EXPERIMENTAL CHARACTERIZATION OF THE EFFECT OF A CHEVRON NOZZLE ON THE TURBULENT FIELD OF A SUBSONIC JET

Igor Albuquerque Maia
César Jose Deschamps
Universidade Federal de Santa Catarina
igor.albuquerque@polo.ufsc.br
deschamps@polo.ufsc.br

Juan Pablo de Lima Costa Salazar
Universidade Federal de Santa Catarina
juan.salazar@ufsc.br

Abstract. *The turbulent jet issuing from engine exhaustion is one of the main sources of noise in an aircraft. This is a topic in the research field of aeroacoustics in which the sound generation mechanisms are not yet fully understood. However, some noise reduction devices have been developed and applied in aircrafts, such as tabs and chevrons. The present work addresses a comparison between the flow fields generated by nozzles with and without chevrons through hot-wire anemometry. The main goal was to understand the chevron effect on the flow field and the noise reduction mechanisms attributed to such nozzles. The results have shown an increase in axial turbulent intensity generated by the chevron in the initial region of the jet (x/D<2) and a decrease in turbulent intensity levels in the subsequent region. The chevron nozzle also increased the spreading of the jet and generated a thicker shear layer. The energy spectra showed the existence of coherent structures in the jet and the chevron was found to affect the energy peaks associated to these structures, specially at Strouhal number 0.3.*

Keywords: *Jet,Chevron Nozzle, Turbulent Field*

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. They observed that the penetration angle of the chevron was the parameter that showed the most influence both on acoustic field and turbulent velocity field. They found that high-penetration designs caused a faster centerline velocity decay. On the acoustic field, the chevron effect was to decrease sound pressure levels at polar angles affected by low frequency radiation. However, at angles close to the sideline, an increase in sound pressure levels was observed. Aiming to understand the effect of the chevron nozzle on the velocity field, Callender *et al.* (2010) performed PIV (PArticle Image Velocimetry) measurements in order to observe mean velocity and turbulent kinetic energy fields of coaxial jets with and without chevrons. They observed that the chevron nozzle increased the jet spreading, producing velocity profiles with larger values in the shear layer at the initial region of the jet. It was also observed an increase in kinetic energy near the nozzle and a strong reduction after x/D=4. This region was associated with low frequency sound radiation in another study by the same authors (Callender *et al.*, 2008). On the other hand, the increase in kinetic energy occurred in a region where high frequency radiation (St>7) was found to dominate.

Alkislar *et al.* (2007) assessed chevron influence on the vorticity field of turbulent jets. Through PIV, the authors observed that the chevron produces a pattern of streamwise vortices that appear in counter-rotating pairs acting on the shear-layer. It was verified that by increasing momentum transfer, the vortices generated a thicker shear layer and a greater spreading rate.

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. They claimed that this change is the streamwise pattern is reponsible for noise reduction in low frequencies.

Gudmundsson (2009) evaluated chevron effect on jet instability. The spatial rate growth of low azimuthal modes of wavepackets was found to be affected by the chevron. The axissymetric mode particularly was the most influenced by this kind of nozzle.

The present work is part of a research project with the goal of studying jet noise and reports hot-wire-anemometry measurements acquired in an experimental setup developed to investigate the underlying turbulence mechanisms responsible for the acoustic modifications introduced by chevrons. 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 chevrons. 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 0.4 and 168 000, respectively.

2. 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) and also used by Maia *et al.* (2014). 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 a compressor with, an air dehumidifier and two 500 l storage tanks. In order to control the Mach number, three valves were used to open the line, reduce pressure oscillation and control flow rate. An schematic of the jet rig is shown in Figure 1.

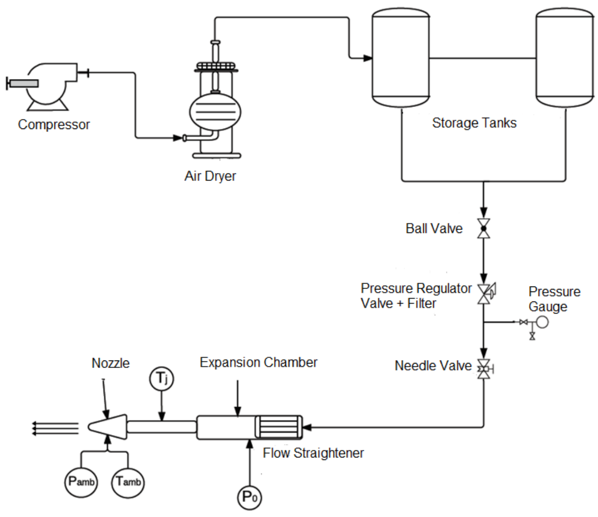


Figure 1: Schmatic of the jet rig.

