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EXPERIMENTAL STUDY ON THE AERODYNAMICS OF A HIGH SUBSONIC JET INTERACTING WITH A FLAT PLATE

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Abstract. *Understanding the turbulent structures and noise source mechanisms resulting from the interaction between the exhausted jet with wing and high-lift devices is essential for both aerodynamic efficiency and noise reduction of the modern aircraft. This work presents an experimental investigation of the mean velocity and turbulence intensity (TI) profiles from an isolated jet and a jet installed beneath a flat plate. Both campaigns are performed in static ambient flow condition and at low and high subsonic velocity. A hot-wire anemometer was used to evaluate the mean velocity and TI for radial and axial profiles. From analysis of the mean velocity, it is evident that a Coandă effect exists in the installed jet case downstream of the trailing edge of the flat plate. The jet is seen to bend towards the plate. A comparison between isolated and installed configurations shows that the presence of the plate also serves to convect the jet asymmetrically downstream (similar to an ejector). Values of mean TI are lower along the shielded lip-line (closest to the plate) than along the unshielded lip-line. Directly after the trailing edge, there is an increase in TI. This fact supports the theory that an additional turbulent structure or wake is created.*

Keywords: *installed jet, subsonic jet, aerodynamics, turbulence intensity, hot-wire*

1. INTRODUCTION

In modern under-wing-mounted high-bypass engines, the nacelle diameter is ever increasing. The engine, thus, must be attached closer to the wing in order to maintain the same ground clearance. Therefore, the exhausted jet interacts strongly with the wing and high-lift devices. The presence of a lifting surface can deflect and modify the jet, changing the mixing noise sources. Additionally, new acoustic sources are created due to interactions between the jet and the trailing edge of the wing or flap. When the noise produced by an installed jet is compared to that generated by the isolated jet, the former can dominate at some frequencies.

Currently, extensive work towards the development of appropriate engineering models is being undertaken at the ISVR. This paper presents a survey of mean and unsteady velocity behavior for a cold, circular, static, subsonic jet installed under a flat plate in four different positions. The main objective is to study the turbulence intensity distribution along the jet and the flat plate, highlighting any changes to the development of the jet. The analysis and data collected will be used in a semi-empirical method being developed to predict jet noise from both isolated and installed jet configurations (Vera et al., 2015).

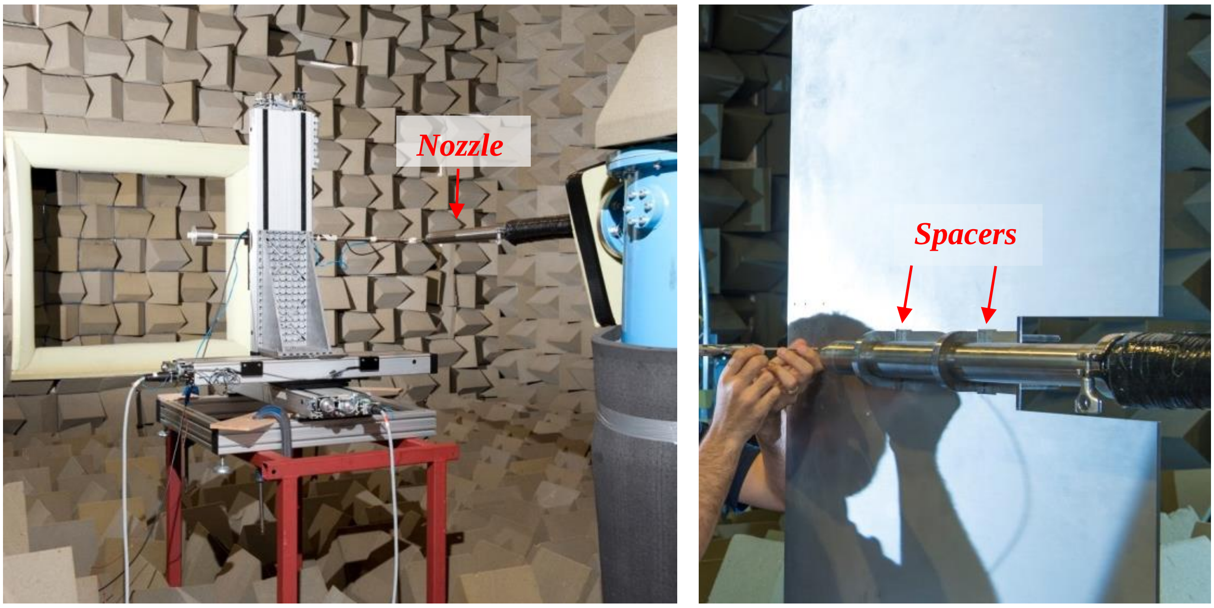
For an isolated, single stream, subsonic jet, most of the noise comes from the shear layer between the jet and the ambient flow. Velocity and correlation measurements using hot-wire anemometry can be used to study the aerodynamic properties of the noise sources (Harper-Bourne, 2013; Morris and Zaman, 2010). In the presence of a solid surface, the jet can bend towards, or away from the surface, depending on the ambient flow conditions and lift forces involved. Intuitively, the closer the surface is to the jet, the greater the Coandă effect will be for a static jet (Lawrence, 2014). Understanding the nuances of the physics associated with turbulence is essential for modelling installed jet noise generation (Lawrence et al., 2011).

