Wall pressure analysis and Background Oriented Schlieren visualization on jet-flat plate interaction

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Abstract.

The interaction between a jet close to the sonic condition and a tangential flat plate was investigated. Measurements have been carried out in the semi-anechoic chamber of the Fluid Dynamic laboratory at the University Roma Tre. The converging nozzle has a conical shape and an outlet diameter of about D=12 mm. Wall pressure fluctuations are acquired at axial distances ranging between 1 < x/D < 6. Measurements are repeated for two different radial positions of the flat plate (H/D = 2 and H/D = 0.75) and they are performed at M_j = 0.9 and M_j = 1 in slightly under-expanded conditions until NPR = 1.94. Fluctuating pressure data are analyzed in time and frequency domain and compared with the flow visualization images obtained through a Background Oriented Schlieren technique. The investigation leaded to deepen the phenomena underlying the interaction between the planar surface and the high-speed jet, clarifying the influence on the shock cell structure.
1. Introduction
Many current and future aircraft designs deal with the problem of the jet noise prediction methods when the flow interacts with part of the airplane structures. This issue is destined to increase for the new generation of the turbofan engines with ultra high by pass ratio (UHBPR), this engine feature leads to a reduction of the exhaust velocity thus creating a significant benefit in terms of the noise emission. The increase of the nozzle diameter will bring about more aggressive close-coupled configuration producing different effects in terms of noise: the flow interacting with the wing increases the radiated noise and stresses the wing panels structures, whereas when the jet plume impacting the fuselage produces interior noise and reemitted vibration noise. To investigate the afore mentioned problems many studies were carried out (see among many: [8, 13, 1]). The wall pressure fluctuations were investigated in several works, providing an analysis in incompressible and compressible subsonic regime [3, 11, 10, 12]. Furthermore it has to be pointed out that the typical Mach numbers of the propulsive jets in cruise conditions range between 0.75 and 0.85, and the flight altitude is usually at 11000m. Due to the high forward speed and thrust requirements, the fan stream from the turbofan engines is generally supersonic and, due to the overall nozzle optimization, it is imperfectly expanded [6]. At such flow conditions a shock system, sometimes referred to as shock-cells is generated. It consists of a series of expansion and compression waves which interact with the aircraft structures raising the stress on the wing panels and the interior cabin noise. Many research studies have been carried out to study the acoustic signatures of under-expanded free jets in different flow conditions [2, 9] to improve and validate the current generation of noise prediction tools [16]. The acoustic propagation tones in subsonic and in under-expanded condition were investigated [7, 5]. A preliminary analysis on the jet flat plate architecture in under-expanded condition were performed by the de Paola et al. [4]. In this work, in order to improve the results founds in the literature an analysis that combines flow visualization, using Background Oriented Schlieren technique (BOS), and wall pressure fluctuations acquired using flush mounted wall pressure transducers was carried out. Background Oriented Schlieren (BOS) has been deployed as an optical technique to non-intrusively visualize density gradients [14] similarly to classical Schlieren and shadowgraph methods but with a less constraining set-up [15].

The present work extends previous investigations [4] and the selected configurations span from exit Mach number $M_j = 0.9$ up to $M_j = 1$ and to a under-expanded condition similar at that encountered in real engines. The pressure signals were processed in time and frequency domain proving a preliminary global statistical analysis.

The present paper is organized as follows. In the section II it is reported the facility description and the experimental set-up. The main results were reported in section III with a series of flow visualizations and statistical analyses. Final remarks are addressed in section IV.

2. Experimental setup
The experiments were performed in the laboratory of fluid dynamics ‘G.Guj’ of RomaTre university. The test facility equipped with a jet and tangential flat plate is installed in an acoustical treated chamber that measures 2m x 4m x 3m, that provides semi-anechoic conditions for frequency above 500Hz. The jet feed line consists of a compressed dry air duct supplied by a 2m$^3$ tank at 8bar, the air is supplied to the tank by a compressor. The velocity at the nozzle exhaust is regulated by controlling the pressure of the incoming flow with an electrically driven valve. Honeycomb panels and turbulence grids are installed in the pipeline in order to have the desired flow quality. The flow conditions at the nozzle inlet are continuously measured by a thermocouple and a pressure transducer, these data are used to evaluate the jet exhaust conditions adopting the isentropic relations.
A rigid aluminum flat plate was placed parallel to the nozzle axis using a rigid traverse system that permit the variation of the plate radial position. The alignment of the plate with respect the nozzle axis was carefully checked using a laser leveling instrument and the plate surface was predrilled with 4 rows of 50 holes in the streamwise direction. The uniform spacing is equal to the nozzle diameter i.e. 12 mm. In Figure 1 a sketch of the experimental setup is reported. For an easier visualization, the frame of reference is reported at the corner of the plate.

