Experimental exploration of an underexpanded supersonic jet

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1 Introduction

Underexpanded jets have been the subject of many studies for a long time. The most often encountered ones issue from a convergent nozzle. Indeed, it is enough that the nozzle pressure ratio (henceforth NPR), defined as the ratio of upstream stagnation pressure to the ambient pressure, be above the critical value $[(\gamma+1)/2]^{\gamma/(\gamma-1)} \approx 1.89$ with γ the ratio of specific heats of the gas, and the jet is underexpanded, the static pressure at the nozzle exit being higher than the ambient. The pressure mismatch at the jet exit generates a quasi-periodic shock cell pattern [13]. These flows present a variety of practical applications. The pioneering studies mainly focused on the flow structure of highly underexpanded flows, featuring a so called barrel shock and a large Mach disc (*e.g.* [1, 8]). More detailed investigations of local mean values taken by important flow variables, such as velocity, static pressure or Mach number, defined by the ratio of local velocity to local speed of sound, have been performed in the past. Donaldson & Snedecker [4] and Hu & McLaughlin [6] have deduced velocity from static and Pitot pressure measurements. Norum & Seiner [10] have led extensive static pression measurements on jet centreline in an attempt to link shock cell structure to shock associated noise. These measurements have been compared to mean flow simulations by Seiner *et al.* [14]. Katanoda *et al.* [7] have measured Pitot pressures in jets with Mach disc and compared that to numerical simulations. Laser velocimetry (LDV) has also been applied to such jets. Eggins & Jackson [5] have performed velocity measurements in highly underexpanded jets (NPR = 6.6) with Mach disc and Nouri & Whitelaw [11] at moderate underexpansion (NPR = 3.6) without one.

However, measurements of velocity and Mach number evolution in shock containing jet plumes are scarce. The purpose of this contribution is to associate pressure measurements, LDV and Schlieren records of underexpanded jets to achieve

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a clearer picture of the development of such jets and link measured features with pattern from the flow visualization.

2 Experimental setup

The supersonic flow originates from a continuously operating compressor fed with dry air. The jet exhausts through a $D = 38$ mm diameter contoured convergent nozzle. So as to ensure a precise setting of the NPR, losses between the regulating valve and the exit plane are circumvented by measuring the wall static pressure fifteen nozzle diameters upstream of the exit. Stagnation pressure is retrieved from the static pressure value by a local Mach number estimate in the measuring section which is known by the use of the area Mach number relation (see *e.g.* [3]). Total temperature is also measured upstream of the exit. In the following, results for a jet of ideally expanded Mach number $M_j = 1.15$ are shown, corresponding to NPR = 2.27.

A conventional Z-type Schlieren system has been used to visualize the flow. It consists of a continuous QTH light source, two f/8 parabolic mirrors with diameter of 203.2 mm, a razor blade set perpendicular to the flow direction as filter and a high-speed CMOS camera. Mean pictures have been computed from a large collection of short-time exposure images.

Measuring static pressure (P_s) in a shock containing jet is no obvious undertaking. The flow local properties are changing over short distances according to the high gradients encountered. Furthermore, the orientation of the local velocity vector is not uniform. A short static pressure probe design rather insensitive to the angle of attack has been proposed by Pinckney [12]. The one built for this study follows a slight modification of the quoted design made by Norum & Seiner [10]. The constructed probe has an outer diameter of 1.5 mm and a tip to static holes distance of about 4.5 mm. Results on the jet centreline have been compared to those from [10] and a good agreement was found. The Pitot pressure (P_p) probe consists in a 1.5 mm outer diameter stainless steel tubing cut square.

A LDV system has been used. An Argon ion Spectra-Physics 2017 laser operated on the green line of wavelength 514.50 nm and power 100 mW. The optical arrangement provides a measurement volume of approximately 100 μm diameter and 1.5 mm length. The fringes are set perpendicular to the jet axis and therefore sense the axial velocity component. It implies that the long measurement volume dimension be perpendicular to the axis. The receiving optics collects the forward scattered Doppler bursts approximately 30° off axis. The Doppler signals are finally processed by a BSA F80 processor with a clock frequency of 180 MHz. Seeding is performed by Laskin nozzles atomising olive oil and added to the flow upstream of the exit. The mean particle size ist found to be around 1 μm. No external seeding has been set up but the measurements presented next remain within the jet potential core and the first two nozzle diameters so this is not expected to lead to velocity overestimation. Ensemble averages have been performed over at least 200000 individual velocities.

