EXPERIMENTAL INVESTIGATION OF TURBULENT FLOW FIELD ASSOCIATED WITH ROUND AND CHEVRON NOZZLES

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Abstract. *The turbulent jet is one the main sources of noise in aircrafts. In spite of decades of research, this problem remains a challenging topic in aeroacoustics while the mechanisms of sound generation are not yet fully understood. Modelling of the generation and propagation of sound in a jet generally requires knowledge of turbulence statistics that are not trivially measured, in addition to the mean-velocity field. This paper presents hot-wire measurements of the flow field of a cold, subsonic jet. A comparison is made between the flows generated by two nozzle geometries: a circular and a chevron nozzle. Several jet properties are assessed, such as potential core length, turbulence profiles and one-point two-time velocity correlations. The purpose of these measurements is to study the modifications in the flow field brought about by the chevron nozzle which could be related to modifications in the acoustic field and the noise spectrum.*

Keywords*: Turbulent jet, chevron nozzle, aeroacoustics.*

1. INTRODUCTION

Aircraft-generated noise is a major concern in the aviation industry because of the environmental problems associated with it and the strict regulations that limit noise emission by aircrafts. Massive investments in research have been made over the last decades in order to better understand aeroacoustic generation and propagation of sound. One of the dominant sources of noise in the aircraft is the jet from the engines, especially during take-off and landing. As a result, attempts have been made to develop new technologies to reduce jet noise.

Tabs and chevron nozzles are two concepts of devices with known beneficial effects in the noise spectrum. They consist of protrusions in the nozzle geometry that modify the flow-field characteristics. Saiyed et al., (2000) carried out an extensive study to evaluate several nozzle designs and their impact on noise and thrust of turbofan engines. Chevron nozzles have shown better results than those of tabbed nozzles regarding noise reduction, blockage effects and thrust penalties. Bridges and Brown (2004) have also extensively investigated the effects of chevron nozzles by evaluating the influence of geometric parameters on the flow and acoustic fields. Among their findings, vorticity was severely increased by the chevron, especially in high-penetration designs. As a result, the shear layer growth rate is increased and the jet decays more rapidly. This causes noise to shift from lower to higher frequencies in the spectrum. This trend in the vorticity field was also observed by Violato and Scarano (2011), who found that the axisymmetric ring-like coherence of circular jets is replaced by streamwise flow structures of azimuthal and radial vorticity in jets emerging from a chevron nozzle.

The mechanisms of noise reduction associated with these changes in the flow field were discussed by Callendar et. al., (2010), who performed PIV measurements of jets with four different nozzle geometries. They observed that the chevrons increased the mixing in the shear layer, which leads to a greater rate of decay of the core and a reduction in the potential core. By reducing the spatial extent where the jet velocity remains at or near the exit velocity, the chevrons provide acoustic reductions near the range of the peak jet noise frequency. According to their study, this effect is most effective at the aft angles and lower frequencies.

Jet noise prediction methods based on acoustic analogies require models for turbulence statistics. Several studies on jet turbulence have been reported. Davies et al., (1963) made space-time measurements of cold, low-speed jets, deriving length and timescales from their measurements. Bradshaw et. al., (1963) expanded the scope, documenting the spatial correlations for all six components of the correlation matrix with three-dimensional displacements. More recently, Bridges and Wernet (2010) have developed a consensus dataset of flow quantities for a range of hot jet flows using Particle Image Velocimetry (PIV), including uncertainty bands. Their goal was to create a catalog of turbulent jet flows, allowing their results to be compared to other measurement techniques. Other than PIV, hot-wire anemometry (HWA) has also been widely used to experimentally investigate jet flows. HWA can provide single point measurements at high sampling rates, enabling spectral analysis of the turbulent flow. On the other hand, PIV is capable of measuring large regions of the unsteady flow field in sequential frames, albeit at a lower frequency than typically capable for other measurement techniques such as HWA (Wernet, 2007).

Morris and Zaman (2010) have adopted one and two-dimensional HWA probes to obtain statistical properties relevant to prediction of jet noise. They modeled the source terms in Lilley's and Goldstein's acoustic analogies as second-order and fourth-order two-point correlations, respectively. They determined the length scales based on the overall spatial correlations as well as the variation of the length scales with Strouhal number at different locations in the jet. It was observed that the statistical properties are very similar in the regions of highest turbulent velocity fluctuations. The authors believe this to be quite encouraging given that statistical models used in noise source modelling are usually assumed to have similar forms in all locations in the jet.