Air flows through a pipe with diameter of 19.05 mm from the storage tanks up to the neddle valve. After this position, the pipe diameter is enlarged twice, at first to a 38.31 mm and then to 88.90 mm and the flow velocity reduces 95%. 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 Mach number was set through an isentropic relation.

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 11.6 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): 15.2°; (iv) penetration (difference in radius from tip to base of the chevron): 0.881 mm.

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).

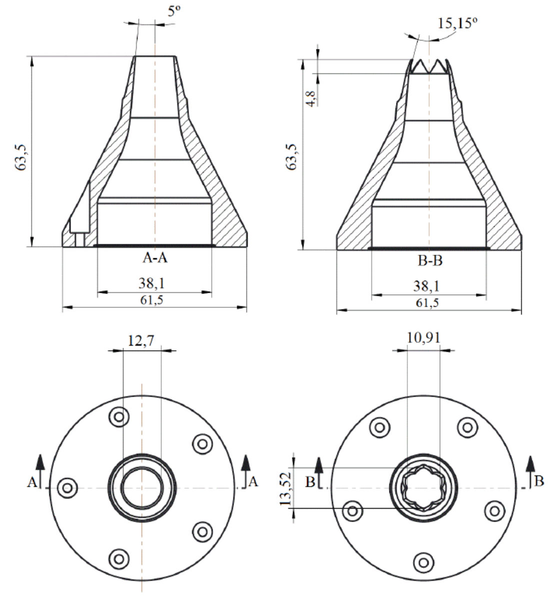


Figure 2: Nozzle geometry and dimensions.

3. RESULTS

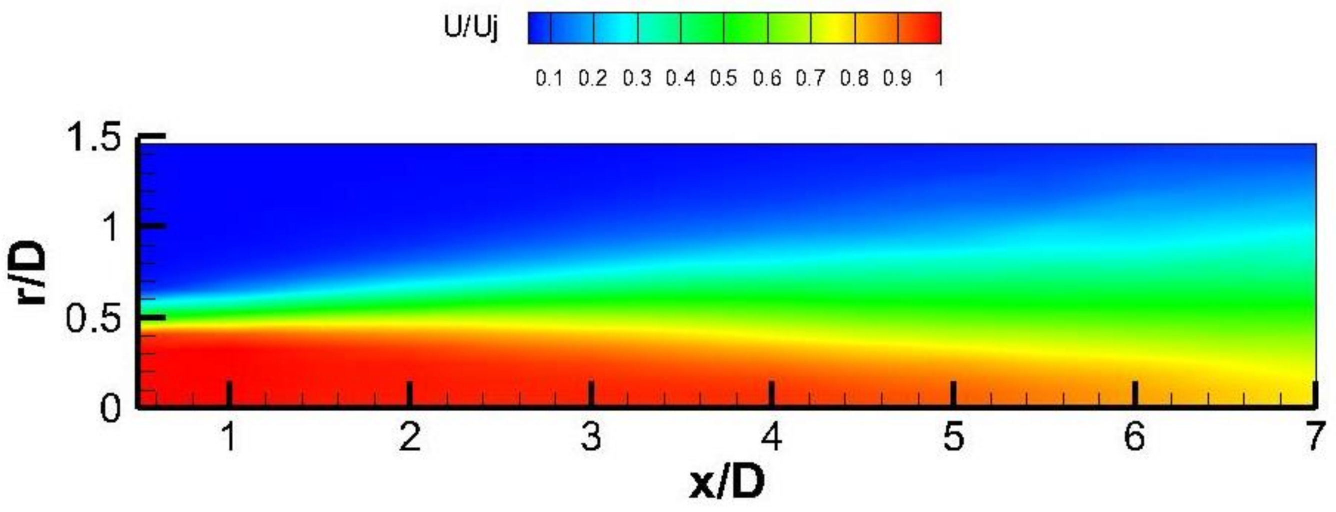
3.1 Mean velocity and turbulence intensities