3 Results and discussion

3.1 Behaviour of the laser velocimeter in the chocked jet

Using the laser velocimetry technique in a shock containing jets raises the question of the particle ability to accurately follow the flow [5]. Particle lag indeed appears when high velocity gradients exist. Some velocity histograms are shown in Fig. 1, where particle lag is visible as an asymmetry. When the flow is accelerating (left), a small bump appears on the side of lower velocities. At the beginning of the compression zone (middle), when the flow is decelerating, the histogram is symmetric. Further in the compression region (right), a small amount of particles travel at faster velocities than the bulk. To keep the trailing bumps to a minimum corresponding to the situation displayed in Fig. 1, the photomultiplier feeding voltage has been raised to about the upper tolerable limit, thus probably enhancing the visibility of small oil droplets at the cost of larger ones. Validation rates above 90% ensure that the Doppler bursts are not altered by this process.

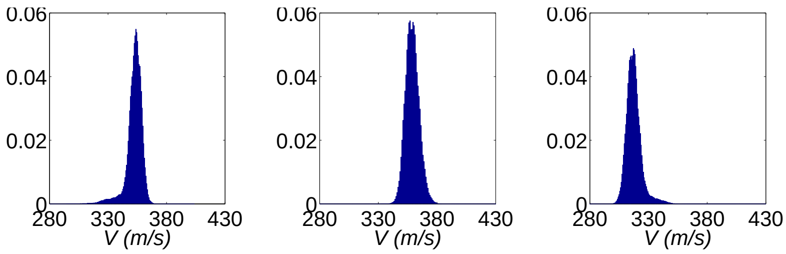

Fig. 1 Probability density functions of instantaneous axial velocity at $X = 0.24\,D$ (left), $X = 0.48\,D$ (middle) and $X = 0.63\,D$ (right) on the centreline.

3.2 Structure of a $M_j = 1.15$ jet

A gathering of the experimental results is presented in Fig. 2. The mean Schlieren picture depicts the well-known diamond shock cell pattern. As can be seen from the quantitative measurements performed on the centreline in Fig. 2 (middle), expansion occurs within the light right pointing triangles of the Schlieren image with the jet static pressure falling and the axial velocity raising. Conversely, compression takes place in the dark left pointing triangles since P_s raises and V falls. This pattern is repeated until the end of the potential core, where velocity and Pitot pressure start to fall for good but still oscillating until the supersonic length is reached and the flow has become entirely subsonic. From the complete pressure measurements at this M_j, the potential core is seen to extend up to approximately $5.5\,D$ and the supersonic core to 7 D downstream of the exit. The axial velocity is at its maximum at the junction between the light and dark zones of the Schlieren picture and at its minimum at the "shock" location. The Pitot pressure P_p is displayed as measured and does not correspond to jet local total pressure due to the shock forming ahead of the probe. It is seen to be almost uniform in both profiles, which can be associated to nearly uniform total pressure at this moderate underexpansion. The P_s signal corresponds to a sightly damped sinusoidal curve about the ambient pressure. The axial offset of the P_s traverses compared to V and P_p will be adressed in the following. The shock cell structure is seen to be weak, the shocks being no discontinuities but instead continuous modulation of the mean flow.

Axial traverses at a radial position $Y = 0.25$ D from the centreline are also displayed in Fig. 2 (bottom). As before, the Pitot pressure is almost uniform. Static pressure and velocity data reveal however the short expansion through the fan attached to the nozzle lip and remain nearly constant downstream until the entrance into the dark triangle of the first shock cell, where compression occurs. The existence of neutral external regions outside the light and dark triangles mentioned above have already been addressed by Nouri & Whitelaw [11].