The present work is part of a research project with the goal of studying jet noise and reports HWA measurements acquired in an experimental setup developed to investigate the underlying turbulence mechanisms responsible for the acoustic modifications introduced by chevrons. Additionally, the work has also the objective of providing data to support the validation of new prediction models. Mean velocity profiles were measured at different locations in order to identify differences in the velocity and turbulence fields caused by a chevron nozzle (SMC006) in comparison to a baseline nozzle (SMC000), without chevronsAxial turbulence intensity and spectra of turbulent kinetic energy were also measured. These statistics are useful to obtain insight about the flow field structure and for inputs in acoustic analogies. The Mach and Reynolds numbers of the experiments are 0.3 and 125 000, respectively.

2. EXPERIMENTAL SETUP

2.1 Experimental Setup

The jet rig used in this work was developed as part of a similar study with chevron nozzles carried out by Froening et. al., (2013). The present study extends the previous Mach range. The rig provides a single, unheated, steady jet which is fed by an air supply system composed of two compressors with 566 l/min and 1640 l/min of capacity and 8 bar of pressure, an air dehumidifier and three 500 l storage tanks. In order to control the Mach number, three valves for flow rate control, a turbine flow meter and pressure and temperature transducers were used. An illustration of the jet rig is shown in Fig. 1.

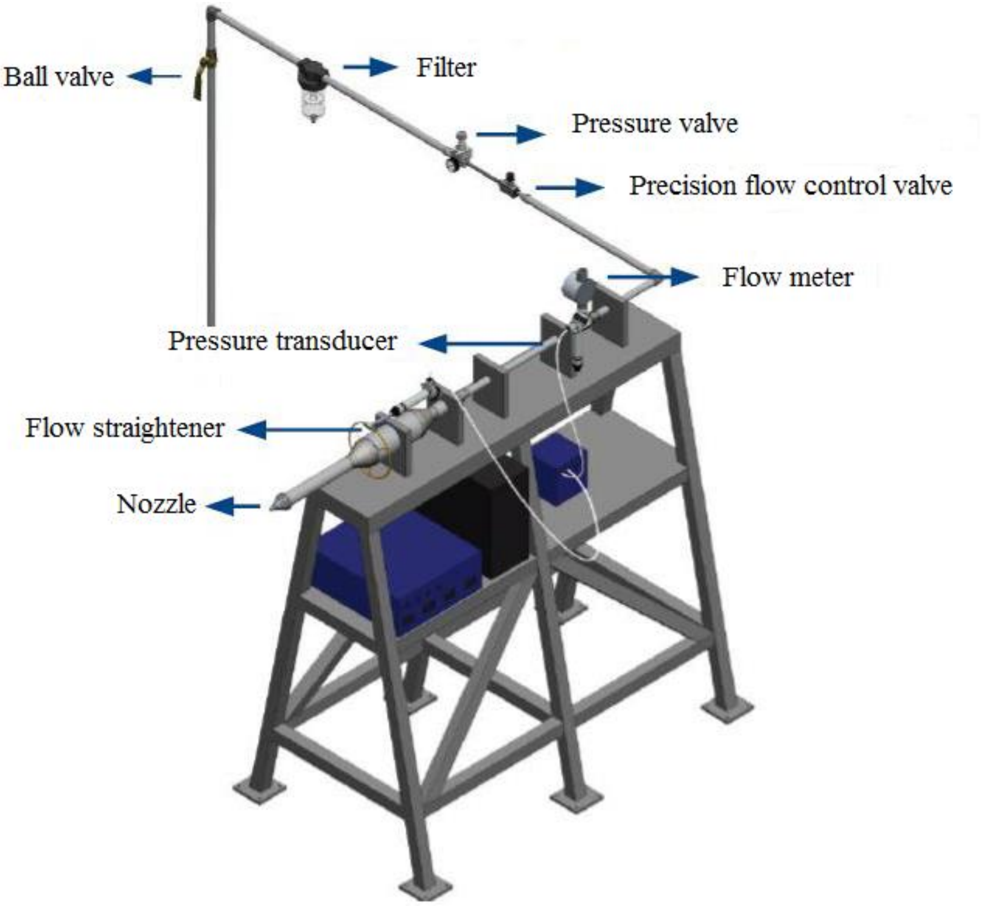


Figure 1. Schematic of jet rig.

