Compressible turbulence of supersonic flows: actions and interactions

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ABSTRACT
We examine here some situations of supersonic flows, in which energy is injected into the turbulent field through distortions. Some peculiarities of compressible turbulence in shear flows are firstly recalled. Some situations in which turbulence do not modify the source of energy injection, typically rapid distortions are recalled and show the peculiarities introduced by compressibility, with the particular role played by pressure. Finally, a number of shock wave/ boundary layer interactions are discussed. A classification is proposed, according to their ranges of influence. Attention is paid to supersonic interactions for which the origin of the observed interactions is discussed.

INTRODUCTION

When considering an action on turbulence, it is supposed that some turbulent field is subjected to an external influence or forcing. This results in modification of turbulence through the amplitude of the fluctuations, through the shape and dynamics of the eddies, producing changes of the rms levels, of the spectra, and in general, of the characteristic scales of turbulence. The notion of interaction implies that the external element will be in turn modified by turbulence. Such complex feedback mechanisms are considered here or at least their macroscopic manifestations in the case of supersonic flows; in this case, compressible turbulence can be found, and the external causes of the actions can assume very particular forms, such as shock waves, expansions, etc. Firstly, a short reminder will be proposed to describe how turbulence can be compressible. Some simple cases of 'actions' will be recalled, in which turbulence is subjected to some distortion, which remains constant. Finally, some other cases will be discussed corresponding to interactions, in situations typical of compressible flows: shock vortex interactions, shock/boundary layer interactions.

ELEMENTS OF COMPRESSIBLE TURBULENCE

From a formal point of view, compressible turbulence may be characterized by the nature of the instantaneous velocity field. It is clear that the mean velocity is in general not divergence free, since as soon as a pressure gradient appears, variations of density produce a non-zero mean velocity divergence. The situation is not totally clear for the fluctuations. An evaluation was proposed in Smits & Dussauge 2006 [1]. For that purpose, a situation of weak compressibility was made, in order to obtain first departures from incompressibility of the fluctuating motion. The divergence of fluctuating velocity was evaluated from the continuity equation in terms of pressure and entropy. The sources of entropy are of course related to viscous heating and molecular heat conduction. The instantaneous relation reads:

$$div\ u = -\frac{1}{\gamma}\frac{d\ln p}{dt} + \frac{\varepsilon}{C_p T} + \frac{1}{\rho C_p T}\frac{\partial}{\partial x_j}\left(k\frac{\partial T}{\partial x_j}\right)$$

A low compressibility hypothesis was made and consisted in assuming that pressure contribution is negligible, and that velocity divergence is produced by the strong heating related to the high level of dissipation occurring at high speeds. After a tedious linearization (linearizing the terms involving dissipation may be tricky), we find the following expression:

$$div\ u' = -\frac{T'}{T}\frac{\bar{\varepsilon}}{C_p T} - \frac{T'}{T}\frac{2\overline{\varepsilon_\theta}}{\gamma T^2} + \frac{\varepsilon'}{C_p T} + \frac{\varepsilon'_\theta}{\gamma T^2} + \frac{1}{\rho C_p}\frac{\partial}{\partial x_j}\left(k\frac{\partial\left(T'/T\right)}{\partial x_j}\right)$$

$\varepsilon_\theta = k\left(\partial T/\partial x_j\right)^2$ is the second dissipation related to temperature inhomogeneities.

The order of magnitude of temperature fluctuations should be assessed. For this purpose, the case of adiabatic flows, without heat sources is considered, in which the Strong Reynolds Analogy is supposed good enough to provide a significant approximation, $T'/\overline{T} = (\gamma - 1)M\ m'$,where M and m' are the Mach numbers based on mean and fluctuating velocities. We consider the energetic fluctuations related to large scale eddies, so that, for the order of magnitudes, the fluctuations are replaced by the rms values and the space scales are of the order of the integral scale. Moreover, ε_θ is taken proportional to ε as in subsonic models. Finally, it is supposed that, as in subsonic flows that the fluctuations of ε are large compared to its mean value, typically $\varepsilon' \sim 10\varepsilon$. Expressing ε in terms of velocity and length scale, it is finally found:

$$\frac{div\,u'}{u'/\Lambda} \sim 10\left(\gamma - 1\right) m_t^2 \left(1 + \frac{M^2}{2\gamma}\right)$$

m_t is the turbulent Mach number based on rms velocity.

