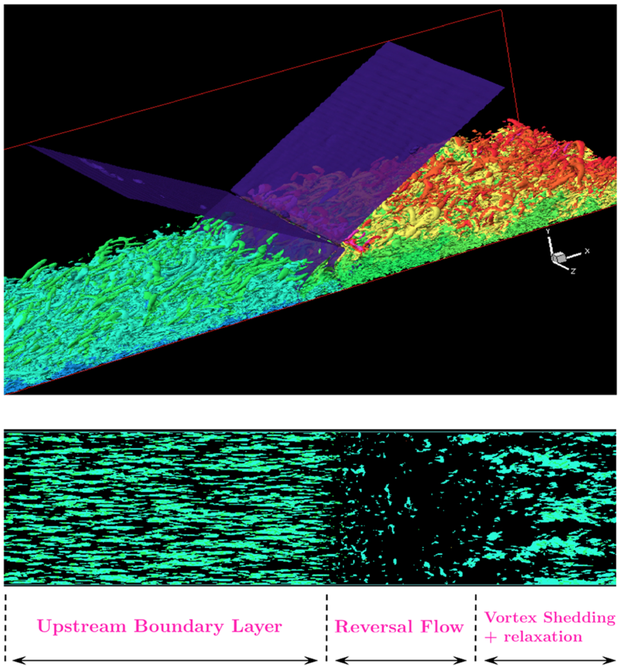


Fig. 2 Illustration of shock/boundary layer interaction. *Top image*: instantaneous 3D iso-surface of the second invariant of the velocity gradient tensor $Q = 0.01Q_{max}$ *colored* by the density field; *bottom image* turbulent velocity fluctuation showing the upstream boundary layer, the reversal flow and the relaxation zone with vortex shedding. From an LES computation performed by the authors

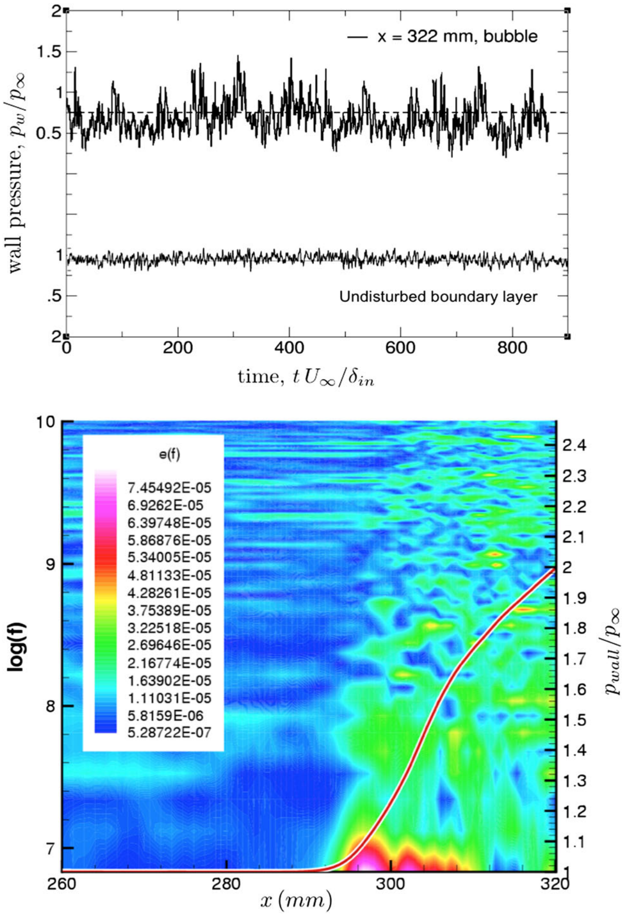


Fig. 3 Illustration of shock/boundary layer interaction. *Top image* instantaneous long time wall-pressure signals taken upstream of the interaction and at the recirculation zone; *bottom image* power spectral density (PSD) of wall-pressure fluctuations normalized using its local integral, plotted with the mean profile of the wall pressure (*red line*). From an LES computation performed by the authors

2 Supersonic flow control: a brief summary

Flow control was introduced by Prandtl at the time of the development of the boundary layer theory and extensively studied thereafter for applications to flows of interest for aeronautics/aerospace industry. The main motivation behind applying any flow control effort is to reduce the detrimental effects of flow separation or compressible mixing with the intention of improving the overall performance. The first and foremost step in this direction lies in altering the characteristics of the incoming boundary layer by adding energy to its mean velocity profile [10]. By doing so, the resulting relatively more energetic boundary layer becomes more resistant to conditions imposed by the adverse pressure gradient, which helps to reduce the overall extent of the separation and the associated flow unsteadiness. Present methods of flow control rely primarily on the use of boundary-layer suction [11–13] or bleed [14] systems wherein the decelerating or retarded boundary layer is either removed (suction) by replacing it with a new, thinner, one or its growth is influenced by adding mass flow into it (bleed). Although these methods are very effective and have found several hardware applications, their associated systems are quite complex. As

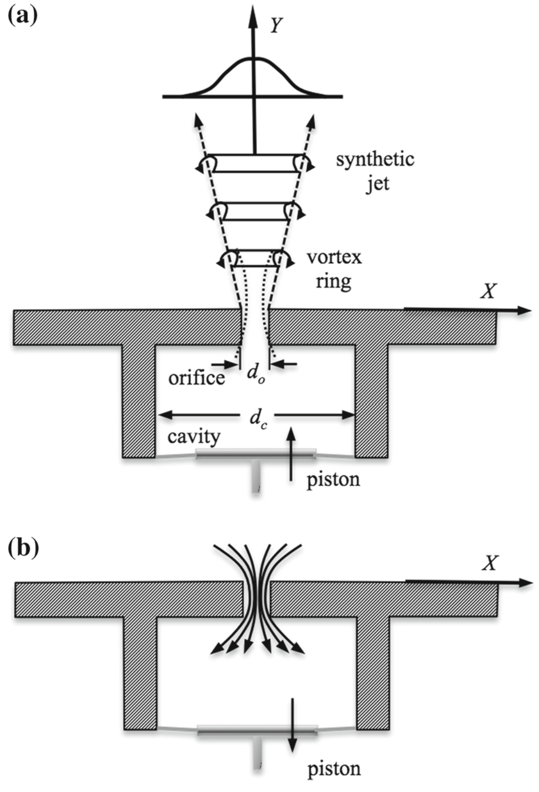
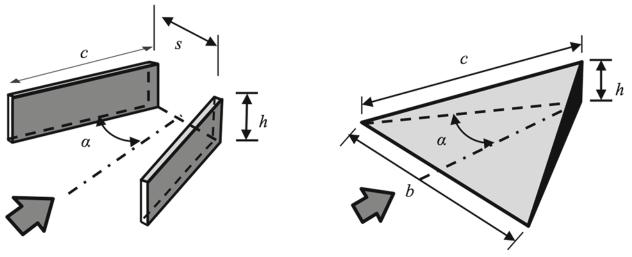


Fig. 4 Schematic representation of a synthetic jet actuator in **a** blowing and **b** suction pulsed processes

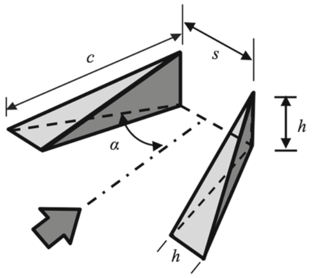
a result, there has always been an interest to explore alternative flow control techniques such as micro-mechanical vortex generators (VGs), plasma- or air-jets, etc. In the latter category, a synthetic jet can be produced by the interactions of a train of vortices that are typically formed by alternating momentary ejection and suction of fluid across an orifice such that the net mass flux is zero (see Fig. 4).

Seifert and Pack [15–17] studied the influence of excitation frequency, amplitude, momentum coefficient and compressibility in active control of separated flows' generic configurations (wall-mounted hump and airfoil) at high-Reynolds numbers and at various Mach numbers. In the presence of shock-induced flow separation, they observed that flow excitation upstream of the shock was more effective than at the foot. Moreover, they also found that periodic excitation was less effective in controlling separation because of compressibility effects. Vadillo et al. [18] also confirmed that synthetic jet actuators are promising devices to control the strength of shock waves and their unsteadiness as well as the shock-induced separation due to SWBLI, and, therefore, are a good candidate for achieving "hingeless" control to reduce drag. On the other hand, McCormick [19,20] developed a new concept, the so-called "directed synthetic jet", whereby energy is transferred to the boundary layer in the direction tangential to the body surface. The effectiveness of the concept was however shown only for leading-edge separation at a very low Mach number. Aspects of low- and high-frequency actuation, for aerodynamic flow control, were investigated by Glezer et al. [21]. These authors discussed, in particular, the relationship between the local instability mechanism of the separating shear layer and the global instability resulting in the shedding of large-scale coherent structures. The coupling between the time periodic shedding of coherent structures and the shear layer was found to be critical for separation flow control over stalled airfoils (the response of a separated flow to actuation frequency depends strongly on its relation to the characteristic unstable frequencies of the separating shear layer). Dandois et al. [22] investigated the frequency effect of synthetic jet actuation on a separated flow over a rounded ramp at a low Mach number. In particular, frequency forcing close to the natural shedding frequency reduced separation, while the latter increased at high frequency (corresponding to an acoustic-mode operation of the jet). Passive and active (by suction) techniques for the control of shock wave oscillations and separated boundary layer interaction in a transonic channel flow were investigated by Galli et al. [23] who showed that passive control had no effect on shock unsteadiness. LES simulations of Franck and Colonius [24] confirmed a slight loss of control effectiveness when comparing the results for the same control parameters at low Mach numbers.

In the mechanical control devices category, rectangular vanes were found to be very effective in controlling jets' and boundary layers' separation [25] and were widely used in various applications. However, these devices were generally large in size ($h/\delta \geq 1$, h being the micro-ramp height and δ the boundary-layer thickness) and introduced significant device drag when used in high-speed aerodynamics (see Fig. 5a). A more recent approach for achieving effective flow control is through the use of "micro" mechanical control devices (with $h < \delta$) that introduce mixing in the boundary layer, are fail-safe and most importantly, are mechanically simpler and rugged [10,26,27]. The boundary layer mixing is achieved by the generation of streamwise vortices (co- or counter-rotating) in the wake of these control devices, near the wall (see Fig. 6). Although micro-VGs have the added advantage of being mechanically rugged, simple and fail-safe, the micro-jet (MJ) control technique, which also provides similar flow control effectiveness, not only has the flexibility of switching off and on [28] or "activating on demand" but can also have the added advantage of being integrated with transpiration systems as well [29]. The former characteristic helps to eliminate the parasitic drag associated with micro-vortex generators (MVG) [25]. In fact, to introduce similar effectiveness of control as micro-jets, the MVGs perhaps would have to be designed much larger in size ($h > 0.5\,\delta$). More recently, pulsed micro-jets (PMJ) or resonance-enhanced micro-jets (REM) have also been found very effective in suppressing certain flow frequencies such as



(a) Vane-type **(b)** micro-ramp



(c) ramp-vane-type

Fig. 5 Example of mechanical control devices

those in screeching free jets, impinging jets, etc [30]. Compared to steady MJs, the PMJs are a more effective alternative as these are more energy efficient and can be tuned to target different frequencies. Other variants of PMJs are the piezoelectric [30] and MEMS PMJs [31]. However, active flow control devices, as already mentioned before, can be complex, expensive and also difficult to implement and maintain [25]. Various groups in USA [29–33], Europe [10,28,34,35], UK [26,27], India [36,37] and China [38] are looking at different methods of shock-induced control in various areas of research applications.

Despite the fact that a lot of research has been focussed on flow control, it is still an open field in terms of control optimization, configuration optimization and its effectiveness for various shock-induced interactions. The flow physics for various control device configurations needs to be studied in detail and their benefits—investigated for different regimes of interactions.

3 Thematic issue on supersonic flow control

The thematic issue focuses on theoretical and experimental aspects of supersonic flow control, which includes various studies reported by different contributors who have conducted detailed investigations using different control devices such as micro-ramps, vanes, shock control bumps, plasma jets, micro-jets, etc. These control techniques were tested in different interactions such as those induced by impinging shock, circular cylinder and impinging jets to demonstrate their effectiveness. The issue includes two review articles on micro-ramp controls and shock control bumps, respectively, while the remaining four papers report the results of recent research being conducted towards efficient implementation of various flow control devices. It is to be noted that, in full accordance with the Shock Waves Journal editorial policies, all manuscripts of the present issue were rigorously peer-reviewed by at least two independent referees, each of which is an internationally recognized expert in the field.

In this framework, the review by Titchner and Babinsky [39] gives an overview of the research conducted by various experts the world over bringing out very strongly the potential of mechanical vortex generators as a possible control device for mitigation of shock-induced separation. The authors bring out two main important observations. Firstly, the success of these control devices was reported more in the transonic flow regime than in purely supersonic interactions. This, however, does not imply that the effective control of supersonic interactions is not possible. In this regard, the study suggests more focussed research, especially for cases where the extent of separation exceeds (5–10) δ, to prove the effectiveness of such devices. Secondly, the detailed comparative review shows that the effectiveness of counter-rotating MVGs is better for $D/d \geq 4$ (where D is the inter-VG spacing) and h/δ between 0.2 and 0.5. The research status in this field also indicates that the vane-type VG shapes are superior in performance when compared to the ramp/wedge-type VGs and, therefore, more innovative designs need to be looked into to match the effectiveness of the former. Although nothing concrete could be ascertained about control location, a rough estimate indicates that this distance is to be somewhere between (15–30) x/h (where x is the distance of the control location from the interaction).

Another experimental study on MVGs focuses on the effects of MVG height and configuration in controlling a flare induced laminar SWBLI [40]. The results were facilitated by time-resolved streamwise surface heat transfer measurements and high-speed schlieren imaging. The paper reports that the MVG height plays a dominant role in intensifying the flow fluctuations in the wake of the MVG device. It is also interesting to note that the shape of the control device seems insignificant for $h/\delta < 0.29$ whereas for $0.29 < h/\delta < 0.58$, the shape seems to show some influence. However, the authors suggest that in order to minimize the MVG-induced drag, the strong local interference effects, the total pressure losses and the flow unsteadiness, the MVG height should be kept approximately at 0.3.

In continuation to the research on mechanical control techniques, the review by Bruce and Colliss [41], which once again focuses on flow control in transonic regime, primarily looks at a new class of control devices called shock control bumps (SCB). Since the control in this device is based on the generation of a system of weaker compression waves ahead

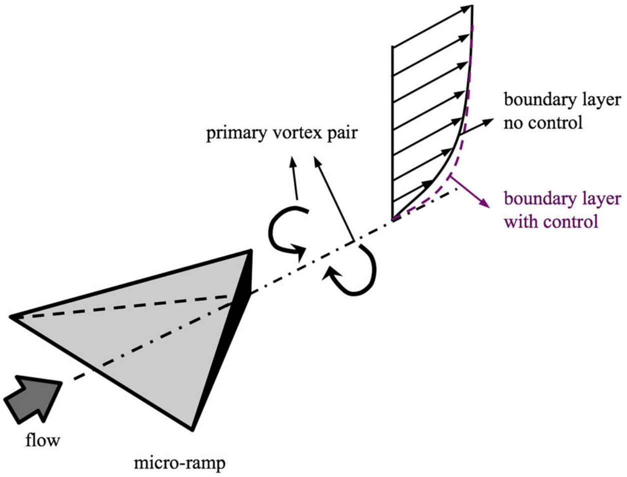


Fig. 6 Example of micro-ramp with primary vortex pair

of the main shock, this type of control was seriously considered for application on the upper surface of the transonic wing and in supersonic flows for intakes. The effectiveness of this control device is based on the two important criteria [41]: (i) their impact on drag at the optimal design (of SCB) and at the optimal design point (of the aerofoil) and (ii) their impact on off-design phenomena such as buffeting. Although both 2-D and 3-D SCB show beneficial flow characteristics, the performance benefit of the SCBs is mainly realized at high values of lift coefficient (C_L) rather than at lower values, where a clean wing scores better [42,43]. This is true for conventional supercritical aerofoils or wings. As a result, it is envisaged that the true potential of SCB for drag reduction can only be realized when the next generation wings are specifically designed to take advantage of the control benefits offered by SCBs [44,45]. The flow characteristics from the SCBs are also found to be very sensitive to shape and angle of its ramp, crest and tail regions. Open challenges lie in using SCB as smart vortex generators as well as understanding the impact of unsteadiness (inherent to buffeting) on their performance and their effectiveness on swept wing flows. The authors strongly suggest that the future of SCB research should focus on active morphing for wing applications [46] and the use of SCBs as a control device in intakes [47,48].

Active flow control—adding external energy into the incoming boundary layer through plasma jets—is another method was explored in the past [49]. The main idea here is to lock the pulsing frequency of the jets to that of the shock front to reduce the magnitude of the peak in power spectra in the intermittent region of the interaction [33]. The study by Greene et al. [50] on pulsed plasma jets in a compression corner induced SWBLI at Mach 3 reports a detailed investigation on the optimal control location, jet configurations (variation in pitch and skew angles) and pulsing frequency (2–4 kHz) to control the separation [50]. The study uses surface oil streak visualization and particle image velocimetry (PIV). Since 90 % of the plasma discharge energy goes into exciting the vibrational modes of the gas and only 10 % is available for jets, the momentum flux ratios of 0.6 were achievable [51]. This restricts the location of control close to the separation ($1.5\,\delta$) as the effects of jets are seen to diminish abruptly beyond $3\,\delta$. A lower pitch angle of 20° combined with zero skewed angle is reported to give the optimum configuration for control. The effectiveness of control results in a decrease in skin friction and overall thickness of the boundary layer downstream of the interaction.

The effect of variation in pitch and skew angles was also investigated by Verma et al. [52] but with an array of micro-jets placed upstream ($20\,\delta$) of a circular cylinder induced interaction in a Mach 2.18 flow. Earlier studies have shown that the shock unsteadiness in the region of separation is undesirable and was found to increase with increasing the shock strength, resulting in undesirable unsteady pressure loads [53–55]. The primary focus of the work is to control the amplitude of the shock unsteadiness associated with these interactions. The study is conducted using surface oil visualization, spark schlieren imaging and real-time wall pressure measurements using Kulite transducers. It is very encouraging to see that the control is sensitive to variations in skew and pitch angles of the MJs. Various MJ configurations not only show a reduction in the separation and the bow-shock strengths as well as in the triple-point height but also considerably bring down the peak r.m.s. value in the intermittent region of the separation. The 90° pitched MJ in zigzag configuration show the best control for injection at the tunnel stagnation pressure. However, at higher injection pressures, the effectiveness of this control configuration reduces primarily due to increase in its obstruction component as well as due to increase in the spanwise jet-to-jet interaction. At these pressures, pitching or skewing the jets to 45° enhances their control effectiveness. The modified jet configurations however, are seen to lose their ability to control the interaction as effectively as a 90° pitched MJ primarily due to the associated modifications in the wake flow development.

Another interesting contribution concerns the use of micro-jets to control the shear-layer growth characteristics in supersonic free and impinging jets [56]. This group in Florida State University has been working on the development of both steady and pulsed jets for almost a decade now. Both acoustic and PIV measurements were conducted on control of a Mach 1.5 ideally expanded free and impinging jets using an array of circumferentially placed 16 steady MJs 400 μm in diameter and with injection angles of 60° [57]. The combined mass flow from the MJ configuration is only 0.5 % of the main jets [58,59]. The velocity field measurements indicate that the MJs result in a rapid nonlinear thickening of the shear-layer growth, particularly near the nozzle exit, as opposed to the uncontrolled case. A detailed linear stability analysis shows that while the convection velocities remain largely unaffected, the nonlinear thickening of the shear layer is responsible for the reduction in the unstable growth rates over the entire range of frequencies with control. For impinging jet applications, the control results in a near elimination of the impingement tones and reduction in broadband noise, whereas for the free jet a 4.5dB reduction in overall sound pressure levels (OASPL) is indicated in the peak noise radiation direction. The authors emphasize that the MJ control has a strong potential, not only in disrupting the feedback mechanism inherent to resonant flows, but also in modifying the growth of coherent structures as well as turbulent mixing in free jets.

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