Air flows through a pipe with diameter of 19.05 mm from the storage tanks up to the flow meter. After this position, the pipe diameter is enlarged twice, at first to a 38.31 mm and then to 88.90 mm. A flow straightener is then used at this low speed condition where temperature and pressure are measured. Before reaching the nozzle, the pipe is again contracted to a 38.31 mm diameter.

The nozzles used were the SMC000 and the SMC006, developed by Bridges and Brown (2004). The SMC006 was the chevron nozzle that has shown the greatest influence in the velocity field and noise spectrum, as verified by the aforementioned study. The SMC000 is the round, baseline nozzle. The equivalent diameters were 12,3 mm for the SMC000 and 12,1 mm for the SMC006. Figure 2 shows the two nozzles. Other characteristics of the SMC006 include: (i) number of chevrons: 6; (ii) chevron length: 5.65 mm; (iii) angle (given by angle to jet centerline): 18.2º; (iv) penetration (difference in radius from tip to base of the chevron): 0.881 mm.

Figure 2. SMC000 (left) and SMC006 (right).

A single wire probe was used to perform measurements. The hot wire anemometry system, from Dantec Dynamics, has two constant temperature anemometer modules, model 90C10, for velocity measurement, one constant current anemometer module, model 90C20, for temperature measurement and a velocity calibration unit, model 90H10. All modules are controlled by a central unit (StreamLine 90N10).

3. RESULTS

3.1 Mean velocity and axial turbulence intensity profiles

Figure 3 and 4 show the centerline velocity and turbulence intensity as a function of the downstream position, respectively for the SMC000 and SMC006 nozzles.