The first factor of the right hand side member is due to dissipation into heat, the second one represents the contribution of temperature fluctuations. The dependence in m_t^2 is consistent with the work of Ristorcelli [2] and of Fauchet & Bertoglio [3]. Taking typical values for adiabatic flat plate boundary layers or even in supersonic mixing layers suggests that producing a significant level of velocity fluctuation divergence through dissipations necessitates very high Mach numbers. On the other hand, an hypothesis of weak acoustic mode has been used. This limitation seems to be justified, as far as the direct observation of events like shocklets inside shear layers has never been really successful. At rather high, probably hypersonic Mach numbers, velocity divergence may be high because of dissipation and of the apparition of shocklets. Finally this analysis is consistent with Vreman, Sandham & Luo's findings [4] from direct simulations: in mixing layers, it seems that the main effect of compressibility is felt on pressure fluctuations, which in turn modify the anisotropy of turbulence, but it does not act directly on velocity divergence. A conclusion is that in many supersonic situations without heat sources, it may be expected that the divergence free approximation will be good enough to describe the turbulence of the shear flows.

ACTIONS

In this section, the particular properties of turbulence subjected to an external constraint which injects energy into the flow, without possible feedback from turbulence on this source of energy are considered: they are considered as an action on turbulence. These are typically rapid distortion situations. They are not considered for themselves, but just as constitutive elements of interactions in which they can take place.

This situation is basically simpler than interactions. Typically we consider some global evolution imposed for example by geometry producing some pressure gradient. Considering the mean momentum equation, the mean distortion is independent from the turbulent field if the pressure gradient is much larger than the friction force. Assuming that the pressure gradient and the friction term are of the form:

$$\frac{\partial \bar{p}}{\partial x} \sim \frac{\Delta p}{L} \text{ and } \frac{\partial \tau}{\partial y} \sim \frac{\rho u_\tau^2}{\delta},$$

where Δp is the pressure step in the distortion of size L, and δ is a typical size of the initial turbulence inhomogeneity, essentially the shear layer thickness, the condition

$$\frac{\partial \tau}{\partial y} << \frac{\partial \bar{p}}{\partial x} \text{ implies that } \frac{\rho u_\tau^2}{\Delta p}\frac{L}{\delta} << 1$$

or:

$$\gamma m_t^2 \frac{\bar{p}}{\Delta p}\frac{L}{\delta} << 1$$

In many supersonic turbulent flows, m_t~0.1 and in most rapid distortions L/δ is of the order of 1, so that the previous condition becomes

$$\frac{\bar{p}}{\Delta p} << 10^2,$$

a condition easily matched with isentropic expansion or compression waves in usual supersonic situations. Note that this condition is valid only far from walls, since at the wall, the non-slip condition imposes $\frac{\partial \tau}{\partial y} = \frac{\partial \bar{p}}{\partial x}$, and this condition is felt in most of the inner layer. In the external layer of boundary layers however, the previously derived condition implies that the mean flow of a shear layer subjected to a (sufficiently intense) compression or expansion wave can be safely computed by Euler equations, and therefore does not depend on the turbulence evolving in the distortion.

Many examples of such flows can be found in the literature. We will retain here two of them, which show clearly the particular role of pressure fluctuations in supersonic flows. The first one is from Dussauge & Gaviglio [5] who studied a turbulent boundary layer subjected to an expansion fan at a Mach number of 1.8. Using a hypothesis of solenoidal fluctuating field, which has been justified in the previous section, they showed essentially that in this case the evolution of the Reynolds stresses in the distortion could be described by low speed modelling, emphasizing that the pure volume changes have an action which is not limited by pressure fluctuations. The other example is taken from Debiève [6] and Debiève, Gouin, Gaviglio [7]. In this work, shock relations for Reynolds stresses were investigated for a steady shock wave. From the equation for the Reynolds stresses, they retained only the production term and could defined a quantity invariant along the mean motion, and then derived the shock relationships, which are in good agreement with experimental observations. The reason why we could neglect the pressure came from the works of Durbin & Zeman [8] and from Jacquin et al. [9]. These authors examined linearised problems, and showed that a 'gradient Mach number' M_g is a key parameter for this problem. M_g can be defined as

$M_g = \frac{\Lambda G}{a}$, where L is a typical space scale, for example an integral scale, G is the velocity gradient in the distortion. Examination of the equations of the problem shows that, when this gradient is large, pressure terms can be neglected in the linear problem. In the case of turbulence subjected to a shock, the velocity gradient to be considered would be the gradient in the shock, which is very large. In the asymptotic case of an infinite gradient Mach number, it may be shown that pressure fluctuation terms in the equations for the Reynolds stresses can be neglected. This can justify, or explain the good success of Debiève's shock formulae, and shows again that even in rather simple linearised problems and even with assumptions of incompressible fluctuating field, the structure of pressure fluctuations is altered, with observable necessary modifications in the pressure strain terms of the Reynolds stress equations.

