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Shock/boundary-layer interactions: Possible sources of unsteadiness

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Abstract

In shock induced separation, the question of the origin of the low frequency motions affecting the shock waves remains controversial. According to the situations, it may be argued that upstream or downstream flow conditions can provide a likely explanation. A short review of this question is proposed, mainly based on the analysis of existing experimental work. One of the recent interpretations is the role which can be played by the long turbulent superstructures of the incoming boundary layer. This is shown to be a valid interpretation in a limited number of cases. An experiment in which perturbations of the same type are formed is shown to bring no modification to an oblique shock reflection interaction. The different cases are discussed and an assessment of the generality of their results is proposed.

1. Introduction

Supersonic flows present specific features for the aerodynamic loads applied to the structures because of the effect of compressibility and the presence of shock waves [see for example Bouhadji and Braza (2003) and Iakovlev (2007)]. In particular, low frequency unsteadiness is a common feature in many shock boundary layer interactions. It is found that shock waves are subjected to motions occurring at frequencies much lower than the energetic incoming turbulence. This is a problem found in many aeronautical situations, for example in overexpanded nozzles or in supersonic air intakes. The low frequencies produced in such conditions may cause serious practical problems, since they are at the origin of significant aerodynamic loads, they can be a source of fatigue of the mechanical structures or they can damage the engines. The objective of this paper is to make a review of the more recent work in this field, and to discuss the origin of the frequencies of the shock motion. Two possible interpretations exist: the influence of incoming turbulent conditions or the effect of the downstream flow organisation. These two points will be considered, and results of an experiment using an incoming boundary layer with characterised perturbations will be given. Discussion and conclusions will indicate possible scenarios.

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2. Characterisation of unsteadiness

A general outline of the organisation of shock boundary-layer interactions has recently been proposed by Dussauge (2006), to which the reader may be referred. The main idea is that a shock wave is an interface between upstream and downstream conditions, which both determine its position. This is a static point of view. On the other hand, the frequency response of a shock wave is not flat, but depends itself on the upstream and downstream conditions to which is subjected. Different results can be obtained, and can lead to frequency selection in some cases, for example in transonic buffeting. In such pathological cases, feedback loops are present; however, in turbulent conditions it is not clear that such loops exist. It seems that shocks behave generally as low pass filters and are preferably sensitive to low frequencies. A possible understanding of the organisation of such interactions can be summed up by a diagram, adapted from Dussauge (2006), Fig. 1.

Fig. 1 refers to the following problems. The incoming conditions are turbulent. Turbulence is distorted by its passage across a shock wave, then is convected downstream and contributes to the formation of a new boundary layer (branch on the right-hand side). Moreover, as represented by the central branch, separation may occur with the formation of large scale eddies and vortex shedding. The level of distorted turbulence may interact with the structure of separation. This part of the flow provides the downstream conditions applied to the shock wave; separation and vortex shedding contain their own frequency ranges of fluctuations and can impose unsteady downstream conditions to the shock. Feedback loops may occur in the separated bubble and in the immediate vicinity of the shock, constituting short-range interactions. They can also be produced by the flow far downstream through acoustic coupling as observed in buffeting problems. Arrows on the left-hand side, in the backwards direction, represent the possible couplings. If there is no separation, only the branch on the right-hand side is active. One of the objectives of this review is to infer what the important factors are in such interactions. The case of buffeting examined by Lee (2001) will not be discussed here, and we will concentrate mainly on situations where the flow immediately downstream of the shock has to be considered. This happens mainly in compression ramp flows, in shock reflection on a flat plate and in interactions around blunt obstacles.

The shock motion occurs at low frequencies. What does this mean and what do the frequencies present in such interactions? Separated zones generally involve frequencies lower than the incoming turbulence in subsonic and supersonic boundary layer as well [see Dupont et al. (2005, 2006a, b), Cherry et al. (1984)]. Moreover, separation does

