THE PHYSICS OF SHOCK WAVE/BOUNDARY LAYER INTERACTION CONTROL: LAST LESSONS LEARNED

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Abstract. In high speed flow, the existence of shock waves most often entails either drag increase or efficiency losses. A major cause of performance degradation is the interaction of the shock with a boundary layer. Then complex phenomena occur which contributes to increase friction losses, especially if the shock is strong enough to separate the boundary layer. To a separated flow are associated typical wave patterns resulting from the shocks induced by the separation and reattachment processes and which play a major role in the production of entropy by the flow. Since shocks cannot be avoided in most situations, control techniques have been proposed to limit their negative effects. The mode of operation of these techniques can be well understood by a clear identification of shock wave/boundary layer interaction properties. The control actions can be performed by a proper manipulation of the boundary layer upstream of the interaction domain in order to increase its resistance to the shock action (by blowing or lowering the wall temperature, or using vortex generators) or by a local action in the shock foot region. Then active, passive or hybrid control which combines the two previous actions can be applied. Other methods can be envisaged, like the installation of a bump in the shock foot region to adapt the surface contour in order to weaken the shock. None of these techniques brings the ideal answer to the problem of shock wave/boundary layer interaction control. Thus, the definition of a solution closely depends on the objective of the control. In addition, the appropriateness of implementing a control device highly depends on economical issues in terms of weight penalty, manufacturing and maintenance cost and energy consumption.
1 INTRODUCTION

Shock waves almost inevitably occur when a flow becomes supersonic or transonic. They are provoked by a change in the flow direction, as at the compression ramps of a supersonic air intake or at a control surface, an increase of the downstream pressure as on a transonic wing, a pressure jump as in an overexpanded propulsive nozzle, a brutal deceleration as in front of the nose of a re-entry vehicle.

The presence of shock waves entails the existence of discontinuities and regions of high gradients which are the shocks themselves and the shear layers resulting from the interaction with the boundary layers developing on the vehicle surface. These gradients “activate” the viscous terms producing entropy, which makes shock waves an important source of drag:

1. directly by entropy generation in the thickness of the shock: this contribution is the wave drag;
2. indirectly, by enhancing dissipation in the boundary layers: hence an amplification of the viscous drag.

In addition, strong interactions with the boundary layers may lead to catastrophic separation with possible occurrence of large scale unsteadiness (wing buffeting, air intake buzz). Shock waves play a dramatic role at hypersonic velocities because of their intensity which leads to spectacular shock-shock interferences with specific and complex wave patterns and strong interactions with the boundary layers\(^1\). In addition, the temperature rise at the crossing of the shocks most often affects the gas thermodynamics properties (the so-called real gas effects) and is at the origin of high heat transfer levels at the vehicle surface\(^2\).

The idea to control shock wave/boundary layer interaction in order to avoid, or minimise, its detrimental effects is nearly contemporaneous with the advent of studies on high-speed flows. Thus, as early as 1941, Regenscheit\(^3\) studied the effect of suction through a slit at the surface of an airfoil tested at transonic velocity. The same arrangement was considered by Fage and Sargent\(^4\) in 1943. Since that time, a great deal of research has been devoted to this important practical problem\(^5\). In fact, the problem of shock wave/boundary layer interaction control is multiple in the sense that according to the objective looked for antagonistic mechanisms can be at work. As it will be seen, the reduction of a profile drag can be obtained by a smearing of the shock entailing a reduction of the wave drag, but at the price of a thickening of the boundary layer and an increase of the friction drag. On the other hand, separation suppression or shock stabilisation most often entails an intensification of the shock, hence an increase of the losses through the shock. Thus, the target of shock wave/boundary layer control must be clearly identified.

The purpose of this paper is to focus on the physical phenomena involved in shock wave/boundary layer interactions first without, then with control action. The results presented and discussed here are mostly based on a recent thorough investigation of various control actions applied to transonic interactions executed within the framework of the European projects Euroshock I and II. In particular, detailed flow descriptions allowed a clear identification of the flow processes at work in different kinds of control devices giving a good status of the art on control techniques in transonic flows\(^6,7\).
2 BASIC PROPERTIES OF SHOCK INDUCED PHENOMENA

The consideration which follow essentially apply to turbulent flows which are more common in usual aeronautical applications than laminar flows. When a boundary layer is submitted to the strong retardation imparted by a shock wave, complex phenomena occur within its structure which is basically a parallel rotational flow with the Mach number varying from the outer supersonic value to zero at the wall. The process has been analysed by Lighthill in the framework of its famous triple-deck theory.8

The interaction resulting from the reflection of an oblique shock (C1) is sketched in Fig. 1. A clear consequence of shock wave/boundary layer interaction is that the presence of the shock is felt upstream of its impact point in the perfect fluid model. This upstream influence phenomenon is in great part an inviscid mechanism, the pressure rise caused by the shock being transmitted upstream through the subsonic part of the boundary layer. The thickness of the subsonic layer depending of the velocity distribution, a fuller profile involves a thinner subsonic channel, hence a shorter upstream influence length. At the same time, a boundary layer profile with a low velocity deficit has a higher momentum, hence a greater resistance to the retardation imparted by an adverse pressure gradient. The dilatation of the boundary layer subsonic region is felt by the outer supersonic flow - which includes the major part of the boundary layer - as a ramp effect inducing compression waves whose coalescence forms the reflected shock (C2). This mechanism, which is amplified by a general retardation of the boundary layer flow, can be interpreted as a viscous ramp effect resulting in a spreading of the shock near the surface, the incident-plus-reflected shock of the perfect fluid theory being replaced by a continuous process. The physics involved in the interaction is in fact more subtle since the viscous terms must play a role in the immediate vicinity of the wall because of the no slip condition, otherwise one is confronted to inconsistencies as it was found by Lighthill. Thus, the interaction results from a competition between pressure plus inertia terms - belonging to the Euler part of the Navier-Stokes equations - and viscous forces tending to counteract the previous terms. This fact explains that the Reynolds number effect is nearly non-existent is fully turbulent flow whereas it has a strong effect in laminar flows which are viscous dominated.

Fig. 1 – Physical features of an oblique shock reflection without boundary layer separation. The upstream propagation mechanism.
Since the retardation effect is larger in the boundary layer inner part, a situation can be reached where the flow is pushed in the upstream direction by the adverse pressure gradient so that a separated region forms. Then, the flow adopts the structure sketched in Fig. 2. The separation process is basically a free interaction process resulting from a local self-induced interaction between the boundary layer and the outer inviscid stream. Hence, it does not depend on downstream conditions, in particular the intensity of the incident shock, the pressure rise at separation $\Delta p_s$ being only function of the incoming flow. Downstream of the separation point exists a bubble made of a recirculating flow bounded by a discriminating streamline (S) originating at the separation point S and ending at the reattachment point R. Due to the action of the strong mixing taking place in the detached shear layer which emanates from S, an energy transfer is operated from the outer high speed flow towards the separated region. As a consequence, the velocity $U_s$ on the discriminating streamline (S) steadily increases, until the reattachment process begins.

![Fig. 2 – Physical features of an oblique shock reflection with boundary layer separation.](image)

The transmitted shock (C3) penetrates in the separated viscous flow where it is reflected as an expansion wave. There results a deflection of the shear layer in the direction of the wall on which it reattaches. At reattachment, the separated bubble vanishes, the flow on (S) being decelerated until it stagnates at R. This process is accompanied by a compression wave ending into a reattachment shock in the outer stream.

A major consequence of the interaction is to divide the pressure jump $\Delta p$ imparted by the shock reflection into a first compression $\Delta p_1$ at separation - with the associated shock (C2) -
and a second compression $\Delta p_2$ at reattachment, the overall pressure rise being such that $\Delta p = \Delta p_1 + \Delta p_2$. The extent of the separated region is dictated by the ability of the shear layer issuing from the separation point S to overcome the pressure rise at reattachment. This ability is function of the momentum available on (S) – or maximum velocity $(U_S)_{\text{max}}$ - at the starting of the reattachment process. Since the pressure rise to separation does not depend on downstream conditions, an increase of the overall pressure rise imparted to the boundary layer - or incident shock strength - entails a higher pressure rise at reattachment. This can only be achieved by an increase of the maximum velocity $(U_S)_{\text{max}}$ reached on the discriminating streamline, hence an increase of the shear layer length allowing a greater transfer of momentum from the outer flow. Thus the length of the separated region will grow in proportion to the pressure rise at reattachment.

When there is separation, the interaction of the shock wave with the boundary layer has deep repercussions on the contiguous inviscid flow. As shown in Fig. 2, the simple inviscid shock pattern made of an incident plus reflected shock is replaced by a pattern involving 5 shock waves:

- the incident shock ($C_1$),
- the separation shock ($C_2$),
- the transmitted shock ($C_3$) emanating from the intersection point I of ($C_1$) and ($C_2$),
- the second transmitted shock ($C_4$),
- the reattachment shock ($C_5$).

The structure involving shocks ($C_1$), ($C_2$), ($C_3$) and ($C_4$) is a Type I shock/shock interference pattern, according to the Edney classification\(^1\). If the slope, or intensity, of the incident shock is increased, the interaction of ($C_1$) with ($C_2$) may be singular, a normal shock ($C_6$) forming between ($C_1$) and ($C_2$) to constitute a Mach phenomenon or Type II interference.

![Fig. 3 – Physical features of a ramp flow with boundary layer separation.](image-url)
Transonic and ramp induced interactions lead to a similar organisation for the separated flow, the boundary layer reacting to a pressure rise, no matter the cause of this pressure rise. What changes is the shock pattern associated with the interaction. In the case of the interaction at a ramp, the shock system is a Type VI interference pattern (see Fig. 3). In transonic flow, the interaction leads to a specific flow organisation which can be considered as a variant of the above situations. Here, the interaction is provoked by a normal shock \((C_3)\) forming on a transonic airfoil or in a channel. As shown in Fig. 4, separation of the boundary layer at point \(S\) induces a deflection of the flow giving rise to the oblique shock \((C_1)\) as in the previous cases, the flow behind \((C_1)\) being still supersonic. The two shocks \((C_1)\) and \((C_3)\) meet at the triple point \(I\) where a variant of the Type VI shock-shock interference takes place. The states 2 and 3 behind \((C_1)\) and \((C_3)\) not being compatible with the Rankine-Hugoniot equations, a third shock \((C_2)\) starts from \(I\) leading to the state 4 compatible with 3. Downstream of \(I\), the two states 3 and 4 separated by the slip line \((\Sigma)\) coexist. A deeper analysis of the solution shows that the shocks \((C_3)\) and \((C_2)\) are strong oblique shocks, in the sense of the strong solution to the oblique shock equations. Downstream of \((C_2)\) the flow can still be supersonic, the further transition to subsonic being most often isentropic. Away from the wall, the flow contains the nearly normal shock \((C_3)\) which caused the separation. The structure represented in Fig. 4 is commonly called a lambda pattern.

Thus, to a shock-induced separated flow is attached a shock pattern in which the simple inviscid flow solution is replaced by a multi-shock system tending to minimise entropy production through the shock. This fact is of great importance in control techniques aiming at drag or efficiency loss reduction.

![Fig. 4 - Physical features of a normal shock interaction with boundary layer separation. The lambda shock pattern](image-url)
3 MECHANISMS FOR CONTROL ACTION

The above physical description of typical shock wave/boundary layer interactions brings out the most salient phenomena involved in an interaction, thus providing indications on the means which can be considered to modify - or control - the interaction.

The upstream influence of the shock and the resistance of a turbulent boundary layer depending mainly of its momentum, a means to restrict the effect of the shock is to increase the boundary layer momentum prior to its interaction with the shock. This can be done by proper boundary layer manipulation:

- One can perform an injection through one or several slots located upstream of the shock origin, this technique being called boundary layer blowing.
- A distributed suction applied over a certain boundary layer run before the interaction reduces its shape parameter, thus producing a fuller velocity profile. On the contrary, distributed injection - or transpiration - increases the shape parameter, which renders the boundary layer more sensible to the shock. Vortex generators can be classified in this category of control actions, since the vortical structures that they create operate a momentum transfer from the outer high speed flow at the benefit of the boundary layer.
- It is also possible to eliminate the low speed part of the boundary layer by making a strong suction through a slot located at a well chosen location upstream of the interaction.
- The interaction being in great part dictated by the boundary layer properties, one can envisage to modify these properties by changing the temperature of the wall. An increase of the wall temperature lowers the Mach number level by increasing the sound speed whereas a lowering of the wall temperature increases the Mach number by diminishing the sound speed. Thus upstream propagation of the shock influence will be affected by this effect, the thickness of the boundary layer subsonic channel being augmented on a heated wall and reduced on a cooled wall. In addition, the temperature level in the boundary layer changes the density in the boundary layer flow. There results a change of the boundary layer momentum, favourable in the case of cooling, unfavourable in the case of heating. The effect of the wall temperature has been mainly studied for the cold wall situation\textsuperscript{11}. In this case, a strong contraction of the interaction domain is observed, with in some circumstances a suppression of the separation bubble. The situation of a heated wall has been investigated for the reflection of an oblique shock on a wall heated to a temperature equal to twice the recovery temperature\textsuperscript{12}. The iso-Mach number contours plotted in Fig. 5 show the extension of the interaction occurring when the wall is heated.
The interaction properties can also be affected by performing an action in the interaction region itself. A key role being played by the velocity - or momentum - level which must be reached on the discriminating streamline to allow shear layer reattachment, any action modifying this level will influence the interaction. Thus, if some fluid is sucked through the wall, topological considerations lead to the flow structure sketched in Fig. 6b. The streamline $(S_2)$ stagnating at the reattachment point R comes from upstream "infinity" and is located above $(S_1)$, the sucked-off fluid flowing between $(S_1)$ and $(S_2)$. Provided the extracted mass flow be moderate enough so as not to entail a total alteration of the general flow structure, the velocity profile through the shear layer is nearly the same as in the basic case of Fig. 6a. As streamline $(S_2)$ is located at a greater distance from the wall, the velocity $(U_{S_2})_{\text{max}}$ on $(S_2)$ is greater than in the basic case: hence, an increase of the ability of the flow to withstand a more important compression and a subsequent contraction of the interaction domain. The case of a fluid injection at low velocity is sketched in Fig. 6c. Now, the velocity on $(S_2)$ is smaller, since $(S_2)$ is located at a lower altitude on the velocity profile. The resulting effect is a lengthening of the separation bubble. However, if the injected mass flow is increased, there will be a reversal of the effect, since the velocities on the bottom part of the profile - and in particular $(U_{S_2})_{\text{max}}$ - will increase if the mass flow fed into the separated region goes beyond a certain limit. A similar mechanism is at work in base bleed aiming at the reduction of base drag through an increase of the base pressure.
4 OBJECTIVES AND APPLICATION OF SOME CONTROL ACTIONS

When considering shock wave/boundary layer interaction control, it is essential to state the objective which is looked for:

- A control action can be considered to prevent separation and/or to stabilize the shock in a duct or a nozzle. Boundary layer blowing, suction, wall cooling can be very efficient for these purposes.

- If the objective is to decrease the drag of a profile, or limit the loss of efficiency in an air intake, the situation is more subtle since the drag has its origin both in the shock and in the boundary layer.

Any action "strengthening" the boundary layer tends also to strengthen the shock since the spreading caused by the interaction is reduced. This effect is illustrated in Fig. 7 which shows,
by means of iso-Mach number contours (deduced from LDV measurements), a comparison between a basic transonic interaction, without control and the flow resulting from boundary layer suction through a slot. In the second case, the entropy production through the shock is more important and the wave drag higher. On the other hand, since the downstream boundary layer profile is more filled, the momentum loss in the boundary layer is much reduced which leads to a reduction of the friction drag. In addition, this active control action reduces significantly the turbulence level downstream of the interaction region, which contributes to produce a more stable flow, less affected by fluctuations. The most favourable location of the slot is at a few distance downstream of the interaction, upstream and centred locations leading to a slightly greater rise of the boundary layer displacement and momentum thicknesses. In evaluating the benefit of local suction in terms of drag, one must be aware of the captation drag caused by the swallowing of a part of the incoming flow.

As seen above, when separation occurs the simple inviscid shock system is replaced by a pattern made of continuous compression waves and multiple shocks through which the entropy production is less compared to the inviscid solution (for identical upstream and downstream conditions). Thus, the smearing of the shock system and splitting of the compression achieved by the interaction reduce the wave drag - or the efficiency loss - due to the shock. On the other hand, the momentum loss in a separated boundary layer is far more important than through an attached boundary layer, so that separation most often results in a sharp increase of drag or efficiency loss (not speaking of unsteadiness).

Since separation has a favourable effect on the wave drag, one can envisage to replace a strong, but not separated interaction, by a separated or separated-like flow organisation. The passive control concept suggested in the early 80s, aims at combining the two effects by
spreading the shock system while reducing the boundary layer thickening\textsuperscript{13,14}. The principle of passive control consists in replacing a part of the surface by a perforated plate installed over a closed cavity. The plate being implemented in the shock region, there occurs a natural flow circulation - via the cavity - from the downstream high pressure part of the interaction to the upstream low pressure part. The resulting effect on the flow is sketched in Fig. 8. The upstream transpiration provokes a thickening of the boundary layer, hence a rapid growth of its displacement thickness which is felt by the outer supersonic flow as a viscous ramp effect inducing an oblique shock (\(C_1\)). The meeting of (\(C_1\)) with the main normal shock (\(C_3\)) at the point I leads to a lambda shock pattern with the trailing shock (\(C_2\)). The situation is similar to the case of a natural shock-induced separation, the "strong" normal shock (\(C_3\)) being replaced by a two shock system in the vicinity of the surface: hence a reduction of the wave drag. The negative effect on the boundary layer, which would increase the friction losses, is limited by the suction operated in the downstream part of the plate. The effect of passive control is illustrated by the schlieren photographs in Fig. 9 which show the splitting of the original shock into a two shock system and the thickening of the boundary layer due to the transpiration effect\textsuperscript{15}. A more quantitative information is given by the evolution of the boundary layer displacement and momentum thicknesses plotted in Fig. 10. The comparison with the reference case, without control, shows the positive influence of an increase of the displacement thickness (viscous ramp effect) and the negative consequences coming from the dramatic rise in the momentum thickness.

Fig. 8 – Principle of passive control of a transonic interaction.
Fig. 9 – Schlieren visualisation of transonic interaction under passive control conditions.

a – reference solid wall case

b – case with passive control
Fig. 10 – Transonic interaction under passive control conditions. Boundary layer characteristic thicknesses.
The obvious merit of the above concept is the absence of an energy supply, the system being self operating. However, the effectiveness of passive control to reduce the total drag produced by the shock is impaired by the high friction drag along the perforated plate, the gain being in general modest when not negative. The concept can be improved by making some suction in order to minimise the boundary layer growth over the control region. There are different ways to combine the passive and active control effects. One can simply perform some suction in the cavity itself. It is also possible to perform suction downstream of the passive control cavity either in a separate cavity or by a slot, as sketched in Fig. 11. This hybrid control device could combine the advantage of passive control to decrease the wave drag and the high effectiveness of suction to reduce friction losses. In fact, experiment shows that it is necessary to extract a relatively high mass flow to substantially reduce the friction losses and make the device efficient.\footnote{7}

Fig. 11 – Principle of hybrid control of a transonic interaction.