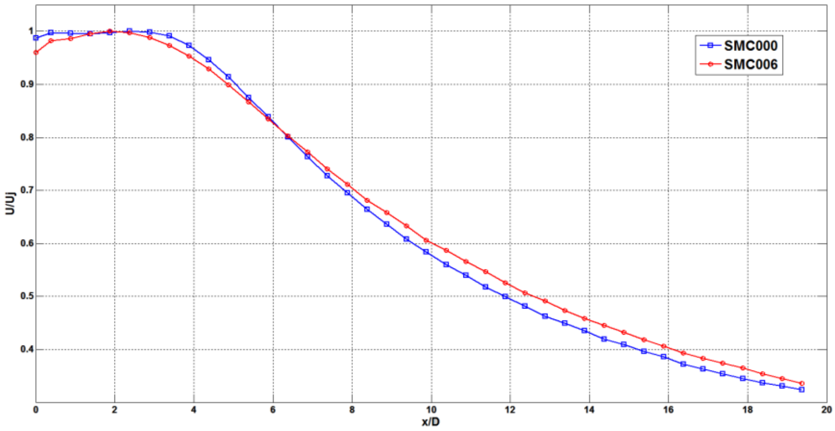


Figure 3. Centerline velocity decay

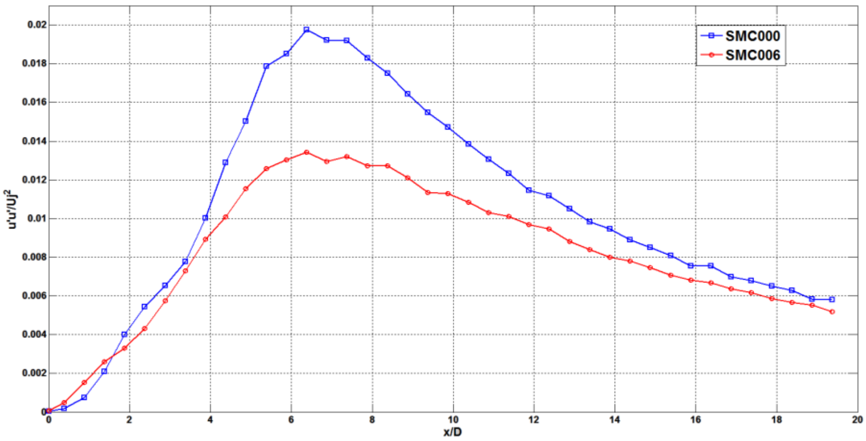
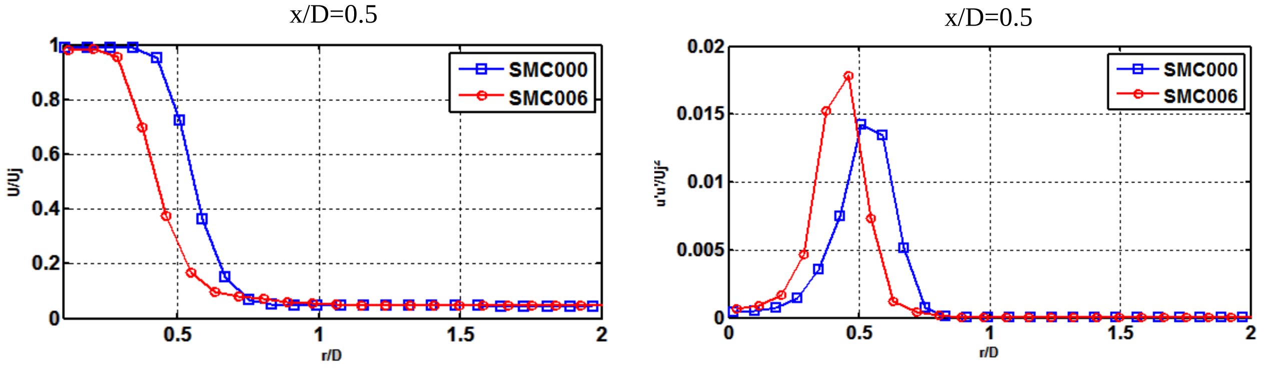