This section presents contours of mean axial velocity U, normalized by jet exit velocity U_j, and axial turbulence intensity, defined as u'/U_j. For the chevron nozzle, two planes were measured: one that passes through the chevron peak and one that passes through the chevron valley, hereafter referred to as SMC006P and SMC006V, respectively. These quantities were measured in a plane parallel to the jet axis and centered on the jet. Figure 3 shows the contours of mean velocity for the two nozzles. The plane covered the region between x/D=0.5 and x/D=7 and r/D=0 and r/D=1.48. The point grid used had an increment of 1mm in the axial direction and 0.5D in the radial direction. It may be observed that in the SMC006P plane there was significant narrowing of the potential core in comparison with the SMC000 nozzle. In the SMC006V plane, there was rapid growing of the shear layer between x/D=0.5 and x/D=2, causing a greater spreading rate of the jet. This is caused by pairs of streamwise vortices generated at the valley plane. As was observed by Alkislar *et al.* (2007), the vorticity magnitude of these structures decay exponentially in the axial direction. Therefore, their influence on jet spreading decays and the shear layer grows at a lower rate after some distance downstream, as may be seen in Figure 3c. Figure 4 show the contours of axial turbulence intensity. It may be seen that the chevron significantly modifies the levels and distribution of this quantity. In the SMC006P plane, there was an increase in axial turbulence intensity from x/D=0.5 to x/D=2. This region was associated to high frequency sound production by Callender *et al.* (2008) in a near-field pressure field investigation. On the other hand, after x/D=4 the chevron reduced the levels of turbulence intensity on both planes. There was an overall reduction of 10% in the maximum value on the SMC006P plane and 23% in the SMC006V plane. This characteristic is associated with noise reduction observed both in the near-pressure field (Callender *et al.*, 2008) and acoustic far field (Bridges and Brown, 2004). Furthermore, the sound produced in the shear-layer after the end of the potential core, the region most affected by the chevron, radiates to polar angles that are dominated by low-frequencies. The overall effect of the chevron was then to increase turbulence intensity near the nozzle and decrease it downstream, after the end of the potential core. This trend is is accordance with the shift in peak noise described by Bridges and Brown (2004).

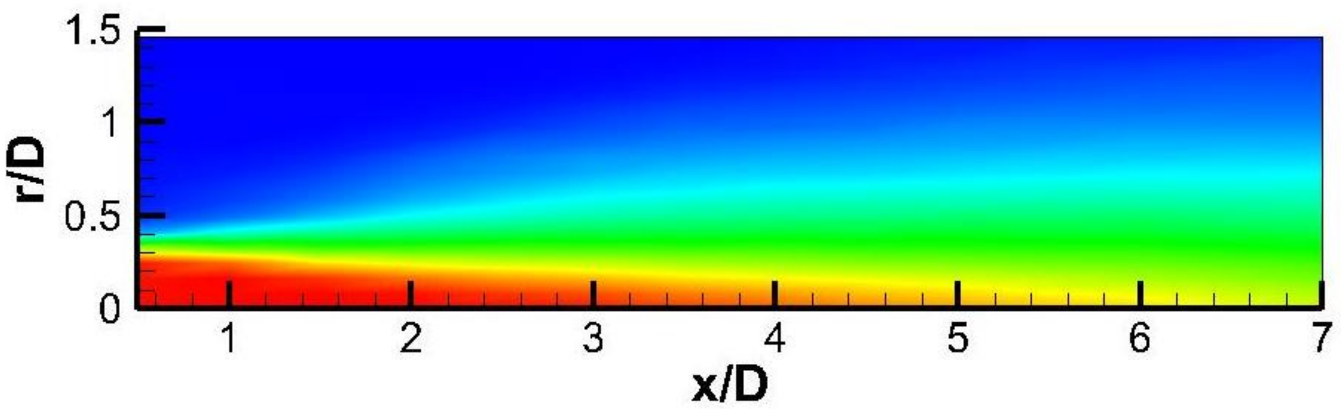
3.2 Energy Spectra

Power Spectral Densities (PSD) for the axial velocity fluctuation signal u' were obtained for some positions in the jet through Fourier series decomposition. The measurements were performed during 10 s, with an acquisition frequency of 125 kHz. A Discrete Fourier Transform (DFFT) was applied in blocks with 50% overlapping, and the PSD was obtained by averaging the Fourier transforms of each block. The Strouhal attained was ΔSt=0.0013.