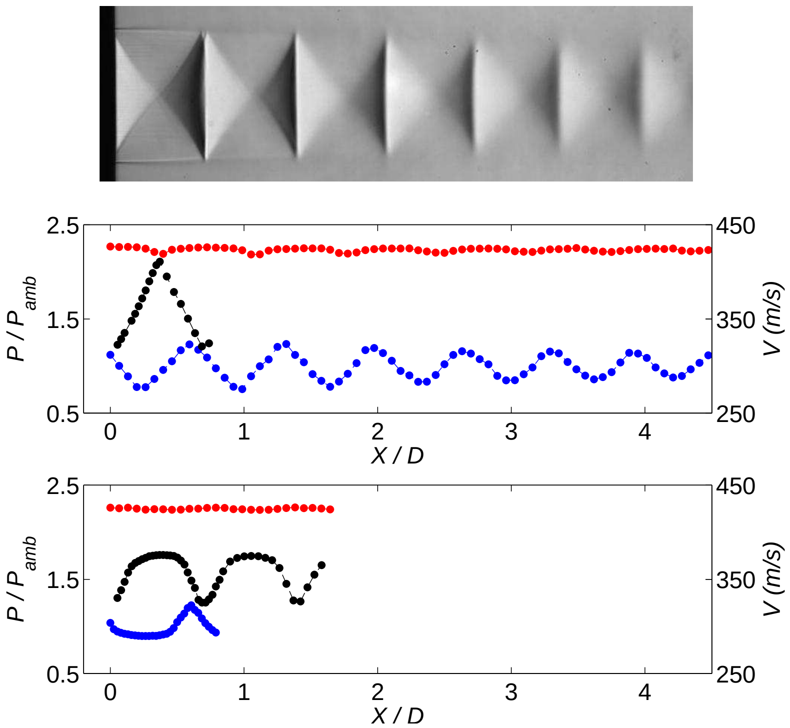

Fig. 2 Mean Schlieren picture from 500 instantaneous frames (top), centreline measurements (middle), and axial traverses at $Y = 0.25\,D$ (bottom). Displayed are static pressure (blue), Pitot pressure (red) and axial velocity (black). P_{amb} is the ambient pressure.

The local Mach number M has been estimated in two different ways. It can be inferred from the LDV results if one assumes that the local total temperature is uniform in the jet and equal to the reservoir temperature, by the formula :

$$M = \{V^2/[\gamma r T_t - V^2(\gamma - 1)/2]\}^{1/2}, \quad (1)$$

where $\gamma = 1.4$, $r = 287.06$, T_t is the reservoir temperature and V the mean flow velocity. The total temperature uniformity hypothesis has been validated in [9] for supersonic shock free jets. However, since the total temperature does not change across a shock, this assumption should hold in shock containing jets as well, at least in the potential core. On the other hand, the local Mach number can be computed from local P_p and P_s values, using Eq. (100) of [2]. The hypothesis is made here that a normal shock forms ahead of the Pitot probe, which enables the use of Rankine-Hugoniot normal shock relations. Corrections in P_p measurement locations to account for the distance between normal shock and probe nose are insignificant in the present case and are not applied. Centreline and off axis Mach number estimates from both methods are shown in Fig. 3. The first striking feature in both figures is the offset between LDV based and pressure based estimates, which is consistent with the results displayed in Fig. 2. Offsetting the measured P_s values by 4.5 mm, the tip to static holes distance of the current static pressure probe, yields the curves marked by triangles in Fig. 3. However short the static probe is, it seems nevertheless that the measured pressure is not the one prevailing at the tip but much more the one at the holes location, because of the high static pressure gradients existing in this type of flow. A careful examination of the static pressure comparisons performed by Seiner *et al.* [14] shows that the measured shock locations are persistently ahead of the computed ones, thus supporting the above hypothesis. The magnitudes the two estimates agree very well apart perhaps from the lower Mach number regions where the measured static pressure should not be as accurate [12]. The centreline Mach number is seen to oscillate as expected about its ideally expanded value, going up to about $M = 1.4$, while the neutral zone of nearly constant Mach number is readily spotted on the off axis plots in Fig. 3 (right).

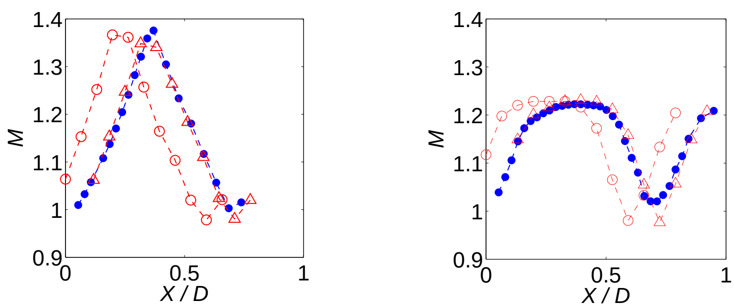

Fig. 3 Mach number estimates from LDV measurements (blue) and pressure measurements (red). Left : centreline values ; right : $Y = 0.25\,D$. ○ pressure-based computation from as-measured data ; △ pressure-based computation with P_s profile translated 4.5 mm downstream.

4 Conclusion

A $M_j = 1.15$ underexpanded free jet has been studied. A LDV system has been set up and the results have been checked for this shock containing flow by observing the velocity distribution histograms. Pitot and static pressure measurements have also been performed and have been compared, together with velocity profiles, to mean Schlieren pictures. All measured mean flow variables are seen to smoothly oscillate about a global mean value, without actual shocks. Off axis profiles show the existence of neutral regions, where pressures and velocity are approximately uniform. Local Mach numbers have been assessed by two methods and a good agreement has been obtained. This strengthens both types of measurements in spite of the high gradients present in this jet making them more difficult than in a perfectly expanded jet.

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