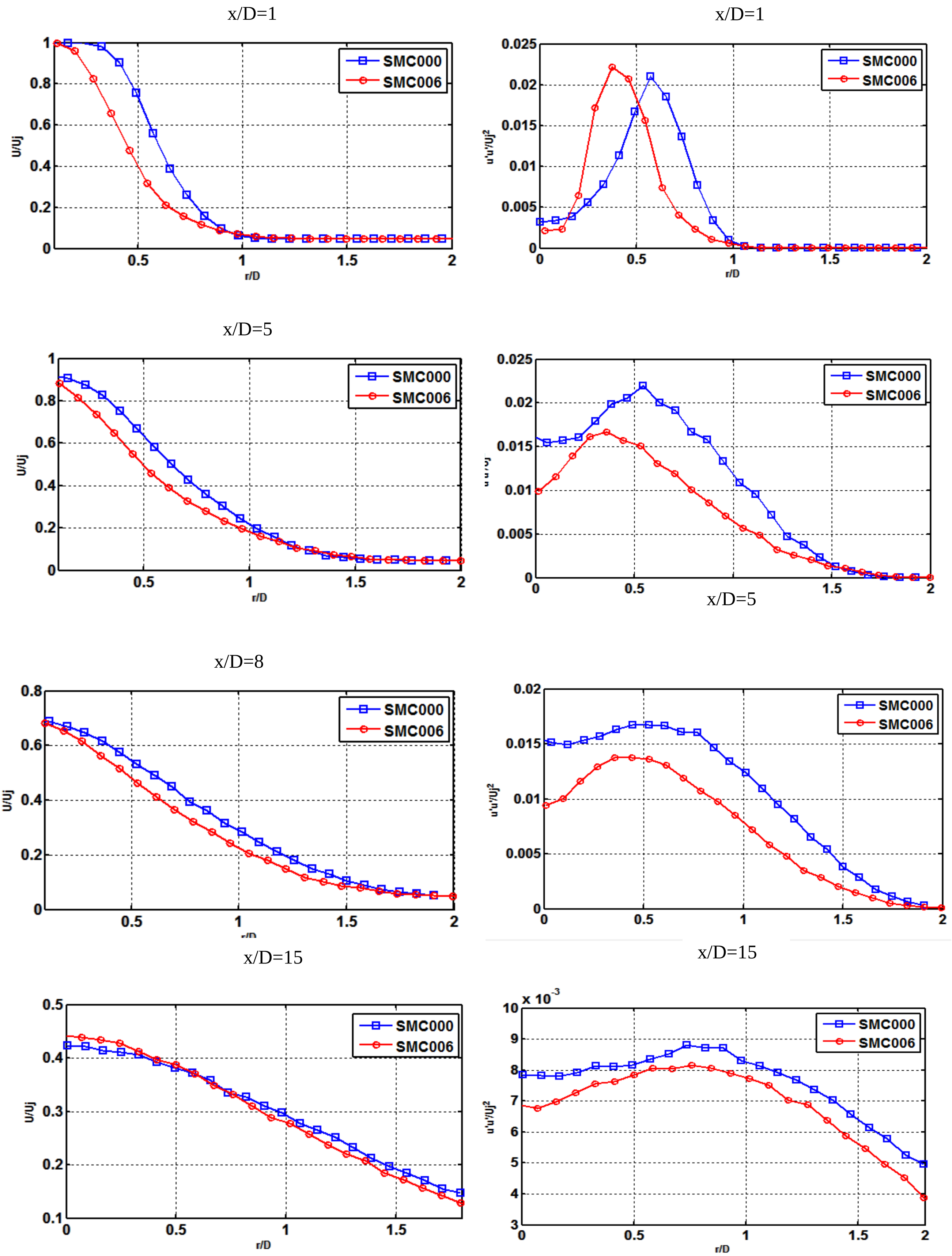
Figure 4. Turbulence intensity

Figure 3 shows that the centerline velocity initially decays slightly faster with the chevron nozzle, which showed a smaller potential core. It may be observed in Figure 4 that both nozzles present a peak in turbulence intensity near x/D=7, after the end of the potential core. This is a region of high interest to the generation of low frequency noise, because of the low wavenumber structures generated in the end of the potential core. The SMC0006 nozzle presented lower values of axial turbulence intensity in most or the region measured, with a peak of 13% approximately, whereas the SMC000 presented a peak of 20%. The lower values of turbulence intensity displayed by the chevron nozzle may indicate a reduction of the low-frequency noise generated by the large structures of turbulence. However, the higher values of turbulence intensity close to the nozzle may indicate an increase in the high-frequency content of the noise spectrum associated with the finer scales of turbulence.

Figure 5 shows radial profiles of mean velocity and axial turbulence intensity for different positions downstream of the nozzle, both non-dimensionalized by the jet exit velocity. The profiles for the chevron nozzle were measured in a plane that crosses the two peaks. One can observe that the mean velocity profiles for the baseline nozzle are wider than the ones generated by the chevron nozzles. Nevertheless, they tend to become closer as one moves downstream of the nozzle. With respect to the axial turbulence intensity profiles, one may observe that the chevron nozzle increases the axial turbulence intensity in a region close to the nozzle, at x/D=0.5 and x/D=1. This is in accordance with results found by Callendar et al., (2010), who found that the chevron nozzle enhances the mixing process and spreading of the jet radially. However, far downstream, the turbulence intensities for the chevron nozzle were found to be lower than for the round nozzle. This is also in accordance with the results found by Callendar et. al., (2010). At x/D=15, the mean velocity profiles for the two nozzle are very similar. As Bridges and Brown (2002) also reported, at a sufficient distance downstream from the nozzle, the similarity theory can be applied even to the serrated nozzle, and both jets tend to forget their initial condition.


x/D=0.5

x/D=0.5



x/D=1

x/D=1

x/D=5

x/D=5

x/D=8

x/D=15

x/D=15

Figure 5. Mean velocity and axial turbulence intensity profiles, non-dimensionalized by the jet exit velocity. (x/D=0.5, x/D=1, x/D=5, x/D=8, x/D=15).

3.2 Turbulent kinetic energy spectra

The spectra were calculated through the discrete Fourier transform of a time series of velocity measurements. The time series was divided into blocks with 50% overlap and the Fast Fourier Transform (FFT) was applied to each block. A Hamming window was then applied to the blocks to reduce truncation effects and they were averaged to give the spectra. An acquisition rate of 250kHz was used and 2500000 samples were acquired for each position. The FFT were calculated with 8000 points. The spectra obtained by this procedure is a function of the wavenumber. In order to obtain a frequency-dependent spectrum, Taylor's frozen field hypothesis was used. With this assumption the frequency is related to the wavenumber by

$$f = \frac{\kappa U}{2\pi} \tag{1}$$

Where κ is the wavenumber and U is the mean velocity at the measurement point.