INTERACTIONS

Introduction

In supersonic flows, many studies have been devoted to shock/boundary layer interactions. We will discuss here to what respect these problems can be considered as interactions. The first thing to be examined is the academic case of the interaction of a vortex with a shock wave. We know from theory that in such a situation, the vorticity is altered downstream of the shock, and that there is a loss of energy by acoustic radiation. There is no real input of energy in the system, so that Lighthill [10] considered that there was a redistribution of energy among the different elements, so that he considered that the energy of shock waves was scattered by the eddies. This is an interesting point of view, since now we considered that the intensity of the shock is modified when the eddy passes through it. Experimental pioneering work was made by Dosanj & Weeks [11], which showed that an initially plane shock wave interacting with a vortex could be changed into an oblique wave of weaker intensity. Note however that no complete energy budget has been performed in a shock vortex (or shock turbulence) interaction, so that many aspects have never been verified. In general, we may have to consider that a shock wave can be modified by turbulence, even if this phenomenon is often of little consequence. For further discussion of the influence of incoming perturbations on the intensity of shock waves, see for example Cambon & Sagaut [12].

Attempts of classification

Now, we can consider the interactions of shock waves with wall layers in different cases, and we can try a first classification. We can list elementary situations, which are of common practice, as follows: interaction on a profile leading to buffeting, interaction with a plane shock in a channel, reflection of a shock and compression ramp flow.

In all these cases, shocks are rapidly strong enough to make the layer separate, and in general the resulting flow is called 'unsteady'. Of course turbulence is unsteady in nature, but here this redundant qualification means that the whole flow system experiences random motions at frequencies much lower than the energetic frequencies identified in the flow. One of the problems of such interactions is to find the origin of these low frequencies.

Now, we can try to classify the previous situations. The buffeting problem appears in the transonic regime, with large subsonic zones in the external flow, through which acoustic wave can propagate and produce a coupling. It is often assumed that the perturbations caused by large eddies at the trailing edge are noise sources sufficiently efficient to provoke a synchronization between the edge and the shock wave producing separation. In this case, there is a feedback by almost all the parts of the external flows, and these cases correspond to long range propagating interactions. A second configuration is the interaction with a plane shock in a channel. The plane shock is generally produced by choking the wind tunnel. Close to the wall a lambda shock is formed. The external flow downstream of the interaction is subsonic. Now, the path of communication by acoustic wave is limited to the flow downstream of the interaction, but perturbations from downstream can contribute to make the shock move in the external flow, while the unsteadiness related to separation can act as an excitation for the lambda shock: this case can be called medium range interactions. Finally, in the case of oblique shock reflection or in compression ramp flows in the supersonic regime, a subsonic zone exists, but is almost limited to the separated region: downstream of reattachment, the layer reaccelerates rapidly, so that the subsonic part becomes small, hindering the backwards communication; these flows can be considered as short range interactions. It is believed that these cases are of simpler analysis, since only contributions in a rather close neighbourhood have to be taken in account. Attention will be focused on the latter cases, which may include physical elements for the understanding of more complicated coupling or dependences.

Now, we can try to see what problems can be found in such interactions. An example is given by the Schlieren of an interaction studied by Délery at ONERA Meudon.

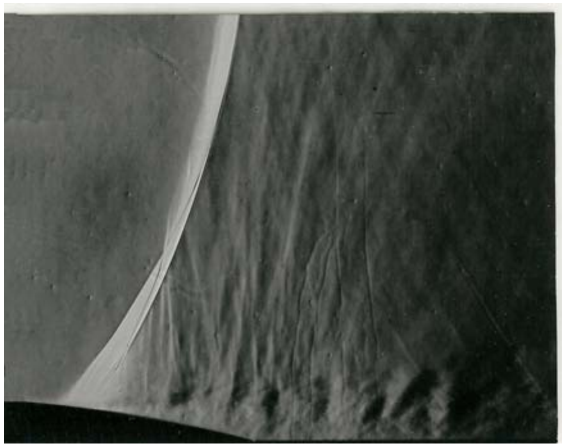

Figure 1: A transonic interaction on a bump

Courtesy J. Délery.