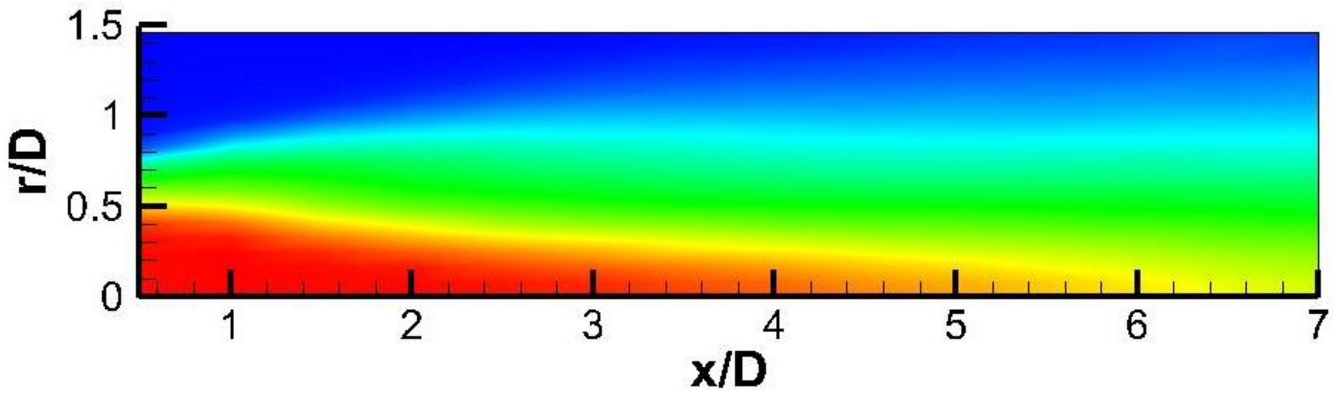
Figures 5, 6 and 7 show spectra obtained for the two nozzles at axial positions x/D=2, x/D=3 and x/D=5, respectively.



(a) SMC000



(b) SMC006P



(c) SMC006V

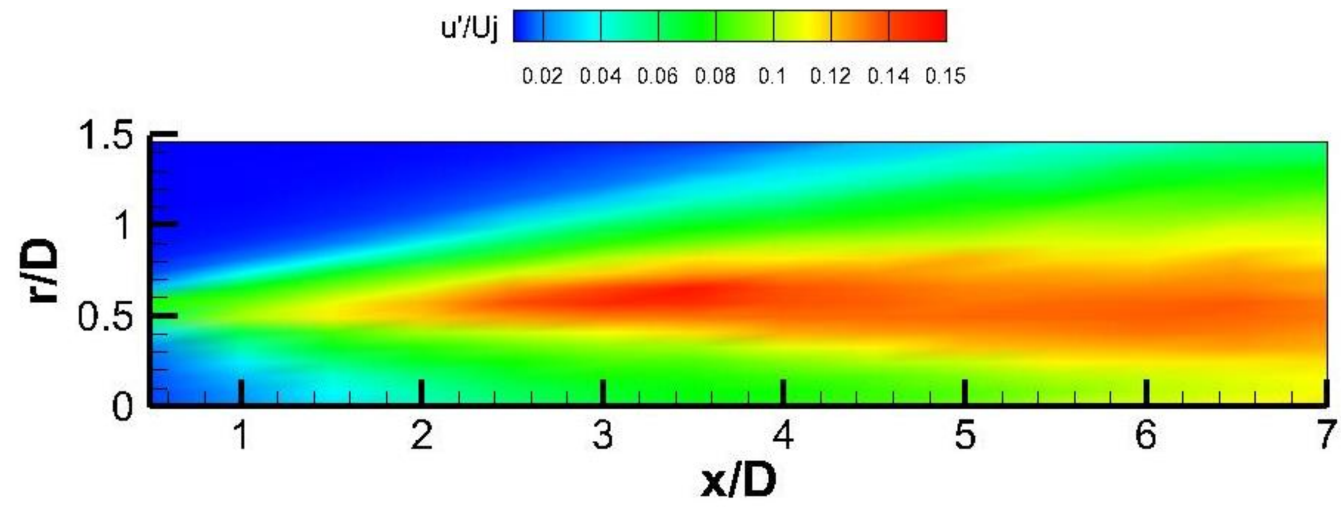
Figure 3: Contours of mean velocity in a plane parallel to the jet: (a) SMC000 nozzle; (b)SMC006 nozzle on peak plane; (c) SMC006 nozzle on valley plane.

