SHOCK MOTION AND STATE OF TURBULENCE IN A PERTURBED FLOW OVER A SPHERE, AT SUPERSONIC SPEED

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ABSTRACT
A flow at M=2.29 around a sphere, perturbed by a horizontal sonic jet placed on its axis of symmetry is explored experimentally by visualizations and wall pressure measurements. The motion of the resulting shock in connection with the laminar or turbulent state of the boundary layer is considered. It is found that, for some jet pressure, the shock system produced ahead of the sphere becomes unsteady; correlatively, strong pressure fluctuations are measured at the sphere surface. It is shown that jets located at other places are less efficient to produce shock unsteadiness, and that a jet at a Mach number close to 2 produces the same qualitative behaviour.

INTRODUCTION
The nature of a perturbed supersonic flow around a sphere is a question of interest to many respects. For example, in the reentry of a body in a dusty atmosphere, the presence of particles or of ice clusters impacting the surface and rebounding on it may alter the laminar boundary layer and the shock system (Fleener, Watson, 1973). This results probably in an early laminar/turbulent transition, and increases considerably the wall heat transfer. This can be understood in connection with some problems recently analyzed. Morkovin (1984, 1988) has remarked that in high-speed flows around blunt bodies, the point of laminar/turbulent transition occurs at rather weak angles, although 2-d linear theory predicts stable waves for such a geometrical configuration. This result was understood as a by-pass transition phenomenon, and was called the "blunt body paradox". More recently, Reshotko & Tumin 1999 have shown that superposition of linear oblique waves can produce algebraic transient growth, which is a possible candidate to explain the blunt body paradox. This points out that the boundary layer over a sphere may be particularly sensitive to perturbations occurring near the stagnation point. Another puzzling feature is the sensitivity of the front shock to downstream perturbations, its stability and frequency selectivity, and correlatively, the influence of shock motion on the flow around the sphere. Recent work has pointed out the frequency selectivity of normal shocks (Robinet, Casalis 1999) In the present experiment, the flow around a sphere at Mach number 2.29 is considered. It is perturbed by a small jet originating from the surface, and normal to it. The case of the jet located at the stagnation point of the unperturbed flow is mainly considered; jet locations apart from the stagnation point (at 10 and 20 degrees) have been also considered. The influence of the stagnation pressure of the jet and of its location on the shock motion and ultimately on the boundary layer transition are the main concerns of this experimental work.

EXPERIMENTAL SET-UP
The experiment is conducted in the supersonic wind tunnel of IUSTI. This is a continuous facility; it is operated at a nominal Mach number of 2.29. A sonic jet is used in most of the measurements. A supersonic jet (M= 2) was also used in some measurements to check that the jet Mach number is not a crucial parameter. The stagnation pressure of the supersonic flow was set constant in the range 0.15×10^5 N/m^2-0.9 $\times 10^5$ N/m^2. The sphere has a diameter of 45 mm. The jet exhaust section has a diameter of 1mm. The jet flow was generated by a bottle of compressed air (Synthetic air of Linde Gas). It was possible to obtain jet stagnation pressure up to 10^6 N/m^2. It was checked that the jet mass flux was small enough to produce no measurable variations the total pressure and temperature of the jet during a run. Mean measurements of temperature and pressure at the wall were performed with classical methods. Schlieren images of the flow were acquired with an ultrafast digital camera PCO Sensicam. The time of exposure was set to 20 microseconds in order to get a sufficient quantity of light. It was therefore possible to resolve phenomena of characteristic frequency smaller than 25 kHz.

Wall pressure fluctuations were performed with LEM piezoelectric transducers (Type 20H48A). The sensitive element has a diameter of 0.8 mm, and the nominal bandwidth is larger than 200 kHz. The transducer was placed behind a pinhole, in order to avoid problems of flushness and resulting wall roughness, and in order to maintain the wall curvature. The resonance frequency of the pinhole was estimated at 25 kHz, so that frequencies below this limit will be considered.

RESULTS

Mean measurements

It was checked that, as expected, the pressure distribution over the unperturbed sphere follows rather closely a modified Newtonian approximation. Cases with a perturbation due to the jet (Fig. 1) shows that the parameter $P=po_j / po_f$ proposed by Finley (1966), where po_j is the reservoir pressure of the jet and po_f is the total pressure downstream of the normal front shock, collapses reasonably well the wall pressure distribution, independently of the total pressure of the supersonic flow po_∞. This suggest that wall pressure distribution does not depend critically on the Reynolds number, and on the state (laminar or turbulent) of the boundary layer. Note that for a given Mach number, P can be related to the ratio $J = \rho_j U_j^2 / \rho_\infty U_\infty^2$ often used for the analysis of cross jets. Our measurements are globally consistent with Finley's results (1966), although in the latter case, experiments were conducted for larger jet diameters and for smaller values of P.

Flow visualisations

Flow visualisations revealed the influence of the jet on the shock system. For Schlieren images observed directly on a screen, for an horizontal jet and very small values of P, the shock is unaltered. When P is increased ($P>8$), a small bump appears on the shock, in front of the jet. For larger P ($8<P<30$), this bump becomes fuzzy, and the mean position of the shock seems to disappear just in front of the jet for small P. If P is still increased ($P>30$), the shock system is formed of two branches. In general, the rest of the shock system, far from the zone of influence of the jet, remains unaffected. When the images are observed directly, as eyes integrate frequencies larger than 20 or 25 Hz, only very low frequency phenomena can be detected: for a value of $P\approx30$, oscillations at very low frequency (probably <20 Hz) of the entire shock system were seen from direct visual observation. For values of P other than 30, the average action of the jet is to modify the shape of the shock or to make it fuzzy or visually non-existent, in a limited zone near the jet exhaust: this influence is of limited spatial extent. The use of the high-speed camera revealed the details of the flow organisation. No particular modification of the front shock was observed for P<8. For larger values of P, a bump is formed in front of the jet, which appears to be unsteady in all cases. Examples of visualisations are given in figures 2-4, for $Mj=1$ and 2, and for a horizontal jet. The supersonic stream flows from left to right, and the jet in the opposite direction. It is clear that the higher the jet pressure the further the shock position with respect to the sphere. Figure 2 gives an example of the incipient unsteadiness for $M_j=1$ and $P=8$; a small perturbation (indeed unsteady) can be observed. Figure 3 shows a large oscillation of the shock for $M_j=1$ and $P=24$. Although the quality of the images is limited by the small amount of light produced in the optical arrangements, some salient features can be recognised. The shock system becomes 3-d, a triple point appears, along with zones of large density variations due to either other shock branches, or more likely, the creation of a complicated shear layer, with deviation of the jet, and a 3-d separated zone. An extreme case is given in figure 4, for $M_j=2$ and $P=93$. In such conditions and for the selected frame, the shock is pushed away from the sphere at a rather large distance, comparable to the sphere diameter. Three cells of the underexpanded jet can be observed. Visualisations with the jet at an angle of 10 or 20 degrees were also performed. They revealed distortions of the shock, with bumps and triple points, but the major qualitative difference is that shock system is much more steady. In particular, it was difficult to observe the case of the fuzzy image of the mean shock. Note that for 10 and 20 degree flow cases, the perturbation brought by the jet is not applied on the axis of the sphere (where the shock is strong), but at angles for which the intensity of the shock is weaker. Cases with Mj=2 revealed no major qualitative difference with the case of the sonic jet.

Wall pressure fluctuations

The rms pressure fluctuations p' were measured at several locations for some values of P. An example is given in figure 5, for transducers placed along the meridian diameter where the jet exhaust is located. The location of a transducer is defined from its angular position θ. Three locations are shown here θ=25°, 50° and –25°. By obvious geographic analogies, there are called respectively North1 (N1), North2 (N2) and South1 (S1). Other locations were also explored, along the arcs West and East, but are not reported here. Figure 5 shows that when increasing P, p' increases, until $P\approx30$, and decreases for larger P. The same behaviour is found on transducers N1, N2 and S1. The overall level of fluctuations decreases when the distance from the jet is increased. The level of fluctuations on the arcs East and West (E1, θ=25°, W3, θ=75°) is found practically independent of P.

This picture can be characterised more precisely from pressure spectra measurements. Figures 6, 7 and 8 present the power spectral density normalised to the variance of pressure fluctuations, vs. frequency in Hz. In figure 6, the spectra of fluctuations in N1 and N2 are given, when there is no jet. The spectrum results mainly from the aerodynamic noise in the wind tunnel, electronic noise (in particular the peaks at high frequencies), and the fluctuations, which may be developed in the boundary layer over the sphere. There are several wide peaks at low frequency of unknown origin, but the overall shape is not typical of developed turbulence. Moreover, the spectra are almost identical at both locations, which suggests that the low frequency part of the spectra (f<100 kHz) is more relevant of the overall flow perturbations rather than of the development of boundary layer instabilities. When a small jet is blown, for $P \approx 4$ (fig. 7), it is clear that the shape of the spectrum measured in N1 is totally altered; in N2,the modification of the shape is not large, although the level is higher than for P=0. For larger P, both spectra seem continuous, without particular peaks or bumps (fig. 8). For very large values of P (not shown), the spectrum in N1 is almost unchanged, but the level of fluctuation in N2 decreases, and is close to the spectrum measured with a small jet: the turbulent activity at low frequency seem to decrease with distance from the jet and with increasing P.

DISCUSSION AND CONCLUSIONS

The present results make a consistent picture of the flow around the sphere, when perturbed by a jet near the stagnation point. In absence of jet, there is no evidence, even for angles θ larger than 45°, that the boundary layer is turbulent or transitional. The presence of the jet introduces new frequencies. It is believed that, near the exhaust a sonic jet of 1 mm in diameter produces near the exhaust, energetic perturbations typically of 50 kHz and above. The perturbations, which are observed are at much lower frequencies, typically between 100 Hz and 5 kHz. For the small jet case, for which the shock system remains steady, such low frequencies are probably related to the toroidal bubble of separation produced by the jet around the exhaust, as described in Finley (1966). Note that the fluctuations seem to be damped along the sphere: this means probably that the excitation produced by the jet does not contain frequencies in a possibly unstable range. For larger values of P, the shock system is unsteady at low frequency: this seems consistent with the significant energy found at low frequency, in particular for $10<P<30$. These observations may have consequences for two problems.

The first one is the question of shock stability. For small values of P (P<7or 8) and a horizontal jet, no motion of the shock is observed. Indeed, Finley reports some motions of the shock, for very small values of P (P<2), which were not explored in the present experiment. For larger P ($8<P<30$), the unsteadiness of the shock is such that the image of the shock at the vicinity of the jet, and low-passed by human eyes is fuzzy; it is tempting to suggest that the zero frequency component of the shock motion is weak. The large value of p' observed in this range seem to be due to the shock motion. For P between 30 and 40, whole front shock seems to oscillate: this is the sign of oscillations along the shock with small wave numbers. It can be underlined that, excepted for this value of P, the effect of the jet on the shock front is efficient at the vicinity of the jet, but the rest of the shock remains barely affected by the interaction. Moreover, the measurements of rms values and of spectra along the equator show that pressure fluctuations are almost independent of the presence of the jet; this suggest that the perturbation is not isotropic over the sphere surface, but is three-dimensional. As the shock is more steady when the jet is located at θ=10°or 20°, it is deduced that the normal front shock is more sensitive to perturbations than the weaker, oblique part of the shock

The second question is related to the stability of the boundary layer and its transition. There are two observations apparently contradictory. Firstly, the fluctuations decrease with distance from the source, suggesting a stability of the layer with respect to the frequency range of the perturbations considered in the present work. However, in the region of influence of the jet, there is a continuous spectrum of pressure at rather low frequency. It is likely that the low frequency motion of the shock system contributes to this unsteadiness. This could be a factor of importance for the interpretation of the results on transition around blunt bodies. Part of the "turbulent" fluctuations found in the present work may be strongly connected to the shock motion near the stagnation point. Consequently, this can be of importance for the modeling of heat transfer for the reentry of bodies in laden atmosphere: the turbulence produced in the boundary layer subjected to external flow unsteadiness and to external vorticity produced by triple points of the shock may have non-standard properties, and therefore probably not relevant of classical models.