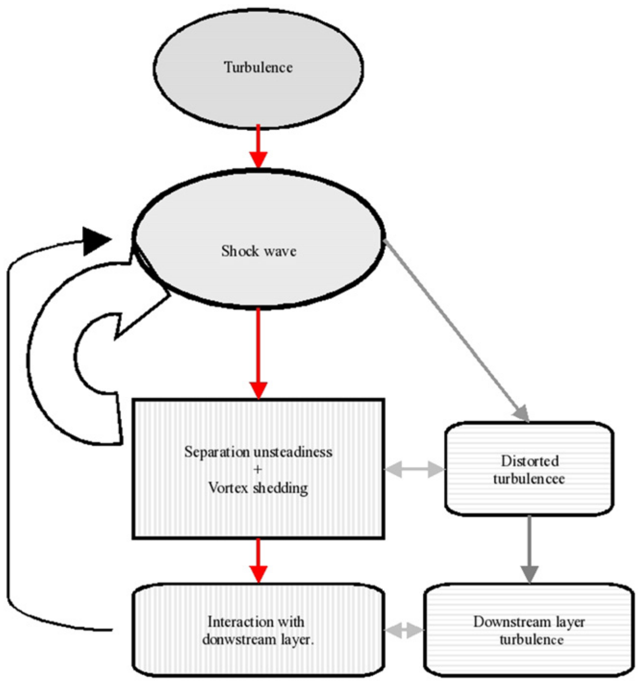

Fig. 1. A diagrammatic representation of shock/boundary-layer interactions.

not involve only a single frequency, but a family of modes related to the formation of vortical structures in the mixing layer bounding the recirculating bubble, and to vortex shedding. All this may be scrambled by incoming turbulence. The frequencies involved by the shock motion are generally still lower, and again with a broadband spectrum. A dominant frequency is generally defined as follows. Fluctuating wall pressure is considered. The shock motion implies the presence of a peak on the longitudinal distribution of rms wall pressure. Considering the frequency spectrum $E(f)$ at the maximum of the rms value, the dominant frequency is defined as the frequency for which $fE(f)$ versus f has a maximum. Using the same attempt as Erengil and Dolling (1991), or by reference to works on subsonic separated flows, for example to Cherry et al. (1984), a Strouhal number is defined by normalising this dominant frequency by the length of the separated zone and the velocity of the incoming flow.

Making such an analysis for many cases of interactions, Dussauge et al. (2006) have confirmed very clearly that the Strouhal number S_L based on separation length and upstream velocity is very low, whatever the geometrical case. If the source of excitation of the shock depends on the flow, there is no reason to have a strict collapse in such a representation. However, S_L takes values between 0.02 and 0.05. If the interaction zone is large enough, this implies that $L/\delta \gg 1$, where δ is the thickness of the initial boundary layer. Therefore, the Strouhal number $f\delta/U_e$ is of the order of 10^{-2} or less. As typical frequencies associated with turbulence in the incoming boundary layer are of the order of U_e/δ, and as it is very easy to get a separated zone of the order of the boundary layer or larger, these results suggest that in most cases, the shock frequency is two orders of magnitude lower than the incoming turbulence.

Another result derived from the same considerations in supersonic interactions [Dupont et al. (2005, 2006a, b), Dussauge et al. (2006)] indicates that the shock velocity is two orders of magnitude below the external velocity, so that its intensity is not affected by its motion.

3. Influence of upstream conditions

It is just obvious that variable incoming conditions will make shock waves move. The question is to know if the incoming turbulence can explain the strong motions observed in the separated interaction.

A first work, which can be referred to, is the experiment of Poggie and Smits (2001). These authors study a shear layer over a cavity, reattaching on a tilted plate, at a Mach number of 2.9. Such an arrangement is known to produce isobaric shear layers. At the reattachment, the flow is deviated so that a shock is formed. An interesting point in Poggie and Smits' experiment is that the shear flow downstream of reattachment can develop freely, since there is no obstacle or no separated zone imposing its aerodynamic conditions or its own frequencies. They studied the structure of the recompression by turning close to the reattachment point for the shear layer in natural and perturbed conditions. The perturbation consists in blowing air in the cavity in a strong enough way to change significantly the large eddies of the shear layer. The mean and rms pressure distribution and the pressure spectra along the plate around reattachment scale consistently with the size of the large eddies, showing that in this case, the shock motion depends primarily on incoming turbulence.

Contributions of incoming turbulent eddies are also found in the numerical simulations by Pirozzoli et al. (2005) and by Pirozzoli and Grasso (2006) of a shock reflection on a flat plate at a Mach number M of 2.25, in which it is clearly seen that the vortical structures passing through the shock are at the origin of some motions, of limited extent, however. Recently, detailed measurements by PIV in a 20° compression ramp flow at $M = 2$ have been performed by Ganapathisubramani et al. (2007). They considered mainly the influence of the very large scale structures of the initial boundary layer. These superstructures have been identified in low speed boundary layers by Adrian et al. (2000) among others. They are constituted of packed hairpin vortices, and, if δ is the thickness of the boundary layer, they can have a length up to more than 30δ. The PIV measurements of Ganapathisubramani et al. (2007) were processed in order to detect the shock front and the edge of the separated zone, suggesting coincidence between the passage of longitudinal structures and the shock motions. Therefore, these authors concluded that they observed a mechanism at the source of the unsteadiness in compression ramp flows.