The spectra were measured at the jet centerline and at the center of the shear-layer, at η=0, where

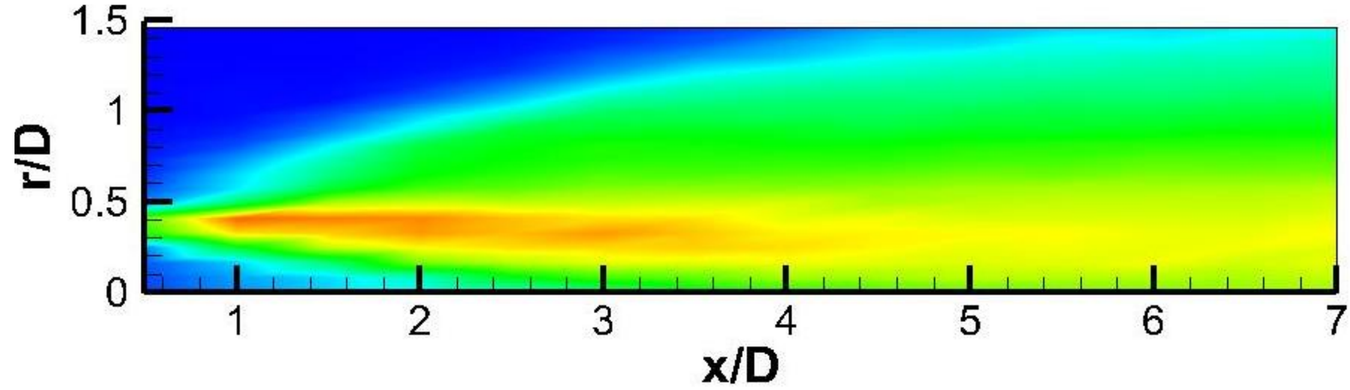
$$\eta = r - r_{0.5}/\delta. \quad (1)$$

r is the radial coordinate, $r_{0.5}$ is the radial position where the axial velocity is half the jet exit velocity and δ is the shear-layer thickness. The spectra were normalizes by jet exit velocity and are shown by Strouhal band.

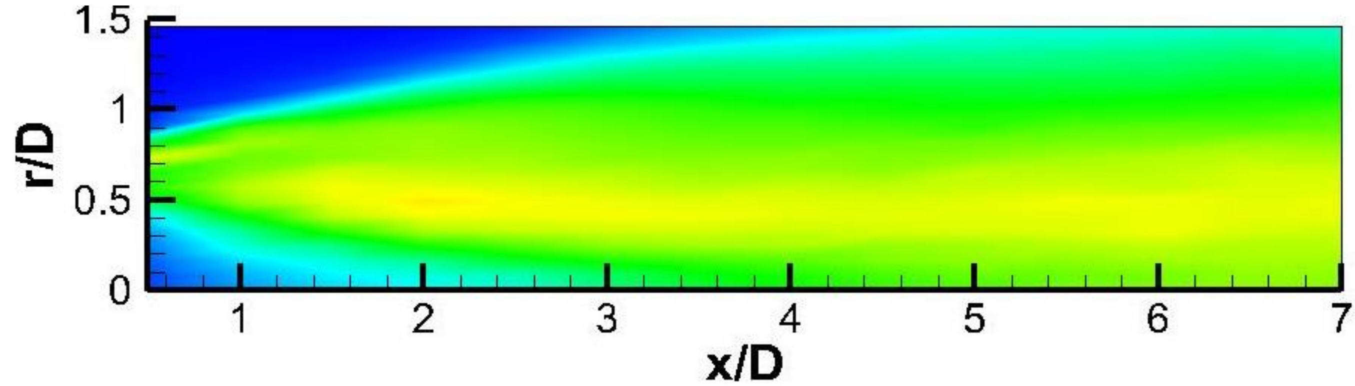
It may be verified that at the three positions there is a broadband peak at the spectra measured on the centerline, that



(a) SMC000



(b) SMC006P



(c) SMC006V

Figure 4: Contours of axial turbulence intensity in a plane parallel to the jet: (a) SMC000 nozzle; (b)SMC006 nozzle on peak plane; (c) SMC006 nozzle on valley plane.