Fig. 12 – Interaction control by a local deformation of the wall or the bump concept.

a – inviscid flow associated to interaction

b – flow induced by a double-wedged bump
Since friction drag production in passive or hybrid control, is frequently unacceptable, one may consider the possibility to reproduce the separated flow structure by a local deformation of the surface having, in the case of the oblique shock reflection of Fig. 2, a double wedge like shape which materialises the viscous separated fluid of the original interaction, as shown in Fig. 12. Such a contour induces a first shock at its origin and a second shock at its trailing edge, thus leading to a shock pattern similar to that of the original reflection. One can hope that this system would not too much destabilise the boundary layer, while reducing substantially the wave drag. This bump concept has been considered for application to transonic interactions with a view to control the flow past civil transport aircraft wings. A large, both experimental and theoretical, programme has been recently executed in the framework of the Euroshock II project. The bump is a local deformation of the airfoil contour located in the shock foot region which produces a nearly isentropic compression in its upstream part thus acting as a compression ramp. The height of such a bump is less than one per cent of the airfoil chord length and it extends over a distance which is of the order of 0.10 to 0.20 chord length. The bump contour must be carefully designed, one method consisting in adopting a shape which reproduces the evolution of the boundary layer displacement thickness in the case without control\textsuperscript{16}. As shown by the iso-Mach number contours in Fig. 13, the bump is very effective to spread the compression produced by the shock in the wall region, thus to reduce the wave drag. At the same time, as shown by the characteristic thicknesses plotted in Fig. 14, the bump has a reasonable effect on the boundary layer properties, in the sense that the boundary layer flow is not very different from what it is in the reference case, contrary to the passive control device. The friction losses are thus limited so that the gain due to the wave drag reduction is not compromised. The drawback of the system is that the effectiveness of the bump highly depends on the shock location with respect to the bump. Considering that the location achieved in Fig. 13 is nearly the optimum, a downstream shift of the shock leads to a steepening of the compression at the wall and a more important thickening of the boundary layer. Moreover if the shock travels to the bump trailing edge region, its strength increases because of the expansion after the bump crest. This leads to the formation of a large separated zone at the bump trailing edge. Thus both the wave drag and the friction drag can be increased.
A comparison of the different tested methods is shown in Fig. 15 by plottings of the iso-Mach number contours deduced from LDV measurements. One sees the deep repercussion of the control actions both on the outer inviscid flow structure and on the boundary layer behaviour.
5 CONCLUDING REMARKS

The signification of shock wave/boundary layer interaction control is ambiguous, in the sense that control can aim at minimising the effect of the shock on the boundary layer properties or reducing the overall losses caused by the interaction, the two objectives being partly contradictory. In the first case, the main objective is most often to avoid boundary layer
separation which can be achieved either by manipulation of the boundary layer prior to its interaction with the shock (upstream blowing, suction through a slot, wall cooling) or by suction or bleeding in the interaction region. In the second case, one has to reduce also the wave drag which is achieved by a splitting or spreading of the shock near the wall, which can be done by creation of a separated-like flow structure by means of a passive control cavity or a bump.

The lessons learned at the issue of the two Euroshock projects could be that application of the above control systems to a wing is hazardous. The gain of passive control is questionable, active control requires extraction of important mass flow at low pressure, bump control is too much dependent on shock location. However, as far as external aerodynamics is concerned, local applications at a smaller scale can certainly be considered as, for example, to control shock-induced separation on the pylon holding a propulsive nacelle.

Control techniques are more suited to internal aerodynamics applications interesting air-intakes, diffusers, nozzles because the size of the region to be controlled is far more reduced and because of the proximity of the energy supply; thus avoiding long redhibitory tubing.

The energetic and economic aspects of interaction control, as also the problem raised by the installation of a control device in an airplane wing, have not been examined in this paper, although their consideration is essential. Neither we have discussed the problems raised by the modelling of an interaction under control conditions, considering the incidence of flow manipulation on turbulence behaviour and the definition of a law to represent the suction/transpiration velocities in the control region. The extensive experimental programme executed within the Euroshock projects has allowed to constitute unprecedented data banks which already contributed to improve the physical models used in the prediction of shock wave/boundary layer interactions under control conditions. This is also a lesson learned.

6 REFERENCES


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