Figure 6, 7 and 8 show turbulent energy spectra for three downstream positions, x/D=2, x/D=3 and x/D=5. For each streamwise position, the spectra were obtained for two radial positions, r/D=0 and $\eta = 0$, where $\eta = (y - y_{0.5})/\delta_c$. In the definition for η, $y_{0.5}$ is the radial position at which the velocity is equal to the half velocity on the jet axis and δ_c is the shear layer thickness. The variable η corresponds to the position in the shear layer center, defined as the point with the highest velocity gradient. This region is relevant to the production of noise, owing to the presence of coherent structures, which are believed to be responsible for low-frequency noise.

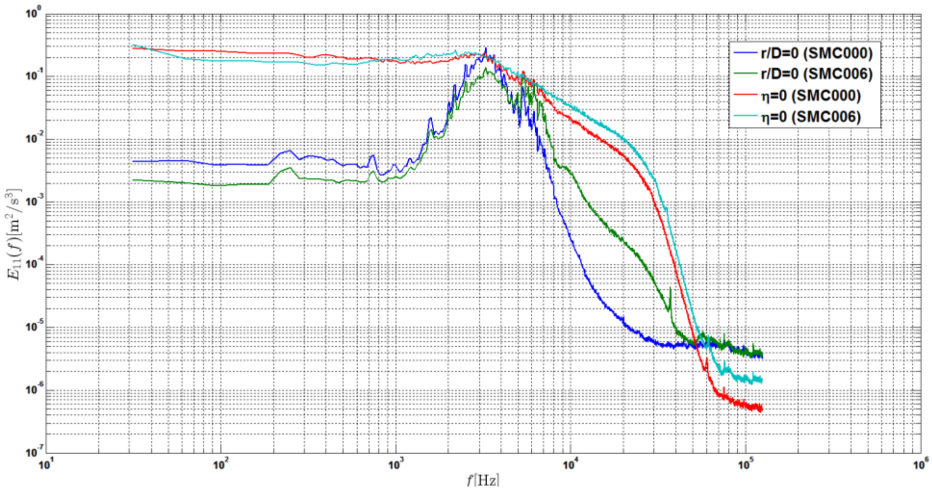


Figure 6. Turbulence spectra at x/D=2.

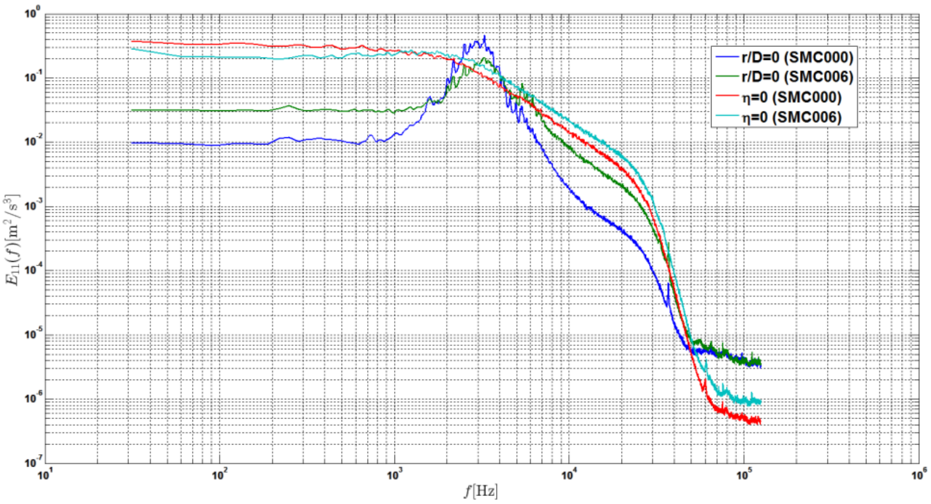


Figure 7.Turbulence spectra at x/D=3.

