On the Wall Pressure Fluctuations induced by a Supersonic Jet over the Wing pressure side

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Abstract. Supersonic jet wing integrated configurations are expected to be relatively louder than subsonic installed configurations, increasing the wall pressure load transmitted inside the fuselage and stressing the wing/fuselage panels with very energetic and frequency localized supersonic effects. In this framework, a model-scale experimental investigation of an installed jet-wing configuration has been performed using a supersonic convergent-divergent nozzle interacting with a wing generated by a NACA4415 airfoil. The measurements have been carried out in the semi-anechoic chamber of the “G.Guj” Fluid Dynamic laboratory at the University Roma Tre. Wall pressure fluctuations are acquired at different axial locations in stream-wise and span-wise directions. Measurements are repeated for different wing radial positions and by varying the NPR between 2.2 and 2.6, thus exploring both over-expanded and under-expanded jet flow conditions. The flow features that characterize the different flow regimes were caught using the Background Oriented Schlieren (BOS) technique. Fluctuating pressure data, acquired with flush-mounted pressure transducers, were analysed in the frequency domain, considering a Fourier-based approach. A comparison of results obtained with an infinite flat plate has been used to highlight effects generated by the discontinuity related to the trailing edge.

1. Introduction
Jet-wing installation effects represent a crucial issue for manufacturers during future aircraft design. The introduction of the modern turbofan, characterized by larger nozzle discharge diameters, involved closer coupled jet-wing configurations, thus boosting the pressure load on the wing pressure side.
The above complications are amplified in the new generation of high-speed commercial aircraft, which are expected to use supersonic propulsive system. Supersonic jet engines should be well-integrated into the airframe/wing to reduce the sonic boom and fuel consumption. Nonetheless, the wall pressure load transmitted to the wing panels is expected to be louder, characterized by supersonic signatures very energetic and well localized in frequency.

A large body of literature has been published on the jet-induced wall pressure fluctuations in the last few decades, especially in the subsonic regime. Fundamental flow physics have been retrieved by experiments using a large infinite flat plate without side effects. Di Marco et al. 2015 [1] for the first time characterized this problem in the incompressible regime, while Meloni et al. 2019 [2] extended the analysis to high subsonic flow conditions. The effect of the nozzle exhaust Re number has been portrayed by considering two different radial plate positions [3] and the application of wall pressure models ([4] and [5]) have been extensively discussed. These applications were extended considering a semi-infinite plate and by varying the distance between the trailing and the nozzle exhaust [6]. Further studies have been carried out by [7] and [8] considering simplified jet-plate configurations, with the scope of clarifying fundamental physical mechanisms associated with shielding/scattering effect of the airframe surface on the far-field noise [9].

Relevant are the works of [10] and [11] which for the first time carried out an experimental analysis on the wall pressure fluctuations induced by a jet flow on scaled jet wing configurations, including also a wind-tunnel generated flight stream.

Despite its importance for the studies in the subsonic case, few works have been devoted to characterizing the complex wall pressure behaviour induced by a jet in the supersonic case. Recently, Camussi et al. 2021 [12] extended the analysis using a convergent nozzle in under-expanded flow conditions, highlighting the signature on the wall pressure load of the BBSAN and of the Screech tones, using an infinite flat plate. This analysis has put the basis of the work provided in [13] which investigated the jet induced wall pressure fluctuation using a convergent-divergent nozzle, thus characterizing the different flow conditions: over-expanded and under-expanded.

This work is a follow up of the previous illustrated analyses and presents for the first time an experimental study of the jet induced wall pressure fluctuations over a wing generated by NACA4415 profile, chosen according to [11]. The jet exhausting flow has been provided using a convergent-divergent nozzle by varying its pressure ratio between NPR=2.2 up to NPR=2.6. The radial position of the wing has been varied between H/D=0.6 and H/D=0.75, thus replicating real small scale configurations. Wall pressure fluctuations were acquired in stream-wise and span-wise direction at the trailing edge by using a couple of flush-mounted wall pressure transducers. We analyzed the data in the frequency domain, providing a characterization of the wall pressure field in multi-variate statistics. Background Oriented Schlieren (BOS) flow visualizations have been performed to provide an overall characterization of the jet plume spatial evolution, identifying over-expanded and under-expanded jet flow conditions.