It shows some constitutive elements common to most of the interactions: firstly the shock which seems to be rippled, probably owing to its three dimensional nature combined with the spanwise integration of the visualisation. We can also see the separated layer downstream of the shock, in which large eddies are formed (the dark spots on the visualization), of size and spacing much larger than the initial boundary layer, and finally some Mach wave radiated by these large eddies. What is clear from this picture is that we have to understand several problems and their possible couplings: the amplification of incident turbulence through the shock, the properties of the separated bubbles, with its own scales of space and time (the vortices shown in the previous Schlieren can probably be associated with low frequencies), the response of the shock wave to these excitations, the vortex shedding of large scale structure into the reattached layer, and finally the merging of these vortices into a new boundary layer relaxing to a new equilibrium. Some experimental data exist. As noticed in [1], from the analysis of measurements in a compression ramp flow, the high level of turbulence found in the separated zone cannot be explained by the rapid distortion of initial turbulence through the shock. This level, instead, is compatible with the high turbulence intensities found in shear layers.

Short range interactions

Shock motions

Firstly, some properties of shock motion can be recalled. They have been derived from linearised theories, [13], [14], [15], [16],. It is known that shock waves can move under the influence of upstream and downstream conditions, and therefore can move under these two influences. Shocks are in general stable or neutral, and can be often considered as low pass filters: they are less stable for lower frequencies Depending on the downstream conditions, shocks may be frequency selective or not; in general in supersonic flows, experimental observations do not show frequency selection. Moreover, it is found that strong shocks are less stable than weak shocks. A last property is useful for interpreting experimental results. If an oblique shock is considered, perturbations propagate along the shock with the direction of the tangential velocity [15]. These ingredients provide some keys for interpreting some observations: if a shock emanating from a wall, produced by a compression ramp or by a wall reflection is considered, the turbulent structures perturb randomly the foot of the shock. It is found that the perturbations propagate along the shock to the outer flow where it is oblique and therefore weaker and more stable: the fluctuations are damped as they move outwards. This corresponds to usual observations or measurements in supersonic interactions. This is also consistent with the results of simulations [17], [18], in which it appears that the shock corrugations due to the turbulent eddies are damped when moving outwards. However, the fined grained corrugations are probably not energetic enough or involve too high frequencies to explain the large fluctuations of the position of the shock. Recent visualisations by Sidorenko, Piponniau, Dupont, Debiève [19] suggest that the large amplitude motions of the shock are directly linked to large amplitude motions in the separated zone, which seems to act as a sliding corner, pushing the shock system forth and back. The point of the origin of the shock motion has been discussed for years (see for example [20] [21] [22] among others). Some small scale motions have been detected by some authors; this is of course possible, since if the shocks act as low pass filter, they may have a rather progressive roll-off, so that higher frequencies corresponding to the energetic eddies are not totally damped, and can be detected and studied. However, it will be shown that in many cases that these frequencies, corresponding to the energetic eddies in the incoming boundary layer, are to high to give a sufficient excitation to the shock system.

Some characteristic scales

The word commonly used to characterise these motions is 'unsteadiness': this means that among all the unsteady motions of turbulence, the shock has the lower frequencies. This seems to be a rather general property. We want here to explore this point more precisely, and more quantitatively: is there some Strouhal number which would have a universal value, whatever the interaction? Note that the answer is not obvious: if the shock motion results from the excitations provoked by upstream and downstream fluctuations, we may have a particular for each particular separation case.

A particular experiment of oblique shock reflection was studied at IUSTI (see for example [23] and the paper by Dupont and Debiève 2006 [24] at the present conference, and *Figure 2*).

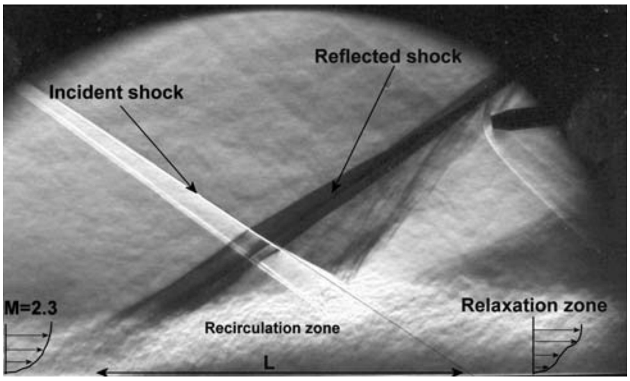

Figure 2: Shock reflection experiment at Mach number 2.3

It is an interaction at a nominal Mach number of 2.3, at a Reynolds number R_θ of 5070. In this experiment wall pressure fluctuations were measured. Measurements at the vicinity of the foot of the reflected shock have shown clearly the unsteadiness of the reflected shock. From their frequency spectra *E(f)*, a characteristic frequency *F* was defined in the usual way, from the maximum of *fE(f)*. A Strouhal number was formed, $S_L = \frac{F\,L}{U_\infty}$, where *L* is the length of the interaction defined from the foot of the mean reflected shock and the reattachment point, and U_∞ is the external velocity in the upstream flow. This was made for several shock intensities producing separation, namely for flow deflections from 7 to 9.5 degrees.

These results have been compared to other flow cases in which experimental results are available. *Figure 3* (from Dussauge et al. 2006) presents some results obtained from experiments in the following configurations: incident shock wave (M=2.3, α =7° to 9.5°, wall reflection [24]); compression ramp (2.2<M<5, 20°≤θ <45°: Erengil & Dolling [25], Thomas et al. [26], Dolling and Or [27], Dolling and Brusniak [28], Bonnet et al. [29], Coe et al.[30]); blunt fin interaction (interaction with a cylinder: Dolling and Smith [31], Dolling and Brusniak [28]); over expanded nozzles with restricted shock separation (Nguyen [32], Bourgoing [33]).

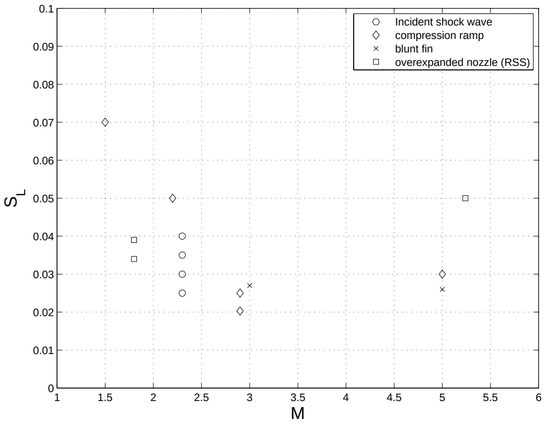

Figure 3: Shock Strouhal numbers in various interactions, from Dussauge et al. 2006 [23].

It can be seen that for this wide range of experimental conditions, the defined dimensionless frequency $S_L=fL/U_e$ groups these experiments together: the Strouhal number is found essentially between 0.02 and 0.05.

Such low values have to be compared to characteristic frequencies inside the detached zone which develops downstream the unsteady shock wave. For our experiments, comparison between Power Spectral Density (PSD) of wall pressure signals in the vicinity of the foot of the shock and inside the recirculating zone is presented in *Figure 4* for the θ=8° case. In this figure, the dimensionless abscissa is defined by $X^*=(X-X_0)/L$, where X is the longitudinal position, and X_0 is the abscissa of the mean shock.

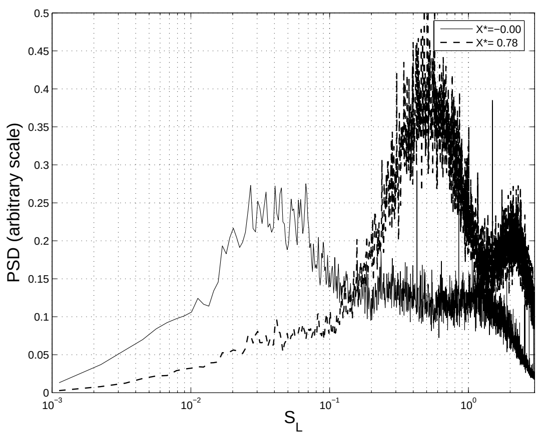

Figure 4: *Wall pressure spectra in the separated zone, shock reflection, θ=8°*

It is clear that energetic scales involved in two regions are totally different (S_L ≈0.5 for the recirculating zone) and that the shock motions cannot be directly linked to the downstream scales. Nevertheless, we can remark that, in the recirculation, low frequencies in the range involved by shock motion contribute for about 25% to the total energy of the signal: this is not completely negligible, and there is no real scale separation between the separated bubble and the shock motion.

The question of the moderately high frequencies (S_L~~0.5 or 0.6) found in the separated zone is not totally clarified. At the end of the separated bubble, the Strouhal number is almost constant, and the influence of the involved frequency band is found far downstream. This phenomenon is interpreted as vortex shedding. In the IUSTI experiment, it has been found that the Strouhal number of this shedding frequency increases with shock intensity (see [24]). The value of this Strouhal number has been examined. In subsonic separations, it is about 0.6, while in IUSTI experiments, it varies with the shock intensity. Recent numerical work by Grasso & Pirozzoli [22] has examined such an interaction at the same Mach number and at a lower Reynolds number. By analogy with cavity flows, they propose to interpret this Strouhal number as the result of an acoustic feedback mechanism in the separated zone. A difference however is that in separated flows, we find no peaks in spectra, but only bumps. It seems however that this explanation does not account for all phenomena, since the predicted frequency varies with shock intensity, while the experimentally observed one does not. Finally such simulations found mainly a shock motion in phase with the passage of large eddies through the foot of the shock. On the opposite, recent visualisations [19] of the shock reflection flow suggest that shock fluctuations of large amplitudes occur at the same time as large amplitude fluctuation of the separated zone: the mechanism probably leading to low frequencies seems to be related to some global motion of the separated bubble, rather than from a local, convective perturbation.

<u>Three dimensional aspects</u>

In this particular case of shock reflection, it was possible to make spanwise PIV measurements, and to get velocity fields in planes x-z parallel to the wall. When cutting the separated bubble, it was obvious that the interaction is fully three-dimensional, with a pair of tornadoes located symmetrically with respect to the axis of the wind tunnel.

An example is given in *Figure 5*, taken in a plane located at y= 1 mm from the wall. It shows the 3-d character of the separation- and of the reattachment lines, with the convergence of the streamlines. Further analysis suggests that the tornadoes are as high as about one half of the initial boundary layer thickness.

Now, the question is to know if such vortices play a real energetic role, or if we can just ignore them. It was noticed that the large amplitudes shock motions seemed to result from some global behaviour of the separated zone, and the tornadoes participate in the organization of this zone. Moreover, mean velocity measurements were performed in the tornadoes. It is found, as expected, that the centre of the vortices produce a solid body rotation zone; the value of the inverse of the maximum velocity gradient is of same order as the average frequency of the shock motion. It is found that some analogies with subsonic situations pointed out by Jacquin [35]. He recalled that, at low speeds, a pair of two-dimensional vortices produces collective instabilities, with a frequency

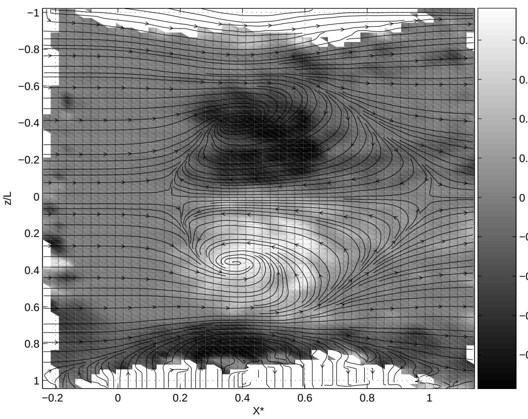

Figure 5*: Velocity field on the interaction. x-z plane parallel to the wall;* θ*=9.5°;y=1 mm. The solid lines are a 2-d representation of the streamlines. Grey scale indicates the level of vorticity normal to the plane. From [34]*

of the order of the inverse of the maximum velocity gradient in the vortex. It is therefore tempting to propose a scenario, in which the three dimensional organisation of the separated zone contain an efficient process to produce the shock motion.

Does this scenario bring all the comprehensive elements to explain the low, almost "universal", Strouhal number value shown in figure 3? The existence of tornado vortices has been reported in some other interactions, in particular in interactions with a plane shock [36], [37]. The case of the leading shock in an interaction produced by a blunt fin [31] reveals a rather complicated vortical structure, very different from our tornado pair. The other question is about the intrinsic character of the three-dimensional structure: is the formation of the vortices inherent to the interaction or to the separation, or is it fortuitously related to the presence of side walls? Can we extrapolate the results found in 2-D situations to an axisymmetric nozzle? This point needs some more investigation. We have some elements in the compression ramp experiments performed at Princeton University. They studied a 24° compression ramp flow, at M=2.9. To minimize the interference between the shock wave and the side wall, they designed the compression ramp with a spanwise gap of about one boundary layer thickness; side plates of limited height were used to preserve the two-dimensionality of the flow. In this flow, no tornadoes were detected. What was found instead was a wavy pattern on the separation and on the reattachment lines. It was conjectured that this undulation was the sign of the development of Görtler vortices in the concavely curved part of the layer. The surprising thing is that in this configuration, the Strouhal number is of the same order of magnitude as in other interactions. A possible guess is that in all cases the shock motion is related to the fluctuations in the separated zone, which is much larger than the boundary layer thickness and therefore implies much lower frequencies. As the shock acts as a low pass filter, differences in the excitation are probably smoothed out. It is clear that some more elements are required to explain and to predict these low frequencies in our supersonic interactions.

CONCLUSIONS

In the analysis of some situations of interaction of turbulent shear flows with shock waves, some properties of compressible turbulence have been recalled, with their consequences on the behaviour of turbulence when subjected to some distortion. Cases of interactions (i.e. cases when there is mutual modification of turbulence and of the distortion) have been defined and a classification of the shock/boundary layer interactions usually found in high speed flows has been proposed. It is shown that, independently of the geometry of the particular configurations, these situations seem to share some common properties, like frequency of the shock system motion conveniently normalized. It is shown from some particular cases that this motion cannot be explained only by simple feedback acoustic loops. It is proposed to explore the influence of the global organization of the separated bubbles on the shock motion, including their three-dimensional aspects. However, it is clear that such questions require further efforts of investigation, including at least the structure of a separated zone in supersonic flow, with the associated frequencies, and the transfer function of a curved shock in such conditions.

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BIBLIOGRAPHY

[1] Smits A.J., Dussauge J.P., *Turbulent Shear Layers in Supersonic Flow,* Springer Verlag, 2006.

[2] Ristorcelli J.R., *A pseudo-sound constitutive relationship for the dilatational covariances in compressible turbulence,* J. Fluid Mech., **347**, pp.37-70, 1997

[3] Fauchet G., Bertoglio J.P., *An analytical expression for the spectrum of compressible turbulence in the low Mach number limit,* Advances in turbulence VII, U. Frisch Ed., Kluwers, 1998;

[4] Vreman A.W., Sandham N.D., Luo K., J. Fluid Mech., **320**, pp. 235-258.

[5] Dussauge J.P., Gaviglio J., *The rapid expansion of a supersonic turbulent flow: role of the bulk dilatation,* J. Fluid Mech., **174**, pp.81-112, 1987.

[6] Debiève J.F., *Etude d'une interaction turbulence/onde de choc,* Thèse de Doctorat d'État, Univ. d'Aix-Marseille II, 1983

[7] Debiève J.F., Gouin H., Gaviglio J., *Evolution of the Reynolds stress tensor in a shock/turbulence interaction,* Indian Journal of Technology, **20**, pp. 90-97, 1982.

[8] Durbin P.A., Zeman O., *Rapid distortion theory for homogeneous compressible turbulence with application to modelling,* J. Fluid Mech., **242**, pp. 349-370, 1992.

[9]J acquin L. , Cambon C., Blin, E., *Turbulence amplificationby a shock wave and rapid distortion theory,* Phys. Fluids A, 5, 2539-2550, 1993.

[10] Lighthill M. J., "*On the energy scattered from the interaction of turbulence with sound or shock waves,*" Proc. Cambridge Philos. Soc. **49**, 531, 1953.

[11] Dosanj D.S., Weeks T.M., *Interaction of a starting vortex as well as a vortex street with a travelling shock wave,* AIAA J., **3**, 216, 1965.

[12] Cambon C., Sagaut P., *Spectral approach to compressible turbulence. Linear and weakly non-linear theory and modeling*, ERCOFTAC Summerschool on Compressible turbulence and mixing, Strasbourg, July 7-11, 2005.

[13] Culick F.E.C., Rogers T., "*The response of normal shocks in diffusers*", AIAA Journal, Vol.21, N°10, pp.1382-1390, 1983.

[14] Robinet J.C. "Stabilité linéaire d'un écoulement présentant une onde de choc", Thèse de Doctorat, *École Nat. Sup. de l'Aéronautique et de l'Espace*. 18 octobre 1999.