This paper is structured as follows. The next section describes the experimental campaign conducted in the ISVR's Doak Laboratory, detailing the hardware used and the test matrix. The first results discussed are the centre-line and lip-line turbulence intensity profiles, which are presented for jet acoustic Mach numbers 0.30 and 0.60. The analysis then shows the radial profiles, initially presenting the mean velocity profiles acquired for isolated and installed jets for plate positions h/D = 0.67 and l/D = 4.00. Radial turbulence intensity (TI) profiles are also shown to evaluate what happens just upstream and downstream of the plate trailing edge (TE). The velocity dependence of the TI is then evaluated for jet acoustic Mach numbers 0.30, 0.50, 0.60, and 0.75.

2. METHODOLOGY

2.1 Facility and test apparatus

The ISVR Doak laboratory is a small-scale anechoic chamber fully anechoic down to a frequency of 400 Hz. The facility has dimensions of approximately 15 m long by 7 m wide by 5 m high. A non-forced exhaust system is composed of a rectangular collector section allowing air to pass through into a small secondary acoustic chamber. Single stream jet measurements can be performed for flow regimes characteristic of civil aircraft. The facility is capable of achieving an exit acoustic Mach number range between 0.2 and 1. The nozzle used in this work is a $1/50^{th}$ scale 38.1 mm diameter, convergent, conical nozzle, which is a scaled version of the 86.1 mm QinetiQ nozzle commissioned in 2008 (Harper-Bourne, 2008).



(a) (b)

Figure 1. ISVR's Doak Laboratory; (a) isolated jet aerodynamic setup and (b) flat plate installed jet aerodynamic setup

In order to perform aerodynamic measurements, the chamber was equipped with an ISEL traverse system next to the nozzle exit. The traverse allowed movement in each of the x, y and z axes independently.

A 6.4 mm thick aluminium flat plate was attached to the 50.8 mm diameter jet pipe with an adjustable clamp to achieve the required values for '*l*'. Spacers were then used to separate the plate from the pipe work to the necessary values of '*h*'. The height or span of the plate extended 20 diameters either side of the jet centre-line to prevent any aeroacoustic edge noise generation. In addition, two additional strips of aluminium were welded onto the back of the plate along the span in order to prevent any deflection. When measurements close to the plate are presented, it is referred as shielded side or upper shear layer. Whilst for free region, the nomenclature used is unshielded or lower shear layer.

The nominal exit velocity is calculated from a pressure ratio between the upstream pressure in the jet plenum and the atmospheric pressure in the chamber. The exhausted jet is then controlled by an algorithm written in Labview. This flow control code monitors the pressure variation resulting from the 'compressor regime-reservoir pressure drop' behaviour and changes the valve opening accordingly to keep the velocity within ±3 m/s. The period of the variation is velocity-dependent. The shortest period is around 100 s at $M = 0.75$. Corrections applied to the data due to the rig velocity variation are discussed in section 2.3.

2.2 Experimental procedure and instrumentation

The test matrix was divided into axial and radial measurements. The axial profiles were measured at the centre-line and lip-line, from the nozzle exit to 10 nozzle diameters downstream of the jet at one diameter intervals. For the centre-line profiles, axial positions x/D = 4.25,4.5, and 4.75 were also measured in order to estimate the end of the potential core.

The distribution of x/D positions for radial profiles are function of the plate trailing edge location. The points measured were chosen to match with the TE position, and also at half-diameter upstream and downstream the TE. Therefore, for the closest (h/D = 0.67), longest (l/D = 4.00) plate configuration, the location of the main radial profiles studied in the present work are x/D = 0, 3.50, 4.00 and 4.50. Additionally, all positions were measured at Mach numbers 0.30, 0.50, 0.60 and 0.75.

A 5 µm diameter, 1.25 mm long plated tungsten miniature hot-wire probe was used in the present work. The single-sensor was controlled by a Constant Temperature Anemometry (CTA) system. The probe was calibrated using a

DANTEC StreamLine Pro Automatic Calibrator over the range of velocities of interest and the calibration coefficients were extracted from a 4th order polynomial curve fit. A thermometer was positioned close to the hot-wire probe to perform the temperature correction. The software Streamware Pro was used to acquire data automatically at the grid points specified. A sampling rate of 20 kHz was used for each 15 seconds measurement acquisition.

In order to validate the hot-wire measurements, a Pitot tube was used to measure the mean velocity profiles. The data from both sensors matched well for all jet-plate configurations and flow velocities analyzed.

2.3 Data normalisation and data correction

As stated before, the velocity profile data must be corrected for a flow variation imposed by the air supply system cycle. As the jet exhausts from the nozzle, the pressure at the tank storage decreases. Then, the compressor pumps the tank up to the nominal pressure, and so forth.

The rig or nominal velocity was measured through a transducer located upstream of the nozzle exit. This sensor was carefully mounted on the roof of the plenum and it measures the stagnation pressure of the flow. The nominal velocity is calculated from the isentropic flow relations, as shown in Eq. (1).

$$U_n = M\sqrt{\gamma R T_j} \tag{1}$$

The aerodynamic Mach number, M, is calculated from the pressure ratio measured in the plenum. The jet temperature, T_j, is measured inside the pipe also upstream the nozzle exit. The heat capacity ratio, γ, is assumed to be 1.4 for the conditions measured, and R is the specific gas constant.

The aerodynamic Mach number is used as a reference to control the flow velocity, and the nominal velocity is applied to correct the data due to the flow variation. Therefore, the nominal velocity measured in the plenum is recorded simultaneously to the jet velocity acquired by the hot-wire. Then, a correction factor can be taken by normalizing the jet velocity U_j by the nominal velocity.

$$U_c = \frac{U_j}{U_n} \tag{2}$$

The correction factor or normalized velocity U_c is presented in few results in which it is possible to see a pressure loss between the plenum and the nozzle exit that will be discussed later. The mean jet velocity is calculated taking into account the rig velocity variation as shown in Eq. (3). It is essentially the jet velocity measured multiplied by the correction factor accounting the flow variation discussed.

$$U_{mean} = \frac{{U_j}^2}{U_n} \tag{3}$$

Finally, the turbulence intensity can be calculated. Davies et al. (1963) showed that a convenient definition of turbulence intensity from single hot-wire data is defined as the ratio of the root-mean-square of the velocity fluctuations to the mean jet velocity.

$$TI = \frac{\overline{(u'^2)}^{1/2}}{U_{mean}} \tag{4}$$

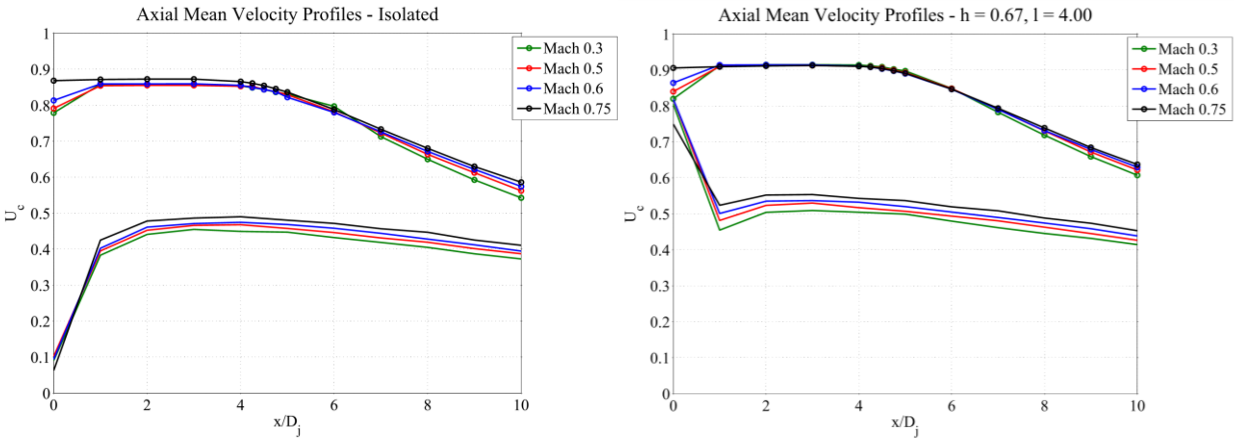
3. RESULTS

3.1 Centre-line and lip-line mean velocity and TI profiles

In this section, results acquired for velocity profiles axial to the plate are discussed. Firstly, the trends for the isolated jet and a single installed jet case (h/D = 0.67, l/D = 4.00) are discussed separately. The analysis then move on to the collapse of data from different configurations.

Figure 2 shows the axial mean velocity profiles along the centre-line and lip-line for different velocities. It is possible to see well established features of the centre-line, such as the end of the potential core between 4.00 and 4.50 diameters, and the linear decay in the transitional region. A small delta between different velocities is seen in both graphs (a) and (b). A vena contracta effect for x/D < 1 is also captured for both isolated and installed configurations and it is also Mach number dependent. It is important to note that there is no information between the exit nozzle and x/D = 1. Therefore, the jet believably reaches the maximum velocity closer to the outlet of the nozzle than x/D = 1.