The paper is organized as follows: the experimental setup is reported in Sec.2 and the results are illustrated in Sec. 3. Conclusions are presented in Sec. 4.

2. Experimental setup
2.1. Facility description
A dedicated experimental campaign has been performed in the semi-anechoic chamber of the 'G. Guj' Fluid Dynamic laboratory at the University Roma Tre. The acoustically treated chamber measures 2m–high, 4m–long, 3m–wide and has wooden–insulated walls covered with sound-absorbent panels (further details are in [2, 14]). A jet with a nozzle connected to an air duct through a pressure regulator is installed in this environment. Compressed air is supplied from a 2m³ air tank at 8 bar, delivering continuous dry air that passes through an 80 mm diameter
Figure 1. A picture of the experimental setup

A plenum, equipped with mesh screens and a honeycomb. The electronically controlled regulator maintains the nozzle pressure ratio within 1% of the desired set point. We obtained supersonic flow conditions using a small contoured convergent-divergent nozzle having a choking section of 12 mm and an exhausting diameter of 12.2 mm. The nozzle theoretical design condition is at around $M=1.2$, with $NPR=2.4$. Measurements were performed by varying the nozzle pressure ratio from $NPR=2.2$ up to $NPR=2.6$ by step of 0.1, allowing us to explore different flow conditions: design, under-expanded, and over-expanded. A 3D printed NACA4415 [11] wing profile, having a 60 mm chord and a 150 mm span, was installed at two different radial locations from the jet centreline, specifically, $H/D=0.6$ and $H/D=0.75$, where $H$ is the vertical distance measured from the wing trailing and $D$ is the nozzle exhaust diameter. The wing has been made using polylactic acid (PLA) with the printer of the laboratory G.Guj, fig. 1.

2.2. Wall pressure measurements

The wall-pressure fluctuations are resolved using a pair of miniaturized pressure transducers (Kulite–Mic190M) installed in a series of holes manufactured into the wing pressure side. They have a sensing diameter that fits the wall-pressure taps and a frequency response up to 100 kHz, the unused holes were covered with tape to avoid any vortex shedding effect and cavity resonance. Data were acquired by setting the cut-off filter of the Kulite signal conditioner at 70 kHz and the sampling frequency at 200 kHz, accordingly with the Nyquist—Shannon theorem. Measurements were performed exploring different stream-wise positions from $x/D=-0.67$ up to $x/D=3.33$. A picture of the experimental setup is reported in fig 1.

2.3. Flow visualization setup

Flow visualizations were performed by applying the BOS technique to provide an overall qualitative description of the flow behaviour in over-expanded and under-expanded regimes. Generally, the BOS technique is based on a background distortion of the reference image when recorded through a variable density field onto a detector plane. The principle is the refractive index variation due to density gradients. Two background images (dots pattern) are thus obtained: the first is through the undisturbed transfer channel and the second through the phase object of interest. Gradients in the path of the imaging rays cause the deflection of the light rays leading to shifts in the reference image recorded. This displacement provides information about the phase object. In this test campaign, a structured background has been
created in MATLAB ambient 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 CCD camera involved in the measurements is a LaVision SX 4M with a resolution of 2360x1776 pixels and a Nikon AF Nikkor lens characterized by a focal length of 50 mm. The recording frequency has been set at 10 Hz. The pattern has been uniformly back-illuminated by a white LED light pad, and the recorded dots have a dimension of about 2 pixels. To determine the background image displacements a particle image velocimetry (PIV) cross-correlation algorithm has been applied using the software Davis LaVision. The interrogation window has been set at a constant size corresponding to 16x16 pixels with a 50% overlap. The acquisition system has been previously used and described in detail in [12,15]. Tests have been performed placing the camera and the back-illuminated pattern at the same distance from the nozzle axis as shown in fig 2. The frame of reference is also reported in the same figure.

For each case, 50 images were acquired and ensemble-averaged, providing a mean pixel displacement on a grey-scale representing the dimension proportional to mean density gradient fields integrated over the line of sight. It has been checked that the related standard deviation ensured sufficient statistical accuracy for estimating the mean values.