It may be remarked that the superstructures detected by Adrian et al. (2000) are associated with velocity perturbations typically of $\pm 2U_\tau$, where U_τ is the friction velocity. According to Morkovin's hypothesis, the turbulent velocity scale in zero pressure gradient boundary layer is $U_\tau\sqrt{\rho_w/\rho}$. As in adiabatic conditions, the velocity scale associated with these structures should be smaller than at low speed. An experiment was made in the same configuration as in Dupont et al. (2006a, b), to check the influence of perturbations with a velocity scale of the order of U_τ. The flow consists in an interaction between an oblique shock wave reflecting on a fully developed turbulent boundary layer. It is installed in the supersonic wind tunnel of IUSTI, and has a nominal free-stream Mach number of $M_\infty = 2.3$. The settings of PIV system are the same as in Dupont et al. (2005). The different characteristics of the flow are listed in Table 1.

Table 1
Aerodynamic flow conditions, shock reflection experiment

M_∞	U_0	δ_0	Re_θ	Cf	T_{te}	U_τ
2.3	$550\,\mathrm{m\,s^{-1}}$	11 mm	5.9×10^3	2×10^{-3}	300 K	$24\,\mathrm{ms^{-1}}$

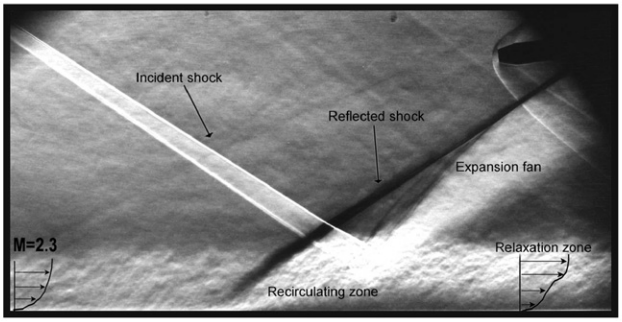

Fig. 2. Spark Schlieren of the interaction.

The main characteristics of the flow are described in the two previous references and can be summed up as follows. The shock is produced by a tilted flat plate with a sharp leading edge, placed in the free-stream, and fixed on the ceiling of the wind tunnel by two masts. It generates an oblique shock wave impinging the boundary layer on the floor. Its angle of incidence, and therefore the flow deviation θ can be varied from $\theta = 0^\circ$ to 9.5°; this generates shocks of various intensities, and various separation conditions. Incipient separation occurs around 5.5°. In the present case, a deviation of 9.5° is considered, for which separation is well developed. The shock experiences low frequency movements, with a typical frequency of 150 Hz. A spark Schlieren visualisation of the separated flow is presented in Fig. 2.

Separation produces streamlines with concave curvature leading to the formation of the unsteady reflected shock upstream of the point of impingement of the incident shock. PIV investigations in the recirculation, with a light sheet parallel to the wall, have shown the three-dimensional structure of the mean flow, with the presence of two contra-rotative vortices, symmetric with respect to the wind tunnel axis (Dupont et al., 2005). This interaction has been studied with two different incoming conditions with roughnesses placed upstream of the sonic neck, in order to see the impact on the development of the incoming boundary layer, and the consequences on the frequencies and on the length scale of the interaction. In the first configuration, wall roughnesses were placed just upstream the sonic section, at a distance of about 80 cm upstream of the test section. They are formed with the letter V on Dymo tapes. Three rows of such tapes are used, with V patterns arranged in a quincunx; their height is 0.5 mm. A picture of these roughnesses is given in Fig. 3, showing that they can produce an excitation in the spanwise direction for a large number of special modes. In a second configuration, three rows of smooth Dymo tapes without the V pattern are placed exactly at the same location as of the previous rough tapes.

Firstly, the influence of these arrangements on the incoming conditions is considered. PIV measurements are used to determine the velocity profiles in a plane perpendicular to the wall, and by setting the laser sheet parallel to the wall, spanwise distributions of velocity in a horizontal plane will be analysed too. The impact of the periodic roughnesses on the incoming boundary layer appears in the study of spanwise distributions of mean longitudinal velocity. This component is clearly affected by the presence of the tapes, and shows a spurious flow organisation.

Fig. 4(a) represents a stacking of 20 mean spanwise profiles, the local mean velocity being subtracted. The PIV measurements were taken in a plane located at 1 mm from the wall. The longitudinal spacing between two consecutive profiles is 0.5 mm, so that the 20 profiles are distributed over a distance of about δ. In such conditions, no observable trend is expected from a profile to another. It should be remarked that the profiles collapse on each other, with some scatter but without longitudinal drift. The flow contains a pattern periodic in space, constant along the flow, with amplitude of nearly $20\,\mathrm{m\,s^{-1}}$, i.e. of the order magnitude of the friction velocity. Larger longitudinal distances of observation have shown the same very conservative behaviour. The space Fourier transform of these profiles has been performed: the value of the fundamental wavelength is typically δ (Fig. 5(a)).