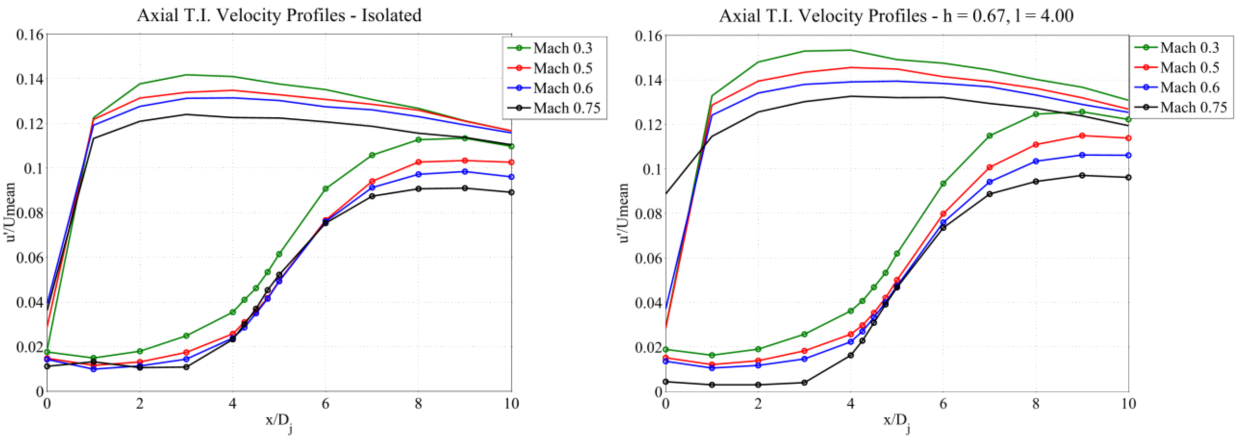
The upper lip-line trend downstream of one diameter also behaves as expected. However, at x/D = 0, isolated and installed jet cases deviate unexpectedly. Some of the following ideas may contain the reason for this deviation. There is a nozzle vibration during the isolated measurement that is not present in installed tests due to the mass of the plate. The vibration has low amplitude, but taking into account the sensor length, it could indeed affect that region measurement. Although it is possible to attach the plate without change nozzle and sensor positions, one cannot neglect a small positioning error that could lead to this difference. The lack of points measured close to the nozzle exit can also be taken into account for the lip-line study.



(a) (b)

Figure 2. Axial mean velocity profiles along the centre-line and lip-line. (a) Isolated jet; (b) Installed jet. Mach numbers 0.30, 0.50, 0.60, and 0.75. Solid-circled lines: centre-line profiles; Solid lines: lip-lines profiles.

A similar analysis can be made for turbulence intensity levels. It can be seen from Fig. 3 that there is an offset dependent on velocity, as also seen in Fig. 2. The three regions of a free jet can be identified: looking at the centre-lines, the TI is low within the potential core (up to x/D = 4), then increases in the transitional region (up to x/D = 8), and after that the turbulence is fully developed (Davies et al., 1963; Abramovich, 1963).



(a) (b)

Figure 3. Mean turbulent intensity profiles at the centre-line and lip-line. (a) Isolated; (b) Installed. Mach numbers 0.30, 0.50, 0.60, and 0.75. Solid-circled lines: centre-line profiles; Solid lines: lip-lines profiles

Axial profiles at the centre-line for different plate locations are shown in Fig. 4. The present data is also compared to Morris and Zaman (2010). It can be seen that an offset exists between both sets of data. Morris and Zaman experiment was performed for an isolated jet at Mach number 0.25. They also presented that the potential core ended between 5 and 5.5 nozzle diameters. Some recent tests performed in the ISVR has shown that the potential core length is dependent on the pipe length upstream of the nozzle exit (also shown by Brown and Wernet, 2014), boundary layer development, and nozzle contraction ratio.

Looking at axial velocity profiles, it is difficult to extract any conclusions regarding the different configurations analyzed or behavior of isolated and plate installed jets. There is no apparent trend for the TI as the plate moves towards the jet. The same graphs were produced for the higher velocities, but without success with regard to detecting a trend in TI with plate location. That was also seen by PIV measurements performed by Brown and Wernet (2014). Even along the upper lip-line, axial TI profiles do not support any clear conclusions on this matter. Figure 5 presents the lip-line profiles for all configurations studied, at Mach number 0.3 and 0.6.