3. Results
3.1. Flow visualization
Flow visualizations obtained with the BOS technique provide an overall estimation of the flow behaviour in over-expanded and under-expanded flow regimes focusing on the shock cell train. Fig. 3 illustrates the results obtained in over-expanded (3a) and under-expanded (3b) condition. The figures show the trend of the axial component of the displacement vector, which better reveals the shock cell characteristics.

According to the literature, [16] it is observed that the cell pattern is significantly modified when moving from over-expanded to under-expanded conditions. The shock cell train exhibits an increasingly pronounced shape, and intensity as the NPR is raised. In addition, the length of the shock cells changes and increases when the pressure ratio is incremented [17]. As expected, this length variation is strongly related to the structure of the shock wave reflection. In the over-expanded regime, the reflected shock wave does not produce an equal deflection, and the subsequent shock occurs in a closer position than in the under-expanded case [18]. For the two
different flow regimes, fig. 4 shows the pixel displacement trends along the jet axis ($y/D = 0$) normalised with respect to the mean value of the under-expanded condition.

The oscillations representative of the two flow regimes are clearly visible providing the possibility of a direct computation of the shock cell length ($L_{sc}$) as the distance between each maximum and the subsequent, [19]. The comparison between the two trends confirms that, as the pressure ratio increases, the shape of the shocks changes and the distance between one and the other is incremented.

3.2. Wall pressure fluctuations

A global picture of the wall pressure fluctuation intensity over the pressure side for the two different radial positions of the wing has been given by the Overall Sound Pressure Level (OASPL), evaluated according to the following definition:

$$OASPL = 10 \log_{10} \left( \frac{\sigma_p^2}{P_{ref}} \right),$$

where $\sigma_p$ is the standard deviation of the pressure signal ($p$) and $P_{ref}$ is the reference pressure equal to $20\mu Pa$. The OASPL trends for the different configurations are reported in Figure 5.

As observed in fig. 5 (a) and (b), the variation of the NPR slightly influences the OASPL magnitude without having any particular effect on its axial trend. The trends agree with the literature [6,11] showing a quick OASPL increase with the $x/D$ that we ascribe to the starting
of jet flow grazing over the wing. We observed different OASPL trends between the two jet-wing radial distances, which we related to both the higher flow development over the surface and the elevated wing intrusiveness at H/D=0.6.

The span-wise axial evolution at the trailing edge of the wall pressure field has been reported in fig. 5 (c) and (d). Also, in this case, the NPR does not influence OASPL trends due to its slight variation. However, different OASPL trends are observed between the two wing radial positions due to a more pronounced jet plume distortion with the wing at H/D=0.6, which enlarges in y-direction the lower jet shear layer [11]. In both cases, the OASPL decay has been observed towards higher y/D due to the less jet wing grazing that reduces the dominating of the hydrodynamic field over the pressure transducers.

The wall pressure fluctuations were analyzed in the frequency domain using the Sound
Pressure Spectrum Level (SPSL) evaluated, using the following equation:

\[ SPSL = 10 \log_{10} \left( \frac{PSD \Delta f}{P_{ref}^2} \right), \]  

(2)

PSD is the power spectral density computed using the Welch method and \( \Delta f = 1 \text{Hz} \) is the frequency bandwidth. The SPSL is plotted versus the Strouhal number, defined as follows:

\[ St = \frac{fD}{U_j}, \]  

(3)

where \( U_j \) is the jet exit velocity. As reported in fig. 6, different spectra behaviour were observed according to the wall pressure transducers locations. At this wing location, the jet interacts with the wing from the first axial location inducing the spectra trend observed in fig. 6. A slight presence of Screech tones has been observed for the higher jet NPRs at \( H/D=0.75 \) fig. 6(b) which seems to disappear at \( H/D=0.6 \) fig. 6(a). This suggests that the small relative jet wing distance disrupt the feedback loop connected to the Screech. Moving the pressure transducers towards the trailing edge, we observed an increase in energy at the lower frequency caused by the jet flow grazing over the wing pressure side (see fig. 6(c) and (d)). Furthermore, a series of very energetic tones at the higher frequencies were observed with the wing located at \( H/D=0.6 \) at all the NPRs, probably ascribed to the jet trailing edge interaction tones. We hypothesize that these tones are generated by the interaction between the vortex structures of the jet lower shear layer with the wing trailing edge, which, as expected, is more intense at \( H/D=0.6 \). However, further investigations that include unsteady velocity measurements are needed to clarify it.