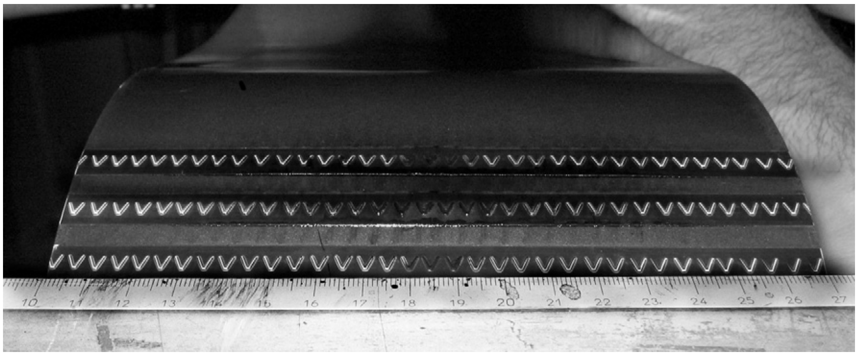

Fig. 3. Periodic Dymo-tape roughnesses placed upstream of the sonic neck.

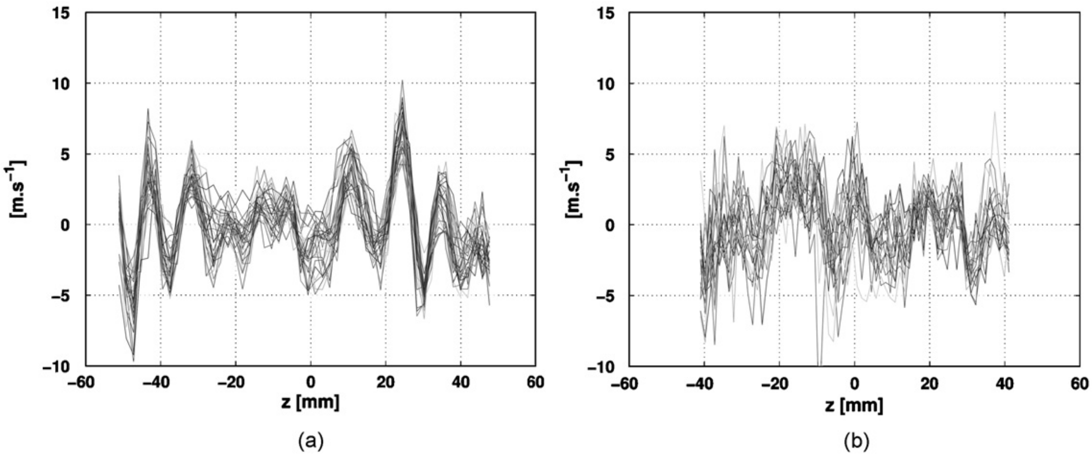

Fig. 4. Profiles of mean longitudinal velocity: (a) rough Dymo tape; (b) smooth Dymo tape.

This wavelength does not reflect directly the periodic roughnesses, since their spacing is 5 mm, and the patterns of the three rows are not aligned (see Fig. 3). Furthermore, this wavelength depends on the stagnation pressure of the flow: increasing the stagnation pressure from 0.5 to 0.8 bar increases this wavelength, from δ to 2δ. Therefore, the signature of the roughnesses is not directly observed, but rather, they provoke a spanwise excitation to the flow which responds by forming structures inside the boundary layer. As the considered boundary layer develops on the floor of the wind tunnel, this suggests that some Görtler vortices have been formed along the concave part of the nozzle wall downstream of the sonic neck. The presence of the roughnesses may trigger the development of this sort of instability, and perturb the incoming boundary layer profiles. However, the presence of Görtler vortices remains only a very likely guess, since the settings used in present PIV measurements were not appropriate to observe directly the three-dimensional structure of such structures.

The analysis of the instantaneous vector fields shows that the vortices are stably imbedded in the flow, with some meandering from one snapshot to another. A spanwise space spectrum of each instantaneous field has been made, and then averaged over 500 fields. The typical wavelength appears, but with a wide bump, pointing out some instantaneous variations of the wavelength.

The flow field obtained by the three smooth Dymo tapes is presented Fig. 4(b); the periodic pattern is significantly attenuated, still revealing some organisation, but to a much lesser extent. The Fourier spectra (Fig. 5(b)) confirm these conclusions: the peak of the previous fundamental component has decreased and is now negligible. It may be concluded that the remaining Görtler vortices, if any, are much weaker and less ordered.

Mean velocity profiles were measured in a vertical plane along the centreline of the interaction. The van Driest transform of the velocity has been determined. These profiles with and without the V-shaped roughnesses are in

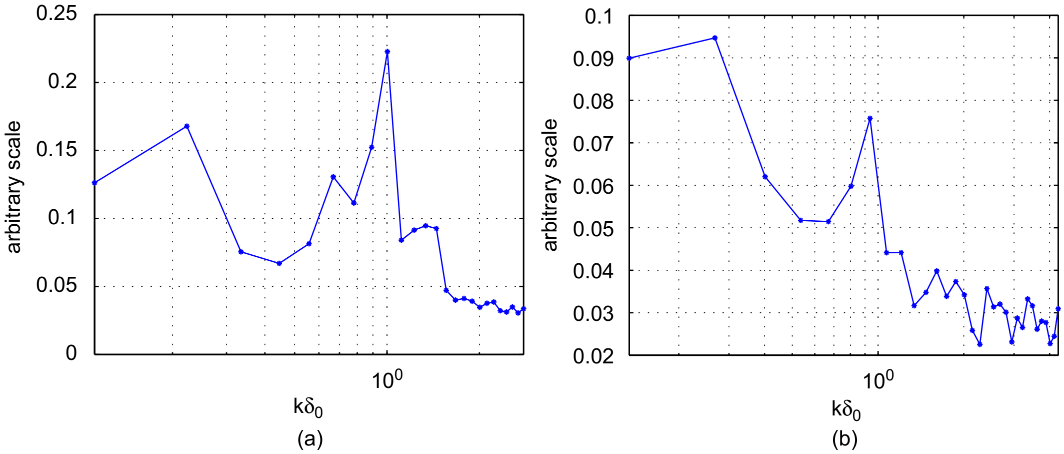

Fig. 5. Fourier spectra associated with Fig. 4. (a) Rough Dymo tape; (b) smooth Dymo tape.

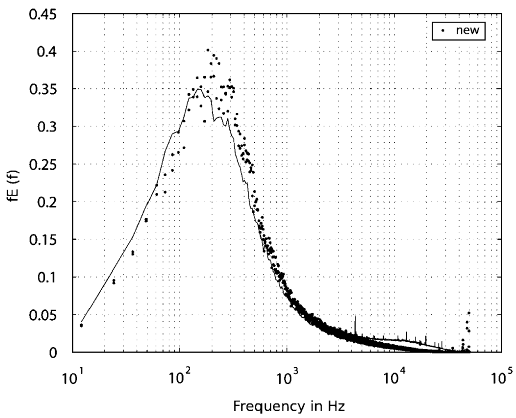

Fig. 6. Pressure spectra at the mean location of the reflected shock, with and without rough tapes.

excellent coincidence, showing no real variation of mean velocity. The profiles present the same logarithmic zone. A consequence is that the friction coefficient remains unchanged. Hot wire measurements have also been performed in the incoming boundary layer; neither the rms value of mass flux $(\rho u)'$ nor its spectrum reveals any significant difference in the two configurations. Therefore, it may be concluded that the two boundary layers are identical, in the same state of turbulence upstream of the interaction.

Wall pressure measurements were performed along the axis of the interaction by Kulite transducers. A very good agreement was found on the rms value of pressure near the shock foot in both configurations, showing that the position and the amplitude of the shock motion is not changed significantly (Figs. 6 and 7). Spectra of wall pressure at the mean location of the reflected shock were also determined (Fig. 6). The two spectra, with and without rough tapes, are identical, the characteristic frequency being close to 150 Hz.

Although the influence of the periodic perturbation on averaged distributions along the centreline is weak, attention is paid to its impact on the organisation of the separated zone. Fig. 8(a) presents mean streamlines in a plane parallel to the wall, at a distance of $y = 1$ mm, without the V-roughnesses, for the interaction at $\theta = 9.5^{\circ}$. The interaction length, defined as the length between the mean position of the reflected shock and the prolongation at the wall of the incident shock as in Dupont et al. (2006a,b), is 71.5 mm. The two contra-rotative vortices are present, and no corrugation appears on the streamlines of the flow. The distance between the centres of the contra-rotative vortices defined as the point of convergence of the streamlines is of about 70 mm.

Fig. 8(b) represents the same interaction, but with the periodic roughnesses. The pattern imbedded in the incoming boundary layer has clearly an impact on the development of the three-dimensionality of the flow. Firstly, it can be noticed that the shape of the separated zone is affected by the periodic roughnesses. The zero-velocity line is also

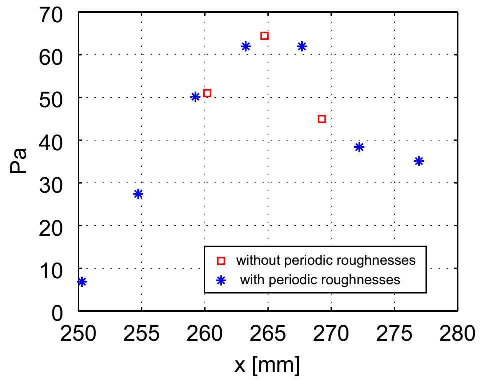

Fig. 7. R.m.s pressure near the foot of the shock.

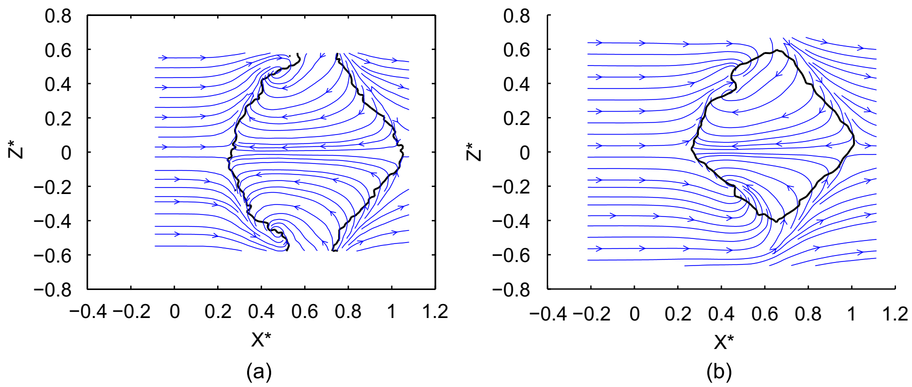

Fig. 8. (a) Interaction without periodic roughnesses and (b) with periodic roughnesses. Bold solid line: zero-velocity line.

perturbed by corrugations in the spanwise direction. The two vortices of the recirculated zone have their location significantly modified since they are found at $Z^* = \pm 0.35$, which corresponds to a distance between their centres, is now about 50 mm. This represents a departure of 50% from the smooth tape case.

The conclusion of this experiment is that perturbations with a typical velocity scale of the order of the friction velocity is not strong enough to change either the longitudinal extent of the interaction, or the rms pressure or the frequencies of the shock motion. However, a more subtle effect is found: the three-dimensional organisation of the separated bubble is appreciably modified.

4. Influence of downstream conditions

As recalled in the previous sections, downstream conditions may also make the shock move. The question is to determine which conditions are predominant. The situation may be flow dependent. Smith and Dolling (1989), Gramman and Dolling (1990), Gonsales and Dolling (1993) among others, examined the case of interaction produced by a blunt body. They showed that the motion of a shock wave produced by a blunt body scales with the diameter of the blunt body, i.e. with the downstream conditions.

The case of corner flows at Mach number 2.9 studied by Selig et al. (1989) can be examined. Fig. 9 presents the position of the foot of the shock in compression ramp flows at $M = 2.9$ (shaded zone) and the extent of its oscillation (solid line with squared symbols). In this flow cases, incipient separation occur for an angle slightly smaller than 16°. It appears that for angles smaller than this upper bound, since there are no particular structures developed downstream, the shock motion depends only on the incoming conditions; the position of the shock and its range of oscillation increases only slightly. When separation occurs, new conditions are imposed downstream by the separated zone; there is a dramatic shift of the position of the foot of the shock and an increase of its range of oscillation. This suggests that the downstream conditions play a major role when separation occurs.

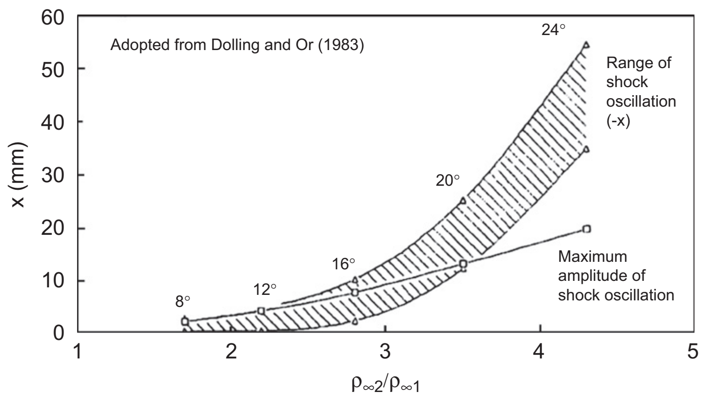

Fig. 9. Position of the shock and range of oscillation in compression ramp flows at Mach number 2.9 (adapted from Selig et al., 1989).