Acknowledgements

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Figures

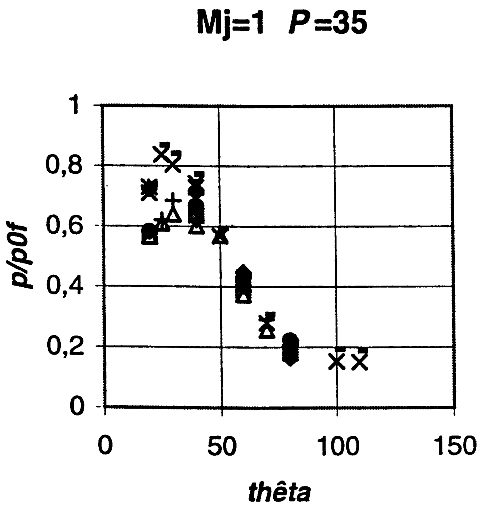

Figure 1: Wall pressure distribution along four half-diameters N, S, E, W. Stagnation pressure in the supersonic flow indicated in mm Hg. Sonic jet, *P*=35. ◆ W 400 mm Hg; ■ E 400 mm Hg; △ N 400 mm Hg; × S400 mm Hg; * W 150 mm Hg; ● E 150 mm Hg; + N 150 mm Hg; ▭ S 150 mm Hg.

Figure 2: Schlieren of the flow, Mj=1, *P*=8, incipient unsteadiness

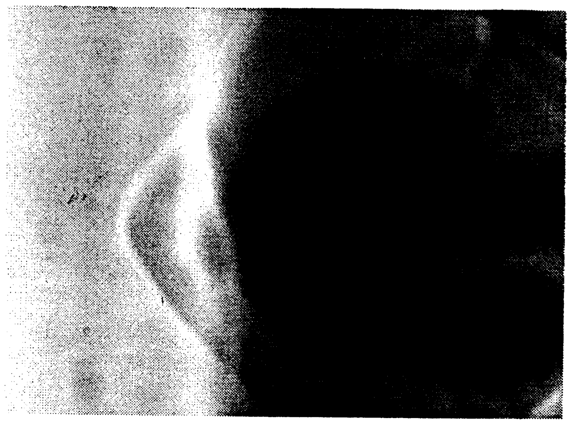

Figure 3: Schlieren of the flow, Mj=1, *P*=20, fuzzy mean shock

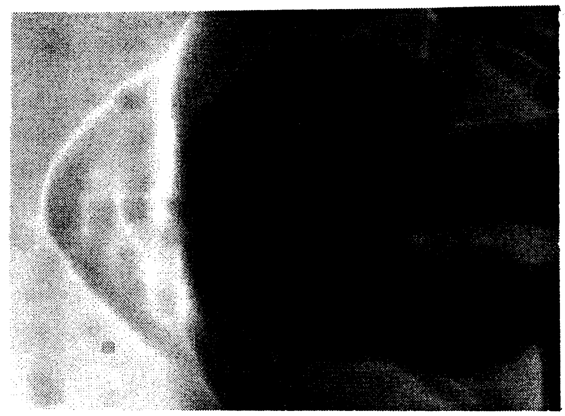

Figure 4: Schlieren of the flow, Mj=2, *P*=90.

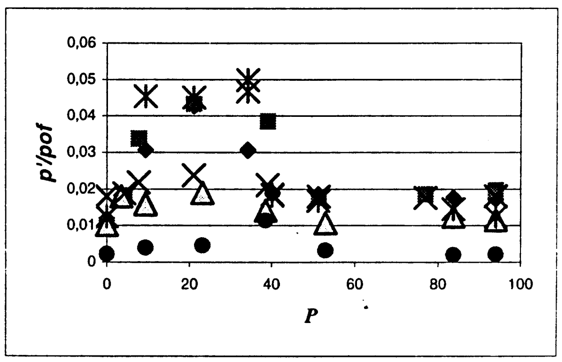

Figure 5: rms pressure fluctuations. Mj=1. ◆,■ N1 θ=25°, * S1 θ=-25°, △,× N2 θ=50°, ● S3 θ=-75°