Fig. 6(e) and (f) reports wall pressure spectra in the spanwise direction at \( x/D=3.33 \) (closest to the trailing edge) and \( y/D=1.33 \), thus in position with low hydrodynamic effects. BBSAN and Screech were well observed at these locations, especially at the higher NPRs (2.5 and 2.6) having the jet under-expanded. The impact of the NPR variation is also here not very evident at the lower frequencies and seems located only in a well-defined, probably acoustic, frequency region included between \( St=0.4 \) and \( St=0.8 \). Higher NPRs move Screech and BBSAN to the lower frequencies, increasing their energy content. The lower jet development over the wing trailing at \( H/D=0.75 \) makes clearer the traces of Screech and BBSAN. A small signature of higher frequency tones, previously observed in the streamwise direction and probably ascribed to the jet-trailing edge interaction, was observed as expected only \( H/D=0.6 \).

Finally, comparisons in terms of wall pressure fluctuations between results previously obtained using an infinite flat plate [13] were reported in fig. 7 for two different NPRs.

The main difference between the two configurations is the energy content increase observed at \( St>0.4 \) in the jet-wing configuration at both NPRs. At the NPR=2.5, fig. 7(b), the Screech is not observed with the wing presence. This effect looks intriguing and could be ascribed to the trailing edge or differences in material (i.e. PLA for the wing and alloy for the flat plate). However, to clarify this effect, further investigations are needed.

4. Conclusions
An experimental investigation detailing the wall pressure field induced by a supersonic nozzle over the wing pressure side has been presented. The experimental set-up consisted of a convergent-divergent nozzle installed in the anechoic jet facility of the FLuid Dynamic laboratory ‘G. Guj’ at the Roma Tre University. The jet was installed adjacent to a NACA4415 profile aerofoil wing generated with a 3D printer. Measurements were performed at different flow regimes considering under-expanded and over-expanded flow conditions and by varying the radial position of the wing. Wall pressure fluctuations were acquired both in stream-wise and span-wise direction at the wing TE and by using flush-mounted pressure transducers. A qualitative
Figure 6. SPL at various axial locations: a) H/D=0.6 y/D=0 and x/D=1.33; b) H/D=0.75 y/D=0 and x/D=1.33; c) H/D=0.6 y/D=0 and x/D=3.33; d) H/D=0.75 y/D=0 and x/D=3.33; e) H/D=0.6 y/D=1.33 and x/D=3.33; f) H/D=0.75 y/D=1.33 and x/D=3.33;
description of the jet flow fields has been carried out using the BOS technique, which provided a visualization of the shock cells and highlighted the different behaviours typical of the over-expanded under-expanded conditions. A global picture of the fluctuating wall pressure, in both stream-wise and span-wise direction, has been achieved using the OASPL, whose trends are significantly influenced by the different radial locations of the wing and slightly influenced by the different NPRs. The frequency-domain analysis performed in terms of SPL highlights different spectral trends according to the Kulite location, both in span-wise and stream-wise directions. The radial position of the wing influences the shape of the spectra, inducing an increase of the energy content at the higher frequencies. This has been ascribed to the anticipated flow development over the wing pressure side. A preliminary comparison between results obtained using a flat plate has been reported highlighting interesting effects mainly located at the high frequencies range.