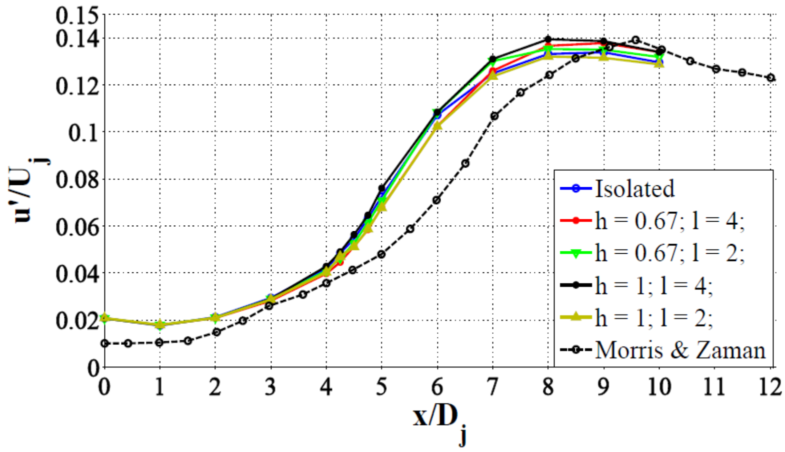
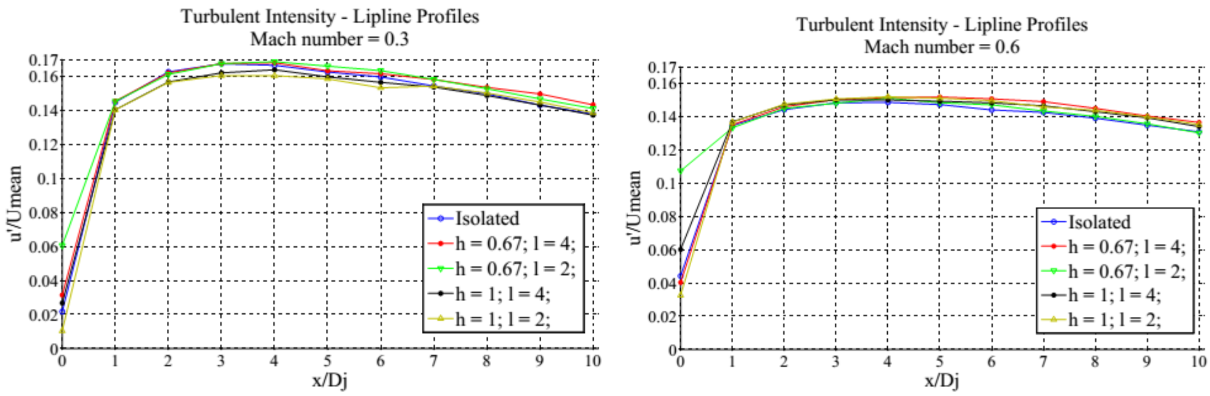


Figure 4. Turbulence intensity profiles for isolated and installed configurations (present work, M = 0.30), and Morris and Zaman (M = 0.25).



(a) (b)

Figure 5. Turbulence intensity profiles – (a) and (b) shown lip-line profiles at Mach numbers 0.3 and 0.6, respectively.

3.2 Radial profiles of mean velocity and TI

Figure 6 shows the mean velocity profile (M = 0.75) at half-diameter before, exactly at, and half-diameter after the TE. Mean velocity profiles are useful to visualise what happens to the flow downstream of the TE location. When the plate is located closest, furthest downstream the jet, it is evident that the jet bends towards the plate, what can be understand as a Coandă effect. It can be verified that the jet loses its symmetry even upstream of the TE. A small injection of momentum can be seen in the region near the trailing edge. Figure 7 shows a comparison between isolated and installed profiles, and it is confirmed that the deflection is conserved downstream the jet.

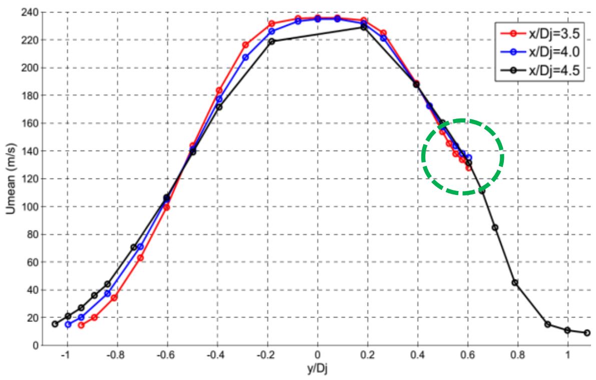


Figure 6. Mean Velocity profiles at x/D = 3.5, 4.0 and 4.5. Mach number 0.75. (Plate: h/D = 0.67, and l/D = 4.00)

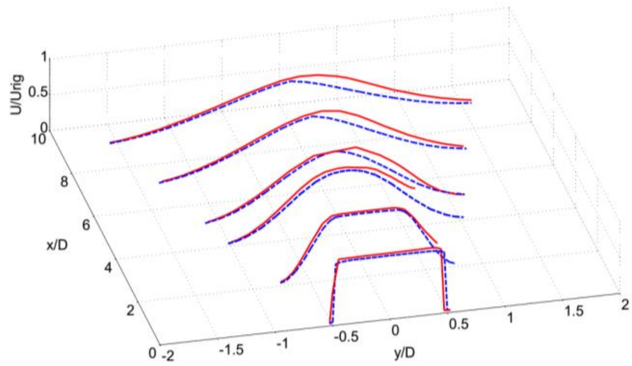


Figure 7. Mean Velocity profiles at x/D = 0, 2, 4, 5, 7, and 9 – Mach number 0.75 – Isolated (blue) and installed (red) comparison. (Plate: h/D = 0.67, and l/D = 4.00)

