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Micro-vortex generators for shock wave/boundary layer interactions

Argyris G. Panaras [a,*], Frank K. Lu [b]

[a] Aerospace Engineering Consultant, Agias Elenis 63, Athens 15772, Greece
[b] Aerodynamics Research Center, Mechanical and Aerospace Engineering Department, University of Texas at Arlington, Arlington, TX 76019, USA

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ABSTRACT

The effect of micro-vortex generators (MVGs) on shock wave/boundary layer interactions (SBLIs) has been reviewed. Experimental and computational evidence has been presented about the dominant role it has in the suppression of shock-induced separation the pair of counter-rotating streamwise vortices, which appears downstream of the types of micro-vortex generators used in SBLIs; these streamwise vortices entrain high momentum fluid, increasing the boundary layer velocity near the wall. The structure of the wake is examined in detail, with emphasis on the strength and decay of the streamwise vortices and on the ring-type or hairpin vortices which have been detected in the instantaneous flow around the wake. Evaluation of the ability of various types of MVGs to suppress shock-induced separation is done. Topics which need to be further studied, like the structure of the flow around devices of small size and the effect of the Reynolds number, are suggested.

Contents

1. Introduction

Boundary layer theory, developed by Prandtl in 1904 [1], is a discovery that enabled breakthrough developments in flight and many other technical achievements. According to this theory, when a fluid flows past an object, frictional effects are significant only in a thin region close to the wall, where large transverse gradients of velocity exist. Within this thin *boundary layer*, the velocity rises rapidly from zero at the wall to the freestream value at its edge. According to Newton's shear – stress law, which states that the shear stress is proportional to the velocity gradient, the local shear stress can be very large within the boundary layer even if the viscosity were small. Thus, the skin-friction drag exerted on a body is not negligible, contrary to what earlier scientists believed. Actually, for slender bodies most of the drag is due to skin friction.

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[*] Corresponding author.
E-mail address: a.panaras@gmail.com (A.G. Panaras).

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The boundary layer concept also explains how a decelerating flow due to an adverse pressure gradient eventually separates from a surface. According to Prandtl [1], since the velocity in the boundary layer falls towards the wall, the closer a fluid particle is to the wall, the smaller is its momentum. This implies that while the outer flow accommodates an adverse streamwise pressure rise by simply decelerating, the fluid particles inside the boundary layer may suffer excessive deceleration and are unable to negotiate the adverse pressure gradient. Even a small increase of pressure may cause the fluid particles near the wall to stop and reverse direction to form a recirculating flow region known as a separation bubble.

The description of the separation phenomenon by Prandtl led to the development of the following separation control techniques: decrease of the imposed adverse pressure gradient, removal of the low-momentum near-wall flow, or addition of momentum to the near-wall flow. Removal of the low momentum, near-wall flow is done by *suction* through slits or holes. Suction is an effective method of suppressing separation in both laminar and turbulent boundary layers. In his original paper, Prandtl [1] described several experiments in which the boundary layer was controlled by suction.

Addition of momentum to the near-wall flow can be achieved by *blowing* fluid through a surface or by deriving the required energy from the freestream by using slats and slotted flaps or *vortex generators*. Indeed, a characteristic feature of vortices is their strong swirling motion, allowing them to promote large-scale mixing of fluids with possibly different momentum and energy. This feature has been exploited for the development of various simple passive or active devices for controlling boundary layer separation.

Passive vortex generators (VGs) are highly effective flow control devices used widely in both external and internal aerodynamics. Vane-type VGs are most often used. Their shape is rectangular, delta or trapezoidal. Usually, a number of VGs is positioned in a row. They project normal to the surface and are set at an angle of incidence to the local flow, thus acting as lifting surfaces producing an array of trailing vortices (see Fig. 1a). The conventional, vane-type VGs have height h on the order of the boundary layer thickness δ. Thus, they transfer high-momentum air, from the outer flow, to the wall region. However, some drag appears because of their dimensions, which partially counter balances their benefits. Experimental studies show that reducing the height of conventional VGs to only a fraction of δ can still energise the boundary layer over a region several times their own height, especially in turbulent boundary layers where the velocity profile is relatively full [2]. These sub-δ-scale VGs are referred to as *micro-vortex generators* (MVGs), or sub boundary-layer vortex generators (SBVGs), or submerged VGs. MVGs installed along the leading edge of flaps, can be stowed in the flap well during cruise resulting in no cruise-drag penalty. An example is given in Fig. 1b, after Meunier and Brunet [3]. Ten pairs of trapezoidal-shaped counter-rotating vanes were placed parallel to the flap leading edge at $x/c_{flap}=25\%$, slightly upstream of the separation point. The authors observed that, according to their numerical results, the flow over the flap could be almost entirely reattached (Fig. 1b).