cover frequencies from St=0.2 to St=1, approximately. These peaks are evidence of the presence of coherent structures, or wavepacekts, in this region of the jet and were also observed by other authors (Cavalieri *et al.*, 2013; Kerherve *et al.*, 2003). On the shear-layer these structures are not observed. This is due to the fact that they only represent a small fraction of the velocity fluctuation energy (Jordan and Colonius, 2013). Hence, it is only possible to identify them inside the potential core, where velocity fluctuations are low. At x/D=2, the SMC006 nozzle presented lower levels of energy up until St=1. It may also be verified that the broadband peak covers a narrower frequency band compared to the SMC000 case. At x/D=3, the SMC000 nozzle showed a higher energy peak whilst the SMC006 nozzle remained with the same peak value at the jet centerline. In the shear-layer, the SMC000 nozzle presented higher energy values both at x/D=2 and x/D=3. At x/D=5, the energy peak becomes more pronounced at St=0.3, which is the frequency formation of the wavepackets (Crow and Champagne, 1971). The chevron nozzle did not show the peak at this position, which means that at this position the wavepackets represent a smaller fraction of the total energy. The energy on the jet centerline represents the energy of the first azimuthal mode of the wavepackets, which is the most acoustically efficient mode (Cavalieri *et al.*, 2013). Hence, it is possible that the chevron nozzle mechanism to reduce noise is the attenuation of the first azimuthal mode of the wavepackets. This trend was observed by Gudmundsson (2009) in the near-pressure field of a chevron nozzle.

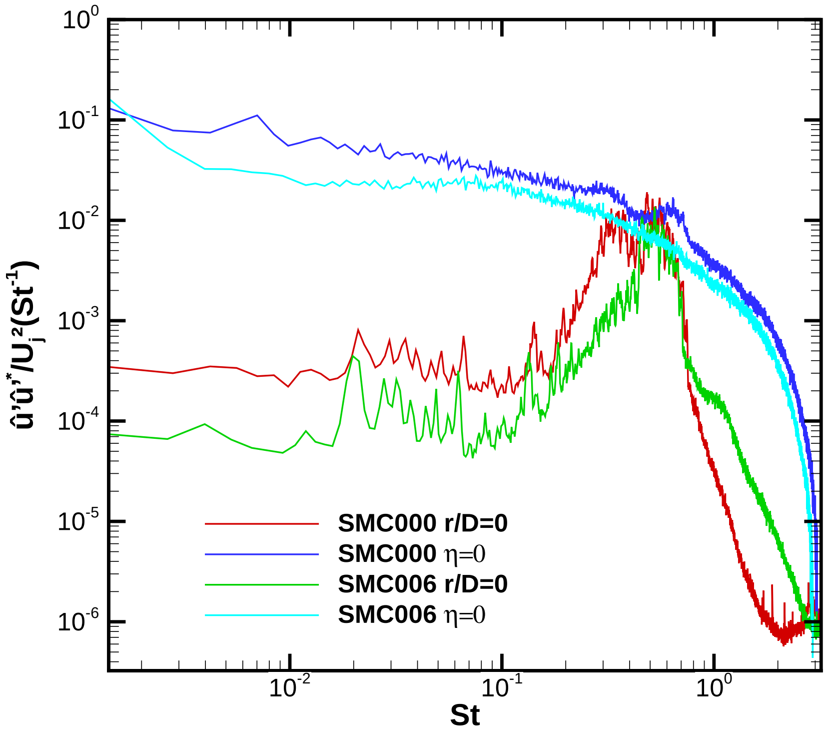


Figure 5: Energy spectra at x/D=2.