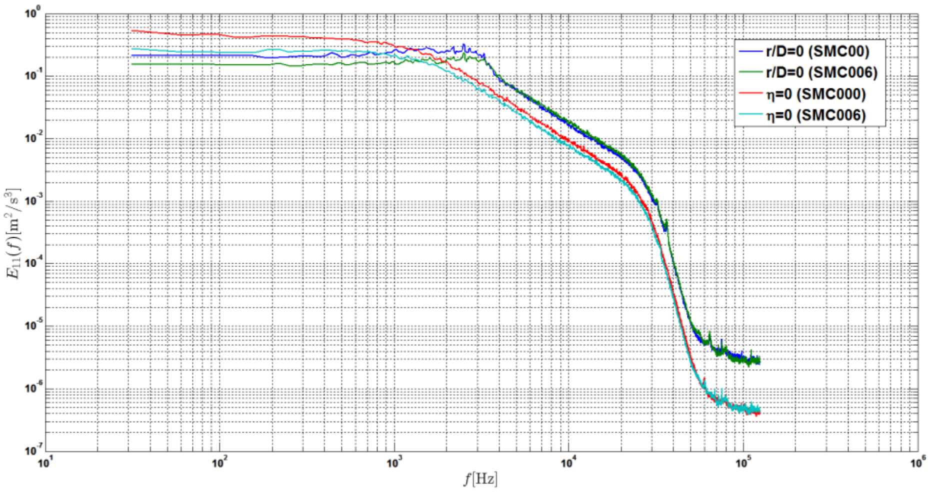


Figure 8.Turbulence spectra at x/D=5.

In the three spectra one may observe broadband content and peaks at y/D=0, in the center of the potential core. These peaks are due to a convective instability known as Strouhal instability, also identified by Kerhervé *et al*. (2003) and Lau (1980). Kerhervé *et al*. (2003) claimed that this kind of instability are generated by large coherent structures that evolve downstream of the jet. One may observe in Figures 6, 7 and 8 that the peak intensity decreases as one moves downstream. At x/D=2 and x/D=3 the chevron nozzle showed lower levels of turbulent kinetic energy at lower frequencies and higher levels at higher frequencies, both at the potential core and the shear layer. This may be related with the changes in the acoustic far field by the *trade-off* mechanism promoted by chevron nozzles. This mechanism was described by Bridges and Brown (2002) and Callendar et. al., (2010), and consists of a shift in noise peaks from low-frequencies to high frequencies. At x/D=5 the SMC000 nozzle showed higher levels of turbulent kinetic energy at both positions measured.

4. CONCLUSIONS

The results have shown that the chevron nozzle provided narrower mean velocity profiles close to the jet exit compared to the round nozzle. However, both jets tend have very similar velocity profiles sufficiently far downstream, as may be observed in Figure 3 for x/D=15. As is also shown in Figure 5, it is clear that the chevron increases the axial turbulence intensity close to the nozzle, whereas its effect is to decrease it downstream. It was also observed that the chevron nozzle generated significantly lower values of turbulence intensity after the end of the potential core, a region of high importance to the generation of noise. This may be associated with a reduction in low-frequency noise observed by Callendar et. al., (2010) and Bridges and Brown (2002).. However, close to the nozzle, the chevron presented higher values of turbulence intensity both in the streamwise and radial directions. This may increase the high-frequency noise that Tam *et al*. (2008) attributed to the finer scales of turbulence. This is in accordance with results found by Callendar et. al., (2010), Bridges and Brown (2002) and Violato and Scarano (2011).

These trends were confirmed by the measurements of the turbulent kinetic energy spectrum. The chevron nozzle showed greater values of energy in high frequencies close to the jet axis, both in the potential core and the shear layer. At x//D=5, just after the end of the potential core, this tendency is inversed, following what was observed in the turbulence intensity profiles of Figures 4 and 5. These changes brought about by the chevron are associated with the *trade-off* mechanism described by Callendar et. al., (2010) and Bridges and Brown (2002), who observed experimentally that the chevron shifts the peak noise to higher frequencies. However, in our experiments we have not actually made any acoustic measurements, therefore it remains to be seen if our statement above is correct.

5. FUTURE WORK

This work could be extended by measuring other components of velocity and verifying if the trends observed for the streamwise component are also present in the radial directions. One and two-point correlations could also be evaluated as these statistics are useful to obtain insight about the flow field structure and as inputs in acoustic analogies. It would also be interesting to evaluate the influence of the chevron nozzle at higher Mach numbers. Bridges and Brown (2002) observed stronger reductions in the potential core length and turbulence intensity at a flow with Ma=0.9. This may indicate that the chevron is more effective in reducing noise in flows with higher Mach numbers. Finally, it is important to perform measurements of the acoustic far-field of the jet, in order to accurately correlate the changes observed in the flow field with changes in the noise spectrum generated by the chevron nozzle.

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