References

[1] Di Marco A, Mancinelli M and Camussi R 2015 Pressure and velocity measurements of an incompressible moderate Reynolds number jet interacting with a tangential flat plate Journal of Fluid Mechanics vol 770 (Cambridge University Press) p 247–272
[2] Meloni S, Di Marco A, Mancinelli M and Camussi R 2019 Wall pressure fluctuations induced by a compressible jet flow over a flat plate at different Mach numbers Exp. in Fluids vol 60, 48–60
[3] Meloni S, Di Marco A, Mancinelli M and Camussi R 2020 Experimental investigation of jet-induced wall pressure fluctuations over a tangential flat plate at two Reynolds numbers Scientific Reports vol 10 (Nature Publishing Group)
[4] Finnveden S, Birgersson F, Ross U and Kremer T 2005 A model of wall pressure correlation for prediction of turbulence-induced vibration Journal of Fluids and Structures vol 20 pp 1127–1143 ISSN 0889-9746 URL https://www.sciencedirect.com/science/article/pii/S0889974605000885
[5] Corcos G M 1964 The structure of the turbulent pressure field in boundary-layer flows Journal of Fluid Mechanics vol 18 (Cambridge University Press) p 353–378
[6] Meloni S, Lawrence J L, Proença A R, Self R H and Camussi R Wall pressure fluctuations induced by a single stream jet over a semi-finite plate International Journal of Aeroacoustics vol 0
[7] Jordan P, Jaumet V, Towne A, Cavalieri A V G, Colonius T, Schmidt O and Agarwal A 2018 Jet–flap interaction tones Journal of Fluid Mechanics vol 853 (Cambridge University Press) p 333–358
[8] Cavalieri A V, Jordan P, Wolf W R and Gervais Y 2014 Scattering of wavepackets by a flat plate in the vicinity of a turbulent jet Journal of Sound and Vibration vol 333 pp 6516 – 6531
[9] Lawrence J, Azarpeyvand M and Self R 2011 Interaction between a flat plate and a circular subsonic jet 17th AIAA/CEAS Aeroacoustics Conference (32nd AIAA Aeroacoustics Conference)

[10] Meloni S, Mancinelli M, Camussi R and Huber J 2020 Wall-pressure fluctuations induced by a compressible jet in installed configuration AIAA Journal vol 58 pp 2991–3000

[11] Meloni S, Proença A R, Lawrence J L and Camussi R 2021 An experimental investigation into model-scale installed jet–pylon–wing noise Journal of Fluid Mechanics vol 929 (Cambridge University Press) p A4

[12] Camussi R, Ahmad M K, Meloni S, de Paola E and Di Marco A 2022 Experimental analysis of an under-expanded jet interacting with a tangential flat plate: Flow visualizations and wall pressure statistics Experimental Thermal and Fluid Science pp 110–474 ISSN 0894-1777 URL https://www.sciencedirect.com/science/article/pii/S089417772101217

[13] Meloni S, Camussi R, Prestianni M, de Paola E and Biondo F 2021 An experimental investigation on the unsteady pressure field induced by an installed jet in supersonic flow conditions AIAA AVIATION 2021 FORUM

[14] Meloni S, Di Marco A, de Paola E, Camussi R and Fava G 2019 Pressure and velocity measurements of a compressible jet interacting with a flat plate Progress in Turbulence VIII (Springer International Publishing) pp 271–276 ISBN 978-3-030-22196-6

[15] De Paola E, Di Marco A, Meloni S and Camussi R 2019 Density measurements of a compressible jet flow interacting with a tangential flat plate using background-oriented schlieren Progress in Turbulence VIII (Springer International Publishing, 185–190)

[16] Arun Kumar R and Rajesh G 2017 Shock transformation and hysteresis in underexpanded confined jets Journal of Fluid Mechanics vol 823 (Cambridge University Press) p 538–561

[17] André B, Castelain T and Bailly C 2013 Broadband shock-associated noise in screeching and non-screeching underexpanded supersonic jets AIAA Journal vol 51 pp 665–673 URL https://doi.org/10.2514/1.J052058

[18] Matsuo S, Setoguchi T, Nagao J, Alam M and Kim H 2011 Experimental study on hysteresis phenomena of shock wave structure in an over-expanded axisymmetric jet Journal of Mechanical Science and Technology vol 25 pp 2559–2565

[19] Mercier B, Castelain T and Bailly C 2017 Experimental characterisation of the screech feedback loop in underexpanded round jets J. Fluid Mech. vol 824, 202–229