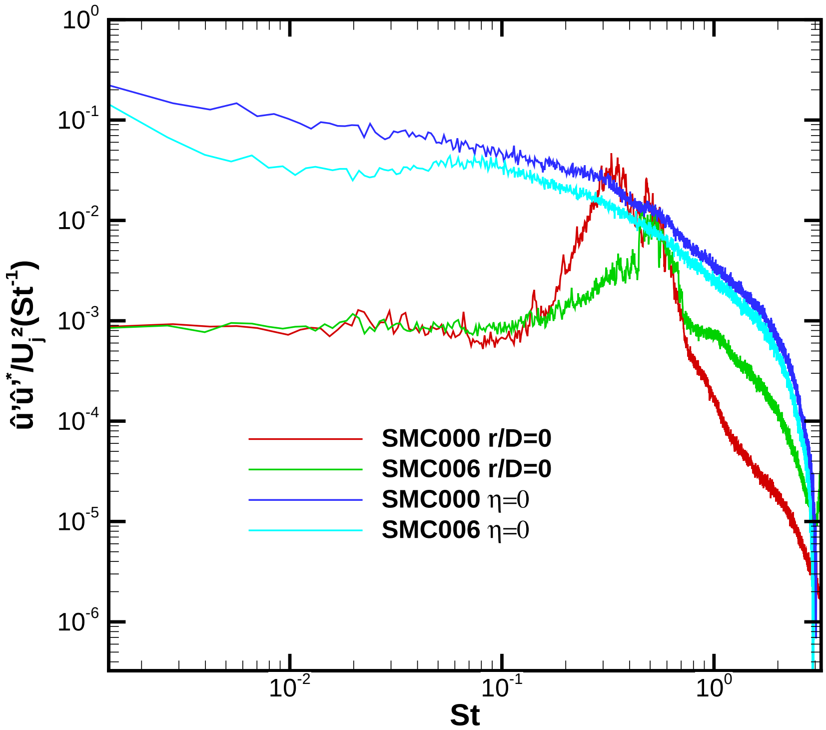


Figure 6: Energy spectra at x/D=3.

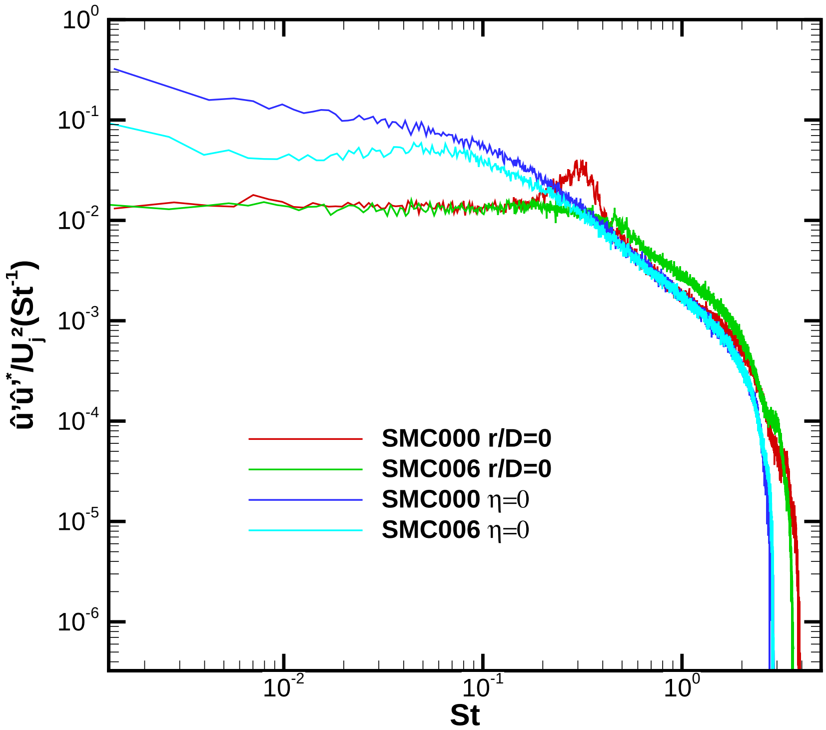


Figure 7: Energy spectra at x/D=5.

4. CONCLUSIONS

The results have shown that the chevron nozzle effect increased the spreading rate of the jet, specially at the valley plane. This results from the action of streamwise vortices generated in this plane. As is shown in Figure 3, 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 Callender *et al.* (2010), Bridges and Brown (2004) and Violato and Scarano (2011).

In energy spectra (PSD) it was possible to observe the presence of broadband peaks associated with coherent structures of wavepackets. These peaks may be observed inside the potential core, where the energy of the coherent structures is high compared to the total energy of the flow. The chevron nozzle shifted the energy levels to higher frequencies (St>1) and affected the peak value, specially at St=0.2, which corresponds to the frequency of formation of wavepackets. It is argued that the chevron mechanism to reduce noise in low frequency is the attenuation of the fist azimuthal mode of wavepackets, whose energy in the velocity field may be measured on the jet centerline.

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