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EