Sādhanā Vol. 32, Parts 1 & 2, February–April 2007, pp. 83–92. © Printed in India

Some thoughts on separation control strategies

P R VISWANATH

Experimental Aerodynamics Division, National Aerospace Laboratories, Bangalore
e-mail: p.r.viswanath@gmail.com

Abstract. Separation control has received considerable emphasis in literature both owing to fundamental flow physics and technological applications. Flow separation generally leads to increased energy losses, instability and so on, and its control is essential to improve aerodynamic performance. Here a brief review is presented of three broad strategies for separation control: these include methods that involve energization of the boundary layer upstream of separation, those that involve altering the bubble flow or dead air zone, and those that may influence the shear layer reattachment directly. Examples from recent research in our laboratories are reviewed and it is suggested that direct manipulation of the reattachment process could lead to effective control/management.

Keywords. Boundary layer separation; separation control; separation control strategy.

1. Introduction

The problem of boundary-layer separation has attracted considerable attention over several decades, both because of fundamental flow physics and technological applications (Prandtl 1952; Lachmann 1961; Chang 1976). Flow separation occurs on airfoils/wings, behind blunt bases, in high speed intakes and in a variety of other engineering systems, including turbomachinery and automobiles. Some of the essential ideas related to boundary-layer separation, and the need to prevent the same from occurring, have been addressed by Prandtl (1952). Flow separation generally leads to increased energy losses, instability and so on, and control of the same is sometimes necessary and often desirable to improve aerodynamic performance. Several interesting and informative review papers related to separation control have appeared in the last two decades. These include Delery (1985), Viswanath (1988), Simpson (1989), Gad-el-Hak (1989), Gad-el-Hak & Bushnell (1991), Greenblatt & Wygnanski (2000), Stanewsky (2001) and Ashill *et al* (2005).

Traditionally, separation control methods have been classified as active or passive, depending on whether control involves energy expenditure or not. From a control-systems point of view, control methodology may be classified as predetermined (open loop) or reactive (open or closed loop) (see the paper by Gad-el-Hak, 1996 for more details).

A list of symbols is given at the end of the paper

Separation control strategy often refers to a clever (or intelligent) fluid dynamic plan, which results in a desired alteration or modification of a separated flow. Keeping in view the major features of the mean flow dynamics of two-dimensional separated flows, we classify separation control strategies broadly under: (i) methods involving energization of the boundary-layer upstream of the separation point (e.g. vortex generators, wall suction, tangential blowing etc); (ii) methods which involve altering/modifying the bubble flow or dead air zone (e.g. base bleed, Bearman 1966) and (iii) methods which may affect the shear layer reattachment directly (Roshko 1954, Bearman 1965).

In this paper, we present a brief review of the different separation control strategies mentioned above, with some emphasis on control (or a significant modification) of a turbulent separated flow, essentially by a "direct or nearly direct manipulation of the shear layer reattachment", which is a key element in the dynamics of separated flows. We demonstrate the above idea through some examples from recent experimental research in our laboratory.

2. Broad features of 2d separated flows

Turbulent boundary-layer separation generally occurs (figure 1) due to sustained adverse pressure gradients (or at a sharp corner as in the case of back step or base flow). The separated shear layer develops nominally under zero pressure gradient conditions initially and the velocity along the dividing streamline (DSL) increases; the shear layer entrains fluid both from the reversed flow zone as well as from the outer inviscid flow (external to the shear layer). This is followed by the reattachment of the shear layer onto a downstream wall (or recompression associated with the confluence of top and bottom shear layers); the reattachment (or recompression) pressure rise and the region over which it occurs may be expected to depend primarily on the shear layer characteristics and the boundary conditions at reattachment. The mass entrained by the shear layer from the reversed flow is returned at reattachment which forms a recirculating bubble. The pressure field in a separated flow is significantly influenced by the shear layer reattachment process and therefore it is a key element in the dynamics of separated flows (Roshko 1966). Our knowledge of the reattachment process has not improved much beyond the early work in search of reattachment criteria or models, and many fundamental issues still remain unanswered.

Any flow control technique applied either ahead of separation or downstream of it in the bubble will have a certain influence, directly or indirectly, on the development of the shear layer and therefore on the reattachment process and the resulting pressure field. In contrast, one could attempt to manipulate or interfere with the reattachment process somewhat directly in order to realize a certain control or modification of a separated flow; this idea has received very little attention in literature. Since the reattachment process provides the closure condition to a separated flow, its manipulation could offer an effective means of control. In what follows,

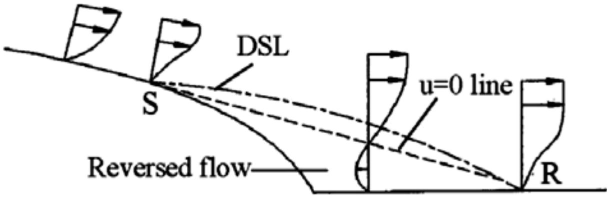

Figure 1. Schematic of main features of a 2D turbulent separated flow.

we briefly review the three broad approaches for separation control (defined in § 1) with typical examples.

3. Results and discussions

3.1 *Separation control by energization of the boundary-layer ahead of separation*

It is the goal of any designer to avoid boundary-layer separation in applications in view of the adverse effects (increased energy losses, instabilities etc). Numerous studies in literature have been devoted to understanding the separation process and control of the same by both passive and active approaches. Traditionally, separation control methods have involved energization of the boundary-layer upstream of the separation point, so that the modified boundary-layer can negotiate adverse pressure gradients without separating. Examples of boundary-layer suction, tangential blowing and passive devices like different kinds of vortex generators for energizing the boundary-layer may be seen in the monographs by Lachmann (1961) and Chang (1976).

3.2 *Separation control by manipulation of the bubble flow*

There are examples in literature showing the engineering benefits of altering the separated flow features by suitable manipulation of the bubble or dead air zone. Prandtl and group demonstrated the use of suction downstream of separation in controlling a diffuser flow at low speeds (Prandtl 1952). The use of base bleed for base-drag reduction is well known (e.g. Bearman 1966) – this involves injection of low momentum air into the base region to raise the base pressure. The use of a splitter plate along the plane of symmetry for suppressing vortex shedding behind a bluff body is well documented (Roshko 1954, Bearman 1965). Figure 2 shows another example of controlling a hypersonic separated flow at a compression ramp using natural bleed, which involves suction at the ramp corner (Ball & Korkegi 1968); suction

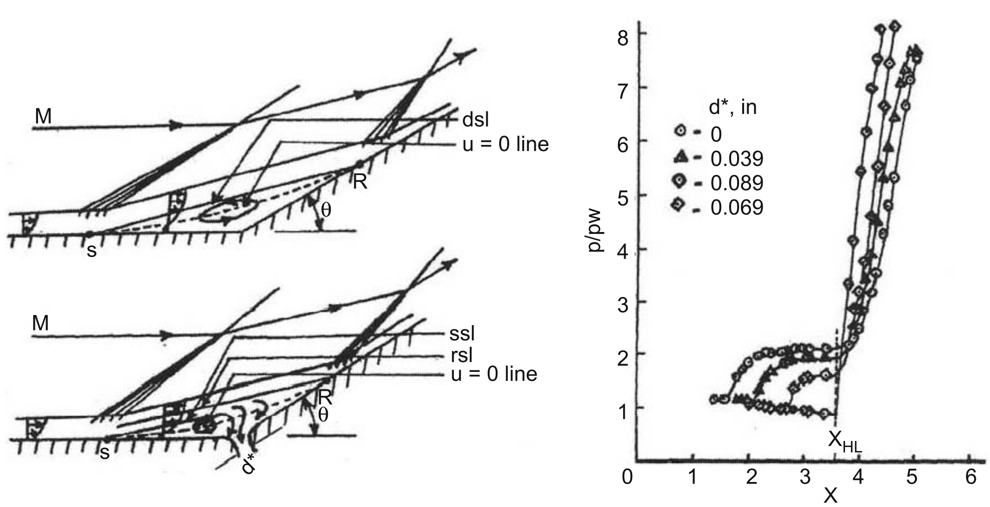

Figure 2. Flow separation at a compression corner and streamwise pressure distributions with suction (from Ball & Korkegi 1968).

is reflected by the gap width d^*, which is proportional to the mass flow rate through the gap. A progressive reduction in the separated region with d^* may be inferred from the pressure distributions.

In all the above cases of blowing or suction in the bubble, the mass balance in the recirculating flow is affected and there by the shear layer entrainment characteristics, which in turn modifies the shear layer at reattachment.

3.3 *Separation control by manipulation of shear layer reattachment*

We demonstrate the above idea through a few examples from recent experimental research in our laboratory. These include use of tangential blowing downstream of separation, but inside the bubble, for suppressing turbulent-separated flows at low speeds and use of a passive control device, applied locally in the zone of shear layer reattachment, for reducing the intensity of surface-pressure fluctuations in a transonic turbulent-separated flow.

3.3a *Separation control by tangential blowing downstream of separation, but inside bubble:* The usefulness of steady tangential blowing through a narrow slot ahead of separation is well documented in literature (Lachmann 1961; Chang 1976). In this context, it is useful to distinguish between blowing upstream of separation (U-type) and blowing downstream of separation (D-type) but within the bubble. The effectiveness of D-type blowing has been investigated on three different configurations involving turbulent-separated flows and some of the salient details of the experiments are summarized in table 1.

Viswanath *et al* (1983) discussed briefly some of the difficulties associated with U-type blowing in supersonic flow and provided the first assessment of D-type blowing in a ramp-induced turbulent-separated flow at Mach 2·50; based on measurements of surface pressures and limited pitot pressures in the separated zone, they showed that D-type blowing was more effective than U-type.

In a subsequent paper, Viswanath *et al* (2000) demonstrated through flow-field measurements in an axisymmetric separated flow at low speeds that tangential injection or blowing inside the bubble can be an effective means of separation control. Figure 3 shows increased static pressure recovery due to blowing at all three values of jet velocity (U_j). In particular, the pressure plateau region associated with separation is eliminated suggesting suppression of wall flow reversal even for jet velocity ratio (U_j/U_∞) = 0·75. The mean velocity profiles show the benefits of blowing in the interaction zone; the reversed flow in the separated

Table 1. Experimental details..

Geometry	M_∞	Slot height (mm)	U_j/U_∞	Remarks
2D ramp (Viswanath *et al* 1983)	2·50	1·08	0·87	Reattachment on solid surface
Axisymmetric (Viswanath *et al* 2000)	Low speed $U_\infty = 20$ m/s	2·5 1·55	0·75, 1·25, 1·55	Reattachment on solid surface
2D Airfoil-like body (Viswanath & Madhavan 2004)	Low speed $U_\infty = 25$ m/s	1.5	0·75, 1·0	Shear layer closure in wake

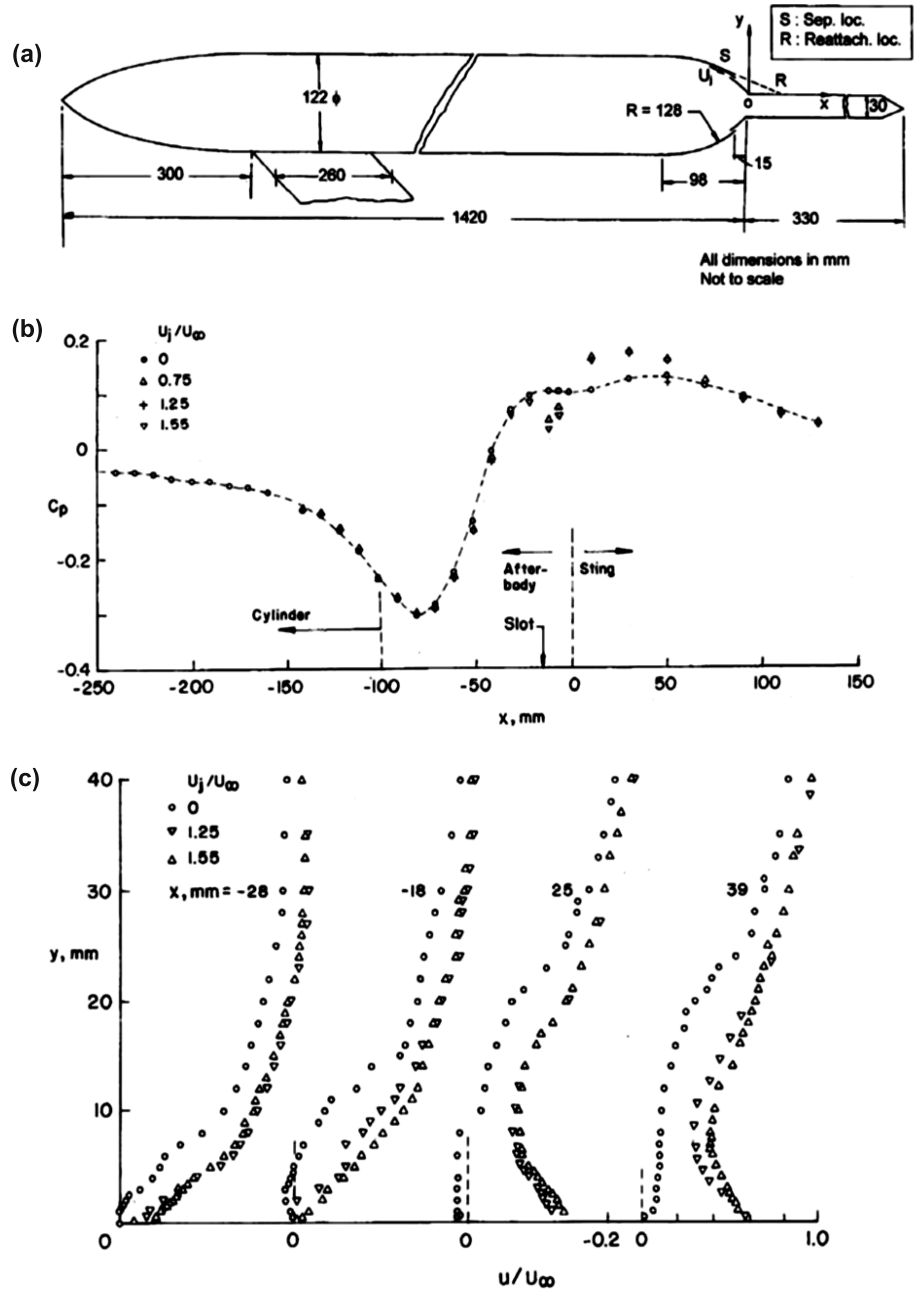

Figure 3. Separation control by tangential blowing inside bubble. **(a)** Axisymmetric model. **(b)** Effect of blowing on surface distributions. **(c)** Effect of blowing on mean velocity profiles in separated region.

zone ($x = -18$ mm, 25 mm) is eliminated at both values of $U_j (= 1{\cdot}25$ and $1{\cdot}55 U_\infty)$. The increased mean velocity all across the layer suggests efficient mixing of the injected jet with the surrounding flow. They also showed the changes and the complex nature of turbulent shear stress and kinetic energy profiles arising out of blowing.

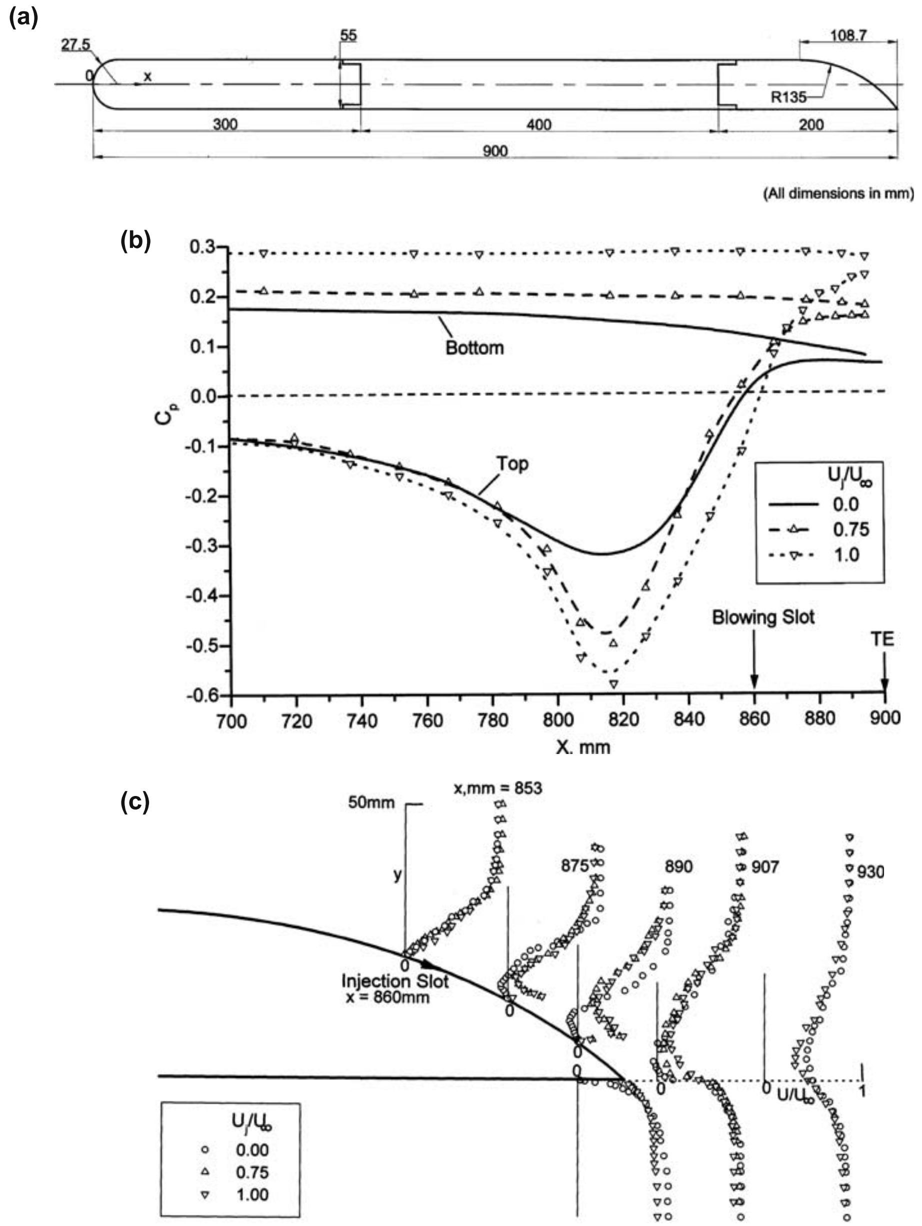

Figure 4. Control of trailing-edge separated flow by tangential blowing inside bubble. **(a)** Geometric details of flat plate-contoured aft-section model. **(b)** Effect of blowing on model static pressure distributions. **(c)** Effect of blowing on mean velocity profiles in the separated zone.

Having seen the success of D-type blowing in two different flows and speed regimes with shear layer reattachment onto a solid surface, Viswanath & Madhavan (2004) recently extended their work on D-type blowing to a trailing-edge separated on an (elongated) airfoil-like body at low speeds; in this case the shear layers merge and close in the near-wake. They studied two blowing slot locations (downstream of separation) and the results of surface

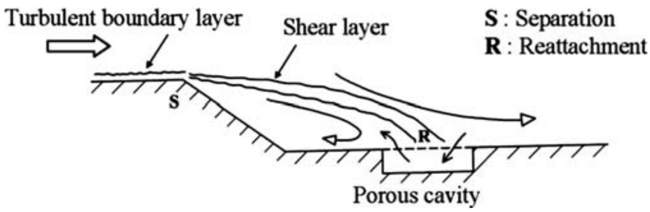

Figure 5. Schematic of passive control concept for reattaching flow.

pressure distributions and mean velocity profiles for the optimum case of slot location (closer to separation point) are presented in figure 4; the results are shown for the rear portion of the model in order to observe the details. Blowing results in the elimination of the plateau region in surface pressure suggesting that wall flow reversal is suppressed; significant pressure recovery all the way upto the trailing-edge may be seen at both values of U_j. The mean velocity profiles reveal elimination of both wall and wake flow reversals (at $x = 875$ and 890 mm) at both values of U_j leading to attached flow at the trailing-edge. This results in increased circulation around the model and a significant lift enhancement.

In summary, the effectiveness of tangential blowing downstream of separation, but within the bubble as a means of separation control has been well demonstrated with shear layer reattachment onto a solid wall as well as shear-layer closure in the wake. The major flow mechanisms with this type of control include: (a) elimination of wall flow reversal due to the interaction of the injected jet (having higher momentum) with reversed-flow (low momentum) boundary-layer which results in surface pressure recovery, and (b) jet entrainment of the reversed flow in the bubble, a strong factor promoting increased mixing near the wall. In essence, the reattachment or wake closure is removed or eliminated, as a direct influence of the injected jet. The blowing requirements for the D-type are small and comparable to U-type and details can be found in Viswanath & Madhavan (2004).

3.3b *Passive control of surface pressure fluctuations in transonic separated flows:* The concept of passive control involving a porous surface and a cavity underneath located in the region of shock-boundary-layer interaction has been investigated for wave drag reduction on airfoils at transonic speeds (Raghunathan 1988). The pressure rise across the shock wave results in

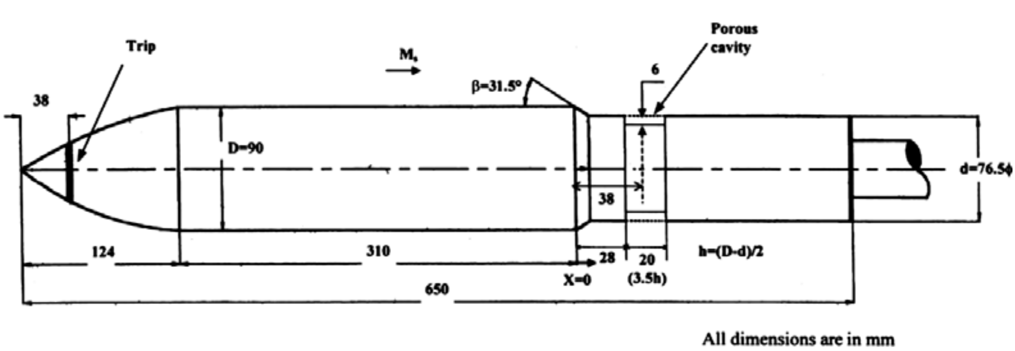

Figure 6. Geometric details of a generic axisymmetric body.

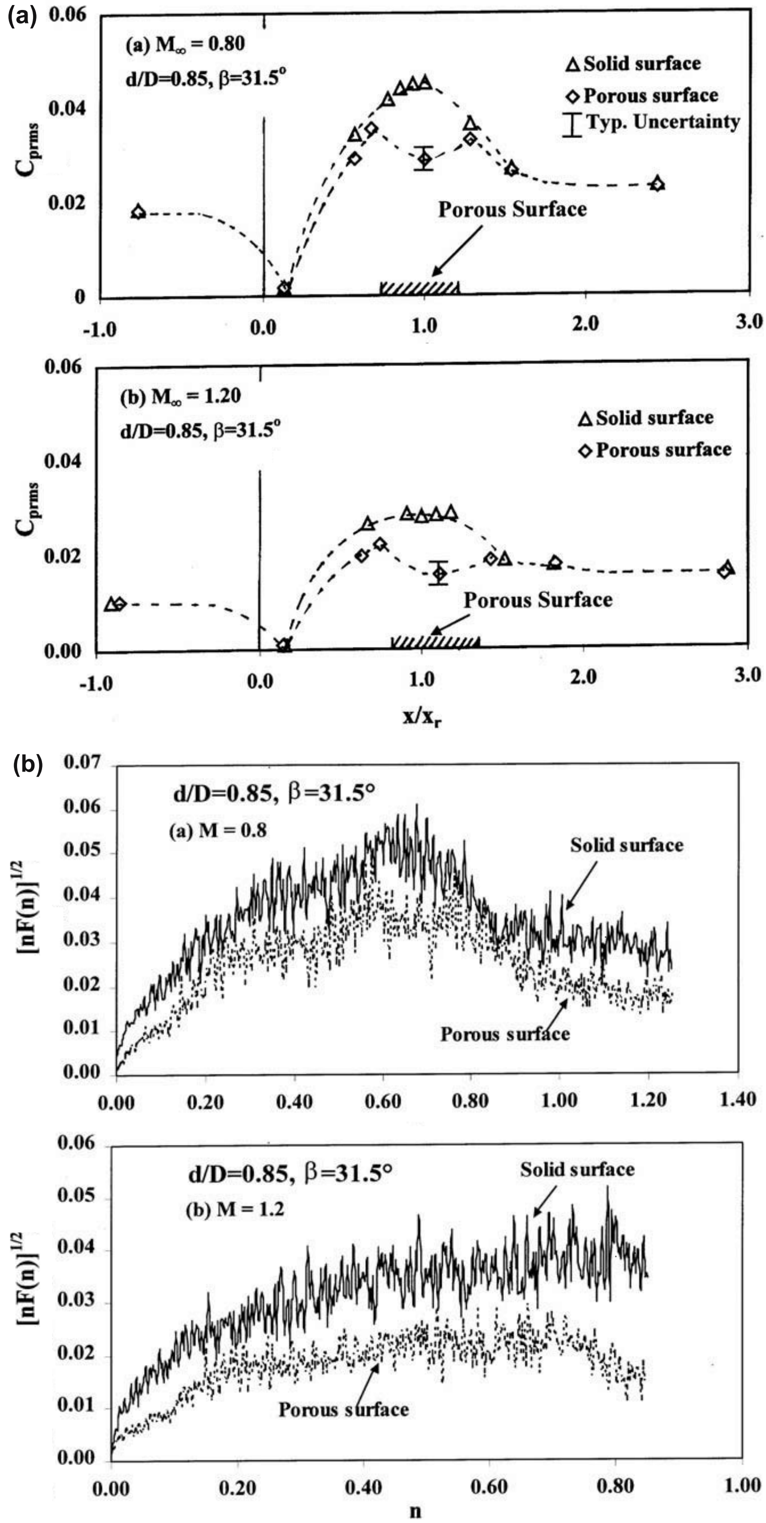

Figure 7. Effect on passive control on surface pressure fluctuations in reattaching flows. **(a)** Effect of passive control on rms pressure fluctuations. **(b)** Spectra of pressure fluctuations in the vicinity of reattachment.

flow through cavity from downstream to upstream of the shock wave: this is equivalent to a combination of suction downstream and blowing upstream of the shock, in turn increasing the communication across the shock wave. In addition to providing wave-drag reduction, the above passive control methodology has been shown to reduce surface pressure fluctuations due to shock-boundary-layer interaction as well. Rajan Kumar & Viswanath (2002) recently adapted the above passive control concept for reducing the surface pressure fluctuations in reattaching flows (figure 5); the control was applied locally in the reattachment zone. These experiments were made on a generic axisymmetric body (figure 6) in the Mach number range of 0·8 to 1·20. The cavity employed had a porosity of 15% and a depth of 6mm and unsteady pressure measurements were made using a number Kulite transducers located in the separated zone; more experiment details are available in the paper by Rajan Kumar & Viswanath (2002).

The effectiveness of the passive control in lowering the r.m.s. value of pressure fluctuations and on the spectral characteristics at a Mach number of 0·80 and 1·20 are displayed in figure 7. Passive control results in reducing the peak pressure fluctuations in the reattachment zone by as much as 35% with some lower reduction in the separated flow region as well (figure 7a). Typical spectra in the vicinity of reattachment show that the energy is appreciably reduced over a wide range of frequencies with a larger effect at low frequencies (figure 7b). Certain small changes in the mean surface pressures in the separated zone were observed as well due to the application of passive control.

The effectiveness of passive control in reducing the surface pressure fluctuations is a direct result of a change in boundary condition at shear layer reattachment, that is, from a solid wall to a porous surface with a cavity beneath it. The control device results in suction downstream and blowing upstream and therefore some changes in the shear layer entrainment are to be expected; further, the spectral characteristics suggest that large scale (or low frequency) unsteadiness including possibly turbulence in the shear layer is inhibited appreciably by the porous surface.

4. Conclusions

We have presented a brief review of different separation control strategies. Examples from recent research in our laboratory are reviewed to show the effectiveness of direct or nearly direct manipulation of shear layer reattachment for separation control. It is suggested that such a methodology could provide an alternate strategy for separation control/management.

The author is grateful to his colleagues Drs K T Madhavan, G Ramesh and Rajan Kumar who have contributed to separation control research over the years at NAL.

List of symbols

C_p surface pressure coefficient based on freestream conditions
C_{pms} unsteady surface pressure coefficient;
d^* suction gap width, in.;
M_∞ freestream Mach number;
n frequency parameter;

p	local static pressure;
R	reattachment;
S	separation;
u	velocity in the boundary-layer;
U_j	jet velocity;
U_∞	freestream velocity;
x	streamwise coordinate;
x_r	reattachment distance;
y	coordinate normal to wall;
θ	ramp angle.

References

Ashill P R, Fulker J L, Hackett K C 2005 A review of recent developments in flow control. *Aeronaut. J.* 109: 205–232

Ball K O, Korkegi R H 1968 An investigation of the effect of suction on hypersonic boundary-layer separation. *AIAA J.* 6: 239–243

Bearman P W 1965 Investigation of flow behind two dimensional model with blunt trailing edge and fitted with splitter plates. *J. Fluid Mech.* 21: 241–255

Bearman P W 1966 Investigation into the effect of base bleed on the flow behind a two-dimensional model with a blunt trailing edge. Separated flows. AGARD CP-4, Part II, pp 480–507

Chang P K 1976 *Control of flow separation* (Washington, DC: Hemisphere)

Delery J M 1985 Shock-wave/turbulent boundary-layer interaction and its control. *Prog. Aerosp. Sci.* 22: 209–280

Gad-el-Hak M 1989 Flow control. *App. Mech. Rev.* 42: 261–292

Gad-el-Hak M 1996 Modern developments in flow control. *Appl. Mech. Rev.* 48: 365–379

Gad-el-Hak M, Bushnell D M 1991 Separation control: Review. *J. Fluids Eng.* 113: 5–30

Greenblatt D, Wygnanski I 2000 The control of flow separation by periodic excitation. *Prog. Aerosp. Sci.* 36: 487–546

Lachmann G V 1961 *Boundary-layer and flow control* (Oxford: Pergamon) vol. 1 & 2

Prandtl L 1952 *Essentials of fluid dynamics* (London: Blackie & Son)

Raghunathan S 1988 Passive control of shock-boundary-layer interaction. *Prog. Aerosp. Sci.* 25: 271–296

Rajan Kumar, Viswanath P R 2002 Passive control of surface pressure fluctuations in reattaching flows. *Aeronaut. J.* 106: 669–674

Roshko A 1954 On the drag and shedding frequency of two-dimensional bluff bodies. NACA TN 3169

Roshko A 1966 A look at our present understanding of separated flows. *AGARD Symposium on Separated Flows*, Brussels

Simpson R L 1989 Turbulent boundary-layer separation. *Annu. Rev. Fluid Mech.* 21: 205–234

Stanewsky E 2001 Adaptive wing and flow control technology. *Prog. Aerosp. Sci.* 37: 583–667

Viswanath P R 1988 Shock wave-turbulent boundary-layer interaction and its control; A survey of recent developments. *Sādhanā* 12: 45–104

Viswanath P R, Madhavan K T 2004 Control of trailing edge separation by tangential blowing inside the bubble. *Aeronaut. J.* 106: 669–674

Viswanath P R, Sankaran L, Sagdeo P M, Narasimha R, Prabhu A 1983 Injection slot location for boundary-layer control in shock-induced separation. *J. Aircr.* 20: 726–732

Viswanath P R, Ramesh G, Madhavan K T 2000 Separation control by tangential blowing inside the bubble. *Exp. Fluids* 29: 96–102