We can go back to consider again the shock reflection case studied by Dupont et al. (2005,2006a,b), at $M = 2.3$. In this experiment, pressure fluctuations in two points along the centreline of the flow have been measured. They found that pressure fluctuations in the upstream boundary layer are in very weak coherence, whatever the frequency, with the fluctuations generated by the shock wave moving forth and back. The coherence between the upstream layer and the separated bubble or the flow downstream reattachment is also very weak. On the opposite, fluctuations at the foot of the mean shock are strongly coherent (almost linearly) with the separated zone and with the flow downstream of reattachment. This suggests that the low frequencies of the shock motion are strongly linked to the downstream flow and particularly to the separated bubble. A tomographic video of the flow was taken for different angles of the shock generator, Dupont et al. (2006a, 2006b). By doing so, different shock intensities, and therefore different developments of separation, were obtained, with the same incoming boundary layer. When the boundary layer is not separated, the reflected shock hardly moves. As soon as separation occurs, the reflected shock moves significantly, for the same incoming turbulence. The maximum extent of the shock motion occurs for the more severe separation, with the lowest frequencies. Therefore, this visualisation has shown that important movements of the reflected shock are associated with the development of the recirculating bubble, and not with the structures of the upstream boundary layer.

This assessment should be moderated by two remarks. The first one is that generally, the transfer function of a shock wave depends on its intensity. By changing the shock generator angle, the shock strength has been modified, and presumably, also its transfer function, which is not known in the cases under review. It is believed, however, that this effect is not the primary one. The second comment comes from a consequence of our experiment on incoming flow conditions. Fig. 4 shows that perturbing the upstream layer results in modifying the three-dimensional organisation of separated zone, and possibly in an indirect modification of its unsteadiness. In the case of the present experiment, the perturbation was strong enough to produce a modification of its three-dimensional structure, but not strong enough to modify significantly its size, measured on the symmetry axis of the interaction or the frequencies of the unsteadiness itself.

5. Discussion and conclusions

The flow examined here show that the nature or the origin of the unsteadiness depends on the cases and on the geometrical conditions. It seems rather clear that, if a shock wave interact with a boundary layer without inducing separation, the shock motion is dominated by the structure of inflow turbulence. This was shown without ambiguity by Poggie and Smits (2001), and this is suggested by the results of Selig et al. (1989), see Fig. 9.

In severe cases where an obstacle is present, the shock motions depends primarily on downstream geometrical conditions. In the other cases, things are not so clear. Pirozzoli and Grasso (2006) analysed the results of their simulation of an impinging oblique shock flow in terms of acoustic feed-back in the separated bubble, by analogy to Rossiter's analysis of cavity tones. Although they observed no peaks on the spectra of the pressure fluctuations in the recirculation show bands of energy which may support this hypothesis. However, their simulations do not reproduce the low Strouhal number of shock motion of 0.03 as observed in the experiments. In the oblique shock reflection studied by Dussauge et al. (2006) and Dupont et al. (2006a,b), it is possible to evaluate the frequency of the fluctuations produced by the passage of superstructures, by assuming that they are 30δ long, and that they are convected with the external flow velocity. This would correspond to a frequency $F_{\rm sup} = U_\infty/30\delta$. The corresponding Strouhal number based on interaction length is therefore $S_L = L/30\delta$. In the more severe case of 9.5° deviation, $L \approx 7\delta$, so that $S_L \approx 0.23$, one order of magnitude larger that the experimental value. Assuming that the superstructures are convected with a velocity of $0.7U_\infty$ would provide a milder condition with $S_L \approx 0.16$, which is still much too large. From this formulation, it may be speculated that a Strouhal number of about 0.03 could be found if $L \approx \delta$, a result which matches rather well conditions close to incipient separation.

This situation corresponds to the case of an oblique shock reflection. In the case of compression ramps, however, the typical frequency of the superstructure and the criterion based on $S_L \approx 0.03$ are consistent. This is not in contradiction with the previously examined results. The reason is that for compression ramp flows, the length of interaction is much smaller, leading to smaller values of the Strouhal number.

Finally, the question of the origin of the unsteadiness remains open. In Dupont et al. (2005), it was speculated that the three-dimensional structure of separation could be at the origin of unsteadiness. The argument was that the three-dimensional vortices formed in the case of the 9.5° case have a circulation of the order of the dominant frequency of the shock motion. However, and even if such eddies contribute to the unsteadiness of the system, it may be argued that for a flow deviation of 8°, no three-dimensional eddies are observed, but significant motions at low frequencies are developed. It may be assessed that no particular flow structure with the appropriate frequency scale has been observed to date. A suggestion of scenario could be found in some global linear stability analysis (Ehrenstein and Gallaire (2007), Alizard and Robinet (2007)). In these works, it is found that in some subsonic separated zones, modes of Kelvin–Helmholtz type are developed with close values, producing beating at low frequency. If such a model can be applied to turbulent supersonic shock induced separation, it could constitute a rather convincing candidate to explain the low frequency shock motion.