[15], Robinet J.C., "Étude des instabilités dans une couche limite décollée incompressible et compressible et réponse de choc oblique à une perturbation", Rapport de Post Doctorat, *Groupe Supersonique, IUSTI,* Marseille, Juin 2001

[16], Robinet J.C., Casalis G., "Critical interaction of a shock wave with an acoustic wave", *Physics of Fluids*, Vol.13, N° 4, Avril 2001.

[17], Knight D., Hong Yan, Argyris G. Panaras, Zheltovodov A. "Advance in CFD prediction of shock wave turbulent boundary layer interactions", *Progress in Aerospace Sciences*; 39 121-184; 2003.

[18], Garnier E., Sagaut P., "Large eddy simulation of shock/ boundary layer interaction", *AIAA Journal,* Vol.40, N°10, 2002.

[19] Sidorenko A., Piponniau S., Dupont P., Debiève J.F., *Unpublished work*, IUSTI, 2006.

[20] Andreopoulos J., Muck K.C., "Some new aspects of the shock-wave boundary layer interaction in compression ramp flow", AIAA-paper 86-0342, 1986.

[21] Dolling D.S., "Fifty years of shock wave/boundary layer interaction research: what next?", *AIAA Journal*, Vol. 39, N° 8, August 2001.

[22] Grasso F., Pirozzoli S., To appear, Phys.Fluids, 2006

[23] Dussauge J.P., Dupont P., Debiève J.F., *Unsteadiness in shock wave boundary layer interactions with separation*, To appear, Aeronautical Science and Technology, 2006.

[24] Debiève J.F., Dupont P., *Some multi time-scale aspects in shock wave/boundary layer interaction,* Conference on Turbulence and Interactions, May 29-June 2, 2006, Porquerolles, France

[25] Erengil M.E., Dolling D.S., "Unsteady wave structure near separation in a Mach 5 compression ramp interaction", *AIAA Journal*, Vol.29, N°5, 1991.

[26] Thomas F.O., Putman C.M., Chu H.C., "On the mechanism of unsteady shock oscillation in shock wave/turbulent boundary layer interaction", *Experiments in Fluids*, Vol.18, pp.69-81, Springer-Verlag, 1994

[27] Dolling D.S., Or C.T., "Unsteadiness of the shock wave structure in attached and separated compression ramp flows", *Experiments in Fluids* Vol.3, N°24-32 , 1985.

[28] Dolling D.S., Brusniak L., "Separation shock motion in fin, cylinder, and compression ramp-induced turbulent interactions", *AIAA Journal* Vol.27, N°6, 1989.

[29] Bonnet J.P., Chaput E., Alaziary de Roquefort T., "Détermination des fluctuations de pression pariétale dans une interaction onde de choc-couche limite turbulente en écoulement supersonique", Rapport final, Convention ONERA 20.391/SAT.2.CDC, Mai 1986.

[30] Coe C.F., Chyu W.J., Dods Jr. J.B., "Pressure fluctuations underlying attached and separated supersonic turbulent boundary layers and shock waves", *AIAA Paper 73-996, AIAA Aeroacoustics Conference,* Seattle, Wash., October 15-17, 1973.

[31] Dolling D.S., Smith D.R., "Unsteady shock induced separation in Mach 5 cylinder interactions", *AIAA Journal*, Vol. 27, N°12, pp.1598-1706, 1989

[32] Nguyen AT. "Décollement instationnaire et charges latérales dans les tuyères propulsives", *Thèse de Doctorat, Université de Poitiers* ; 10/06 2003.

[33] Bourgoing A., "Instationnarité et dissymétrie d'un écoulement supersonique décollé dans une tuyère plane", *Thèse de doctorat de l'Université Paris 6*, Juin 2002.

[34] Piponniau S., Rapport de stage de DEA, IUSTI, Université de Provence, 2005

[35] Jacquin L., Communication privée, 2005.

[36] Bourgoing A., Reijasse P.H., "Experimental investigation of an unsteady and asymmetrical supersonic separated flow". *CASI, 8th Aerodynamic Session Symposium*. Toronto; 29 April-2 May 2001

[37] Doerffer P. and Szwaba R., "Shock wave- boundary layer interaction control by streamwise vortices", *11th ICTAM Symposium*; Warsaw, Poland. 15-21 August 2004.