![Figure 1. Sketch of the wall pressure measurement experimental set up](image)

The non-intrusive flow visualization was performed using the Backgound Oriented Schlieren (BOS) technique that is based on the refractive index variation due to density gradients. The first step of this method is the acquisition of a reference image generated by recording the background pattern observed through air at rest before the experiment. In the second step, an additional exposure through the flow under investigation leads to a locally displaced image of the background pattern. The resulting images of both exposures can then be evaluated by image correlation methods. Existing evaluation algorithms, which have been developed and optimized, for example, for particle image velocimetry can be used to determine the displacement of patterns at multiple locations throughout the image. The deflection of a single beam contains information about the spatial gradient of the refractive index integrated along the line of sight.

In the present study a structured pattern background was created using MATLAB program generating a 2000x2000 size matrix of random numbers whose elements are normally distributed and then printed out as a binary image of white dots. The size of the recorded dots is kept of about 2-3 pixels. The CCD camera used for the measurements is a LaVision SX 4M with a resolution of 2360x1776 pixels and equipped with Nikon lens characterized by a focal length of 50 mm. Recording frequency was set to 10Hz. The pattern has been uniformly back-illuminated by a white LED screen. To determine the background image displacements a particle image velocimetry (PIV) cross-correlation algorithm has been applied using the Davis software provided by LaVision. Interrogation window has been set at constant size corresponding to 16x16 pixels with a 50% overlap. Tests have been performed by placing the camera and the back-illuminated pattern at the same distance from the nozzle axis as shown in Figure 2.

The wall pressure fluctuations acting on the flat plate were acquired in streamwise direction using two flush mounted pressure transducers (Kulite-Mic190M). They have a diameter that fits the pressure tap and a frequency response up to 100kHz. The pressure signals were acquired setting the cut off filter of the Kulite signal conditioner (Kulite KSC2-C3) at 70kHz and accordingly with the Nyquist-Shannon theorem setting the acquisition frequency on the Yokogawa DL708E digital scope at the value of 200kHz. In order to avoid the cavity resonant peak the pressure transducers were carefully flush mounted on the plate surface and the pressure taps not involved in the measurements were covered to remove spurious effect.
3. Results

The jet flow visualization is reported in terms of pixel displacement for different NPR around the sonic condition and for two radial positions of the flat plate, H/D=2 and H/D=0.75. It is possible to observe that vectors point to regions of increasing density. As shown in Figure 3 (a)(c)(e) at H/D=2 the flow is symmetric with respect of the jet centerline and a careful examination of the BOS images exhibits, that decreasing the radial distance of the plate, at Mach=0.9 a Coanda effect is highlighted only at H/D=0.75. The presence of the surface induces a bending of the mean flow in good agreement with velocity measurements presented in the literature [10].

Figure 3. BOS flow visualizations in terms of pixel displacement: (a) NPR=1.7 and H/D=2. (b) NPR=1.7 and H/D=0.75. (c) NPR=1.84 and H/D=2. (d) NPR=1.84 and H/D=0.75. (e) NPR=1.94 and H/D=2. (f) NPR=1.94 and H/D=0.75.

At sonic condition (Figure 3(c)(d)) the jet begins to adjust to ambient pressure, shock cells
start to occur and appear increasingly pronounced with increase in degree of underexpansion (Figure 3 (e)(f)).

Results obtained for the different radial positions of the plate were compared showing that the surface does not influence the shock cell structure except for the intensity which is slightly higher decreasing the distance. However, the BOS system may not have been sensitive enough to detect the magnitude of the image displacements resulting from shock cells in the region further from the nozzle exit ($4 < x/D < 6$) where the effect of compressibility starts to be less evident.

The wall pressure fluctuations were analyzed in the frequency domain using the power spectral density (PSD) evaluated with the Welch method. The reported analysis was carried out in streamwise direction addressing the effects of the different NPR, and the different jet-plate distances $H$. The autospectra for different positions in streamwise direction over the plate surface are reported in Figure 4. The autospectra axial evolution underlines an increase of the spectra magnitude moving downstream along the flat plate. This effect is correlated to the development of the jet flow over the plate surface for larger axial positions, Figure 4 (a)(b)(c). The autospectra peak reported in the frequency range between $0.2 < St < 0.5$ is associated to the Kelvin-Helmholtz instability and it disappears at $x/D = 6$ because this position is at the end of the jet potential core.

![Figure 4](attachment:image.png)

**Figure 4.** Streamwise evolution of the PSDs: (a) NPR=1.70 and $H/D=2$. (b) NPR=1.84 and $H/D=2$. (c) NPR=1.94 and $H/D=2$

Furthermore by increasing the NPR to 1.84 to reach in the sonic condition it is possible to observe a decrease of the peak associated to the Kelvin-Helmholtz mode. This effect can be ascribed at the development of upstream modes associated to the shock cell, as shown in Figure 2(b) where a series of small shock cells is visible also at NPR=1.84. Therefore by increasing the NPR to 1.94, in order to obtain an under-expanded condition, it is possible to observe that the
autospectra shape remains the same except for the onset of an energy bump at high frequencies corresponding to \( St > 1 \). This signature moves to higher Strouhal numbers increasing the axial position of the pressure transducers and maybe can be associated to the broadband shock associated noise (BBSAN). This peak disappears at the end of the potential core \((x/D=6)\), as it is possible to observe in Figure 4(c), and it is undetectable at the first axial distances \((x/D=1 \text{ and } x/D=2)\).