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References

Adrian, R.J., Meinhart, C.D., Tomkins, C.D., 2000. Vortex organization in the outer region of the turbulent boundary layer. Journal of Fluid Mechanics 422, 1–54.

Alizard, F., Robinet, J.C., 2007. Influence of 3D perturbations on separated flows. In: IUTAM Symposium on Unsteady Separated Flows and their Control, Corfu, Greece, June 18/22, 2007.

Bouhadji, A., Braza, M., 2003. Organized modes and shock vortex interactions in unsteady viscous transonic flows around an airfoil: part one, Mach number effect. Computer and Fluids 32 (9), 1233–1260.

Cherry, N.J., Hillier, R., Latour, M.E.M., 1984. Unsteady measurements in separated and reattaching flow. Journal of Fluid Mechanics 144, 13–46.

Dupont, P., Haddad, C., Ardissone, J.P., Debiève, J.F., 2005. Space and time organization of a shock/wave turbulent boundary layer interaction. Aerospace Science and Technology 9, 561–572.

Dupont, P., Piponniau, S., Sidorenko, A., Debiève, J.F., 2006a. Tomographic video of an oblique shock reflection, Unpublished work, Institut Universitaire des Systmes Thermiques Industriels.

Dupont, P., Haddad, C., Debiève, J.F., 2006b. Time organization in a shock induced separated boundary layer. Journal of Fluid Mechanics 559, 255–277.

Dussauge, J.P., 2006. Compressible turbulence of supersonic flows: actions and interactions. In: Proceedings of the Symposium Turbulence in Interaction, Porquerolles, France, May 29–June 02.

Dussauge, J.P., Dupont, P., Debiève, J.F., 2006. Unsteadiness in shock wave boundary layer interactions with separation. Aerospace Science and Technology 10, 85–91.

Ehrenstein, U., Gallaire, F., 2007. Global low-frequency oscillations in a separating boundary layer flow. In: IUTAM Symposium on Unsteady Separated Flows and their Control, Corfu, Greece, June 18–22, 2007.

Erengil, M.E., Dolling, D.S., 1991. Correlation of separation shock motion with pressure fluctuations in the incoming boundary layer. AIAA Journal 29, 1868–1877.

Ganapathisubramani, B., Clemens, N.T., Dolling, D.S., 2007. Effects of upstream coherent structures on low-frequency motion of shock induced turbulent separation, AIAA Paper 2007-1141, 45st Aerospace Sciences Meeting and Exhibit, January 8–11, 2007, Reno, NV, USA.

Gonsales, J.C., Dolling, D.S., 1993. Correlation of interaction sweepback effects on the dynamics of shock-induced turbulent separation, AIAA Paper 93-0776, 31st Aerospace Sciences Meeting and Exhibit, January 11–14, 1993, Reno, NV, USA.

Gramman, R.A., Dolling, D.S., 1990. Detection of turbulent boundary layer separation using fluctuating wall pressure signals. AIAA Journal 6, 1052–1056.

Iakovlev, S., 2007. Submerged fluid cylindrical shell subjected to a shock wave: fluid structure interaction effects. Journal of Fluids and Structures 23, 117–142.

Lee, B.H.K., 2001. Self-sustained shock oscillations on airfoils at transonic speeds. Progress in Aerospace Science 37, 147–196.

Pirozzoli, S., Grasso, F., 2006. Direct numerical simulation of impinging shock wave/turbulent boundary layer interaction at $M = 2.25$. Physics of Fluids 18, 065113.

Pirozzoli, S., Grasso, F., Gatski, T.B., 2005. DNS analysis of a shock wave/turbulent boundary layer interaction at $M = 2.25$. In: Proceedings of the Fourth International Symposium on Turbulence and Shear Flow Phenomena, Williamsburg, Virginia, USA, June 27–29, pp. 1207–1211.

Poggie, J., Smits, A.J., 2001. Shock unsteadiness in a reattaching shear layer. Journal of Fluid Mechanics 429, 255–277.

Selig, M.S., Andreopoulos, J., Muck, K.C., Dussauge, J.P., Smits, A.J., 1989. Turbulence structure in a shockwave/turbulent boundary layer interaction. AIAA Journal 27, 862–869.

Smith, D.R., Dolling, D.S., 1989. Unsteady shock induced separation in Mach 5 cylinder interactions. AIAA Journal 27, 1598–1706.