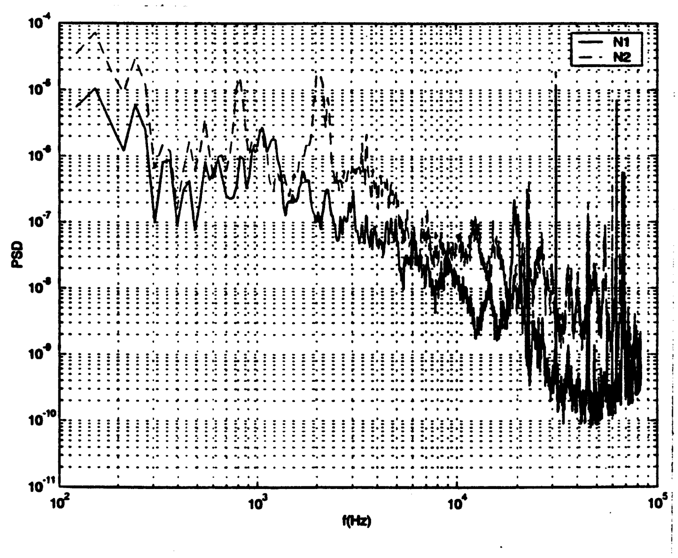

Figure 7: Wall pressure spectra. Flow without jet

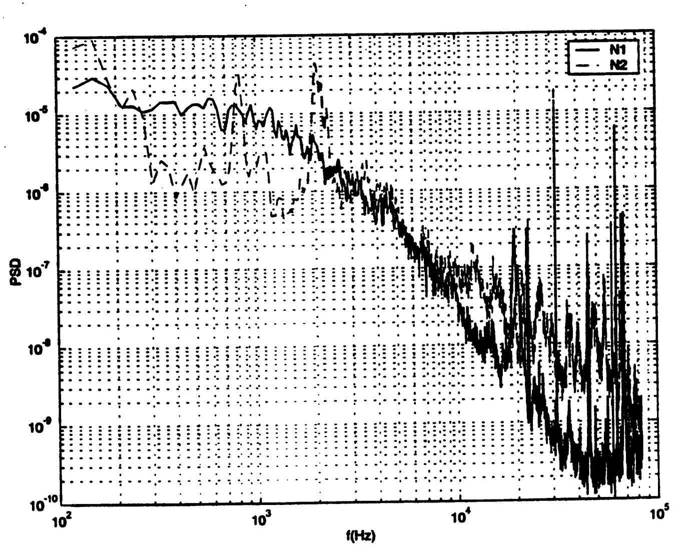

Figure 8: Wall pressure spectra *P*=4.5

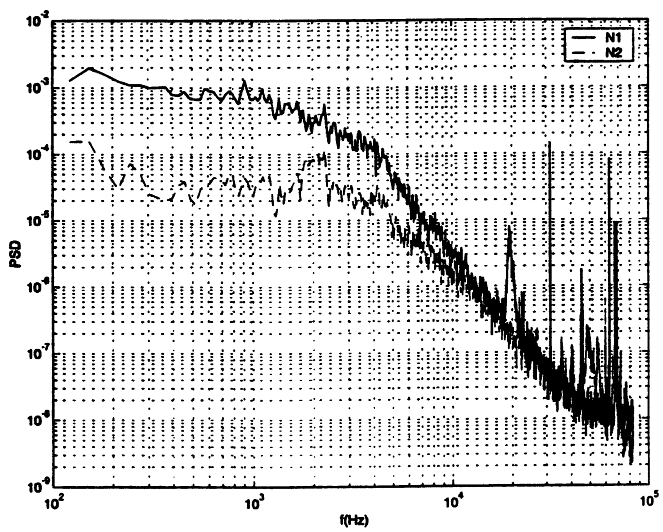

Figure 9: Wall pressure spectra *P*=20, fuzzy shock.