Figure 5 (a) reports a comparison of the autospectra for all the different NPR considered in this paper and at a fixed axial position \(x/D=3\). To the extent of addressing the effect of the radial position of the flat plate the analysis is repeated for a smaller radial distance corresponding to \(H/D=0.75\). The results are shown in the Figure 5(b).

![Figure 5](image)

**Figure 5.** PSDs comparison: (a) At different NPR with fixed axial position \(x/D=3\) and plate radial position \(H/D=2\). (b) At different NPR with fixed axial position \(x/D=3\) and plate radial position \(H/D=0.75\). (c) At different plate surface radial positions with fixed axial position \(x/D=3\) and NPR at 1.94.

It is highlighted that by reducing the radial position of the flat plate, the shape of the spectra changes, becoming very similar to a boundary layer spectra with a more broadband trend. It is possible to observe that the peak associated at the BBSAN disappears in the \(H/D=0.75\) configuration and the spectral energy contents increases.

The mutivariate statistics of the wall pressure fluctuations were investigated in the time domain through the cross correlation function computed between two contiguous pressure transducers. The cross-correlation is defined as:

\[
R_{pp} = < p(x,t), p(x + \xi, t + \tau) >
\]

where \( \xi \) is the distance in the streamwise direction between two transducers (in the present study \( \xi = 1D \)), \( \tau \) is the time lag and the symbol \(< > \) denotes an ensemble average. The cross-correlation is normalized dividing by the product of the standard deviations of the two pressure
signals and it is plotted in Figure 6 for different positions in the streamwise direction. By increasing the axial distance the oscillations disappear and a negative positive bump is found at the end of the potential core. For higher Mach numbers in under-expanded conditions two peaks of the cross-correlations are detected, these disappear at the end of the potential core.

![Figure 6. Streamwise evolution of the cross correlation functions: (a) NPR=1.70 and H/D=2. (b) NPR=1.84 and H/D=2. (c) NPR=1.94 and H/D=2](image)

A comparison of the cross correlation coefficients for different NPRs, but at a fixed axial position x/D=3 and radial position of the plate surface H/D=2 is reported in Figure 7 (a). It is underlined that increasing the NPR, the cross correlation first peak decreases and it takes a more oscillatory trend. This analysis is repeated reducing the radial distance of the flat plate at H/D=0.75, obtaining a cross correlation functions narrower. Hence the plate has the effect to break the large scale turbulent structures as it approaches to the jet. Furthermore in this case the effect of the NPR on the cross correlation first peak becomes smaller. For a better understanding of the effect of the plate surface a comparison of the two cross correlation functions evaluated at the two different plate radial positions it is reported in the Figure 7 (c). It is highlighted in this way a more different behaviour obtained in the two different configurations.

4. Conclusions
In this paper a preliminary analysis of the wall pressure fluctuations induced by a compressible jet flow over a tangential flat plate was investigated by varying the NPR from 1.7 to 1.94 thus providing slightly under-expanded conditions. The radial position of the flat plate was varied from the less intrusive found in the literature H/D=2 to the more intrusive H/D=0.75. The flow visualizations were carried out, using the BOS technique, to highlight the compressible effect induced by the high velocity jet flows, the shock cell development and the effect of the different...
radial position of the flat plate on the jet plume. The wall pressure fluctuations were evaluated through a pair of flush mounted pressure transducers.

This work represents a further evolution of previous studies carried out by the same authors on the installation effects in subsonic conditions. The flow visualizations were reported in terms of pixel displacement that is related to density gradient of the jet plume. This is a quite good way to provide a qualitative representation to the extent of understanding the jet flow behaviour in the transonic condition, reporting also the shock cell visualization. The wall pressure field over the plate surface was characterized in the frequency domain using the PSDs addressing both the effect of the NPR and the radial position of the flat plate(H). The increasing of the NPR reduces the amplitude of the wave modes associated at the Kelvin Helmholtz instability. Moving to the underexpanded condition a peak at about St=1 was found, and maybe it is associated at the BBSAN.

It is underlined that reducing the flat plate radial position the autospectra became more broadband and the peak associated to the BBSAN disappears. The statistics of the wall pressure fluctuations were also studied in the time domain using the cross-correlation functions. The increase of the NPR reduces the amplitude of the cross-correlation first peak and this effect became less significant at H/D=0.75.

Figure 7. Cross correlations comparison: (a) At different NPRs with fixed axial position x/D=3 and plate radial position H/D=2. (b) At different NPRs with fixed axial position x/D=3 and plate radial position H/D=0.75. (c) At different plate surface radial positions with fixed axial position x/D=3 and NPR at 1.94.
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