Additional to the Coandă effect, there seems to be a consistent acceleration of the jet towards the plate that increases as the plate moves closer to the jet. Figure 8 presents the mean velocity profile for all five configurations at *x/D* = 0, 2, 7, and 9. The normalization was performed according to the rig velocity, upstream of the nozzle exit. It explains why the maximum velocity does not peak at 1. It was later found that there was a leaking issue at the pipe connections, and the pressure loss was confirmed by Pitot tube measurements. The acoustic Mach number chosen is equal to 0.6, and the data is consistent across the entire velocity range studied. It can be seen that the entire jet is accelerated as the plate is located closer to the jet.

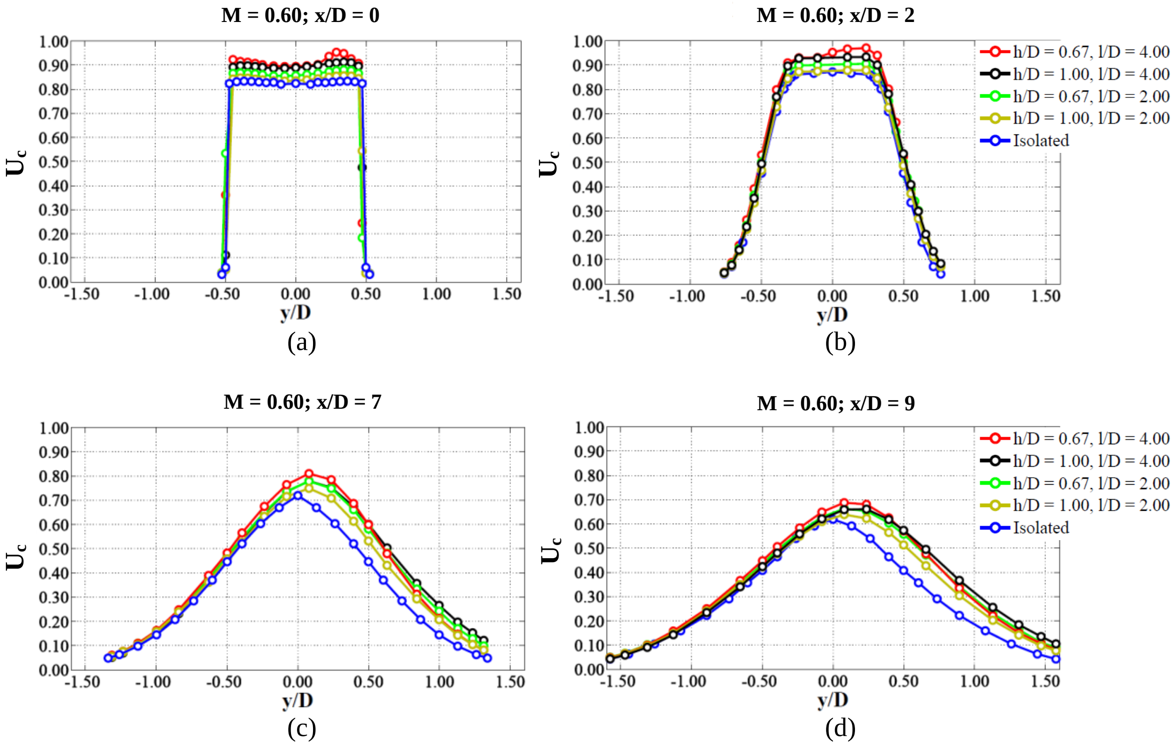


Figure 8. Radial mean velocity profiles normalised by the rig velocity at: (a) *x/D* = 0; (b) *x/D* = 2; (c) *x/D* = 7; and (d) *x/D* = 9; M_a = 0.6

Installed configurations are compared in terms of axial locations in Fig. 9 and Fig. 10. In the former, a reduction in the turbulence intensity can be seen in positions close to the plate, compared to the unshielded side. This behavior is more prominent when the plate is closer to the jet (*h/D* = 0.67, lines with a circle marker) and the plate trailing edge is located further downstream (*l/D* = 4.00), which is consistent with other recent works (Brown and Wernet, 2014; Di Marco et al., 2015).