Active vortex generators are being studied for separation control during aircraft takeoff and landing, and drag reduction during aircraft cruise conditions. These devices potentially have an advantage over conventional VGs because, since they are activated when necessary, they can eliminate the parasitic drag that arises with passive VGs. One variety consists of angled oscillatory pulses of fluid which are injected through orifices. The angular injection causes the production of streamwise co-rotating vortices. These vortices can cause an otherwise separated flow to become attached, thus leading to improvements in aerodynamic performance. This actuation technique is referred to as pulsed vortex generators (PVGs). Active flow control devices are complex, difficult to maintain, and expensive.

Flow control techniques to alleviate the adverse effects of shock wave/boundary layer interactions (SBLIs) continue to be of interest. Boundary layer control and shock control techniques have been developed. In the former, the boundary layer ahead of a shock is energized by adding high-energy air, so that it becomes more resistant to shock-induced separation. On the other hand, shock control techniques are concentrated on the formed shocks, attempting to reduce their strength at the interaction zone, so that the wave drag will be smaller. To assist the reader, elements of shock wave theory are provided here. Air that passes through shock waves is subjected to non-isentropic compression (adiabatic flow). *Total temperature remains constant* but *total pressure is reduced*. The *strength of a shock wave* is defined by $P=(p_2-p_1)/p_1$, where p_1 and p_2 refer to the static pressure upstream and downstream of a shock respectively. It can be shown that the entropy increase across a normal shock is related to the total pressure drop and to the shock strength by

$$s_2 - s_1 = -R\ln\frac{p_{t_2}}{p_{t1}} \quad \frac{s_2-s_1}{R} = \frac{k+1}{12k^2}P^3 - \frac{k+1}{8k^2}P^4 + \cdots \tag{1}$$

In particular, the cubic dependency of the entropy rise to the shock strength implies that reducing the shock strength will greatly reduce the entropy rise and thus the wave drag. If the flow across a main shock can traverse through two consecutive, weaker shocks, then the latter flow will suffer less total pressure loss and result in a lower wave drag.

Shock control techniques in general aim at replacing a strong shock by a weaker one plus a succession of upstream isentropic compressions, or by a λ-shock formation. This replacement results in reduced wave drag because the entropy increase and, consequently, the total pressure drop become smaller. Most representative methods of shock control are *bumps* and *porous cavities* as shown schematically in Fig. 2. The bumps have very small height, less than half percent of the airfoil chord. To be effective, these devices have to be installed underneath the foot of the formed normal shock. The flow then develops as shown in Fig. 2a. Because of the existence of the bump, a local compression is induced upstream of the shock, leading to one of the aforementioned flow structures. Equivalently, by placing a porous strip on the surface over a cavity underneath the foot of the shock, a secondary flow is induced into and out of the cavity, as shown in Fig. 2b. The resulting bubble of recirculating air acts as a bump on the airfoil surface, which leads to an array of oblique compression waves (which can be isentropic) that constitutes the upstream leg of a λ-shock. Just as in the case of the bump, to be effective, the porous strip must be located beneath the shock for the operating Mach number and incidence angle. The sensitivity of bumps to flow conditions is reduced by optimizing them, considering various design points. However, according to published material, active contour bumps, which can change height and also move to follow the shock wave, would likely be required in practice on an actual aircraft. They will be a part of future adaptive designs, in which they will deploy actively at particular regions of a wing beneath of normal shocks. Details are given in the book by Panaras [4]; see also Ogawa and Babinsky [5].

Returning to boundary layer control techniques, suction, passive or active vortex generators and MVGs have proved successful in mitigating or preventing shock-induced separation. However, restriction or complete elimination of a separation bubble, formed underneath of a normal shock, results in a stronger shock formation, which according to Eq. (1) induces larger stagnation pressure losses. Thus, to some extent, the two techniques of control have contradictory effects; boundary-layer control tends to increase