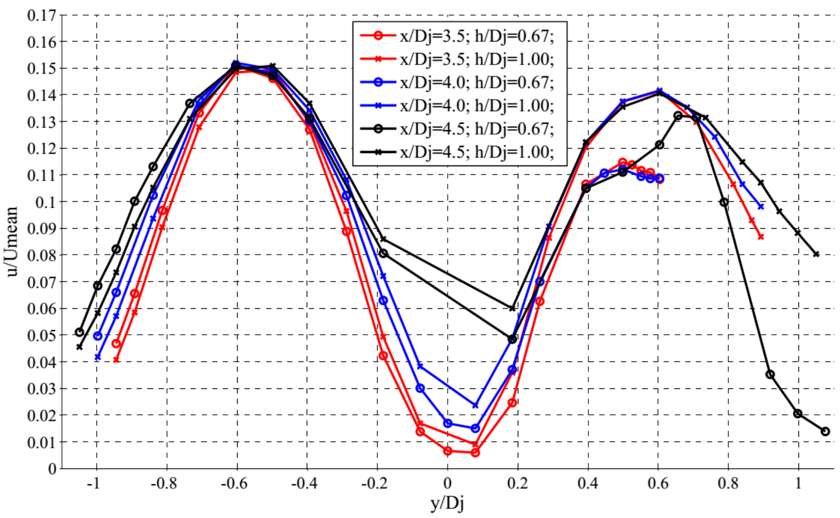


Figure 9. Turbulent intensity profile at Mach 0.75. *x/D* = 3.5, 4.0 and 4.5; *h/D* = 0.67 and 1; *l/D* = 4.00

As the analysis moves on to profiles further downstream, the jet axisymmetry seems to be partly recovered. Figure 10 shows profiles for TI at *x/D* = 5, 7, and 9, for different positions of the plate. The Mach number chosen is 0.75, and the same trend has been observed for the other velocities. At *x/D* = 5 (the red series), the delta between each peak of the profile is higher than 1%, and reduces downstream the jet. Additionally, the higher difference seen in Fig. 9 when the plate was positioned at *h/D* = 0.67, rather than *h/D* = 1, vanishes downstream and even imply to behave in the opposite way.

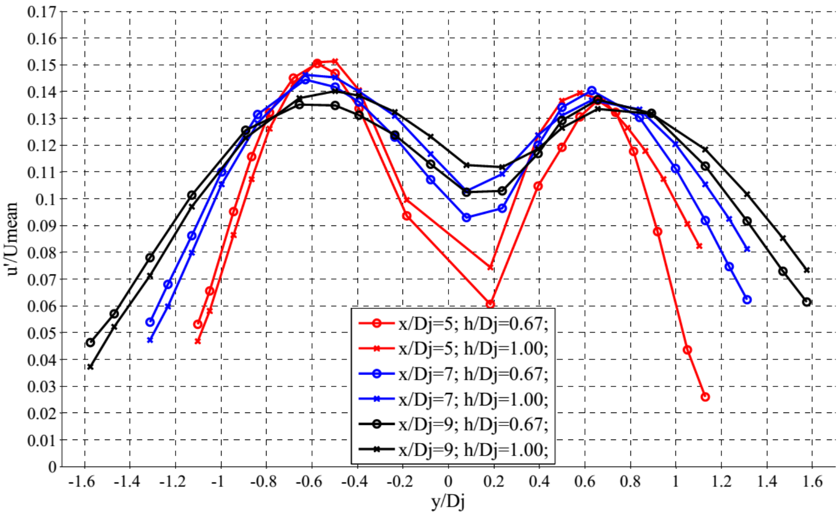


Figure 10. Turbulent intensity profile at Mach 0.75; *x/Dj* = 5, 7 and 9; *h/Dj* = 0.67 and 1.00; *l/Dj* = 4.

The presence of the plate strongly affects the entrainment on the shielded side. This fact alters the shear layer spreading, mainly on the region upstream of the TE of the plate. Additionally, the coherent large eddies developed axisymmetrically in free jets are disrupted when in contact with the plate. It is well-known that these coherent structures are the dominating components of the turbulent mixing layer and play a major role in the jet's development (Yule, 1978). The authors suspect that the changes in the entrainment and large-scale structures are responsible for the lower TI levels seen in the previous figures.

Figure 11 shows the turbulence intensity radial profile at *x/D* = 4.5 for the Mach numbers analyzed. Although the turbulence intensity seems to decrease as the Mach numbers increases between *y/D* = -0.6 to 0.6, there is a point downstream of the trailing edge that seems to be independent of jet velocity. The TI level is around 13% at the trailing edge for the Mach number range 0.3 to 0.75. The peak TI is expected to occur on the centerline of the mixing layer (Goldstein, 1996), and that can be seen at the lower shear layer furthest from the plate (at ≈ 15%). At the side closest to the plate, this peak moves to the TE radial location after the end of the plate (apart at Mach 0.30). In that region, the constrained jet can first mix freely with the ambient air, what explains the sudden increase in TI levels.

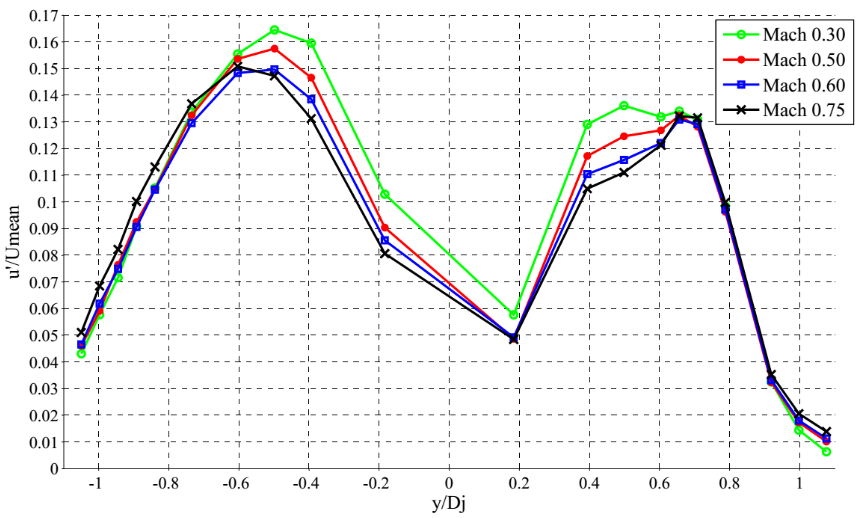


Figure 11. Turbulent intensity profile at *x/D* = 4.5; *h/D* = 0.67; *l/D* = 4; Mach numbers 0.30, 0.50, 0.60, and 0.75

4. CONCLUSIONS

The present work has shown an extensive hot-wire investigation in a jet installed beneath a flat plate. The main objective is to get a better understanding of the physics related to this problem in order to model the aerodynamic behavior of the flow and, thus, the noise produced due to the interaction of the jet's hydrodynamic field with a wing/flap trailing edge.

Mean velocity and turbulence intensity profiles were analyzed for a range of Mach numbers and plate locations. Results shown that the presence of the plate close to the jet bends the flow towards the plate. This is understood as a Coandă effect, and it is maintained consistently downstream the TE of the plate. From comparisons of mean velocity profiles from isolated and installed jet configurations, it can be seen that the plate also serves to convect the jet asymmetrically downstream. This effect is seen to increase as the plate is positioned closer to the jet. Finally, the turbulence intensity profiles shows that at least the streamwise component of the unsteady velocity is lower on the shear layer close to the plate. It happens not only at the wetted region, but also close to the nozzle exit and to distances downstream as far as seven nozzle diameters. For the closest plate case (h/D = 0.67, l/D = 4.00), there is a sudden increase in TI levels right after the trailing edge. This increase appears to be velocity independent. This fact supports the theory that an additional turbulence structure or wake is created.

Next steps concerning this work is to evaluate the spectra content of the studied cases. Frequency information about isolated and installed jets will be compared. This spectrum shape will also be collapsed to data from surface pressure transducers installed along the plate. Finally, a database will be created to supply semi-empirical methods being currently developed to predict installed jet noise.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Abramovich, G. N., 1963. "The Theory of Turbulent Jets", The MIT Press Classics.
Brown, C., and Wernet, M., 2014. "Jet-Surface Interaction Test: Flow Measurements Results", 20th AIAA/CEAS Aeroacoustics Conference, Atlanta, GA; United States.
Davies, P. O. A. L., Fisher, M. J., and Barratt, M. J., 1963. "The characteristics of the turbulence in the mixing region of a round jet", Journal of Fluid Mechanics, vol. 15, issue 03, pp 337 - 367.
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, pp. 247–272.
Goldstein, M. E., 1996. "Aeroacoustics", McGraw-Hill, New York.
Harper-Bourne, M., 2003. "Jet Noise Turbulence Measurements", 9th AIAA/CEAS Aeroacoustics Conference and Exhibit 12-14 May.
Harper-Bourne, M., 2008. "Commissioning and Validation of New Jet Rig for the QinetiQ Noise Test Facility", 14th AIAA/CEAS Aeroacoustics Conference, Vancouver, 5-7 May, AIAA-2008-2958.
Lawrence, J. L. T., 2014. "Aeroacoustic Interactions of Installed Subsonic Jets", Eng.D. Thesis, Faculty of Engineering and the Environment, Institute of Sound and Vibration Research, Univ. of Southampton, Southampton.
Lawrence, J. L. T., 2011. Azarpeyvand, M., and Self, R. H., "Interaction between a Flat Plate and a Circular Subsonic Jet", 17th AIAA/CEAS Aeroacoustics Conference, Portland, Oregan, USA, 5-8 June, AIAA-2011-2745.
Morris, P. J., and Zaman, K.B.M.Q., 2010. "Velocity Measurements in Jets with Application to Noise Source Modeling", Journal of Sound and Vibration, 329, pp. 394–414.
Vera, J., Kingan, M., and Self, R. H., 2015. "The Prediction of the Radiated Pressure Spectrum Produced by Jet-Wing Interaction", 21st AIAA/CEAS Aeroacoustics Conference.
Yule, A. J., 1978. "Large-scale structure in the mixing layer of a round jet", Journal of Fluid Mechanics, vol. 89, part 3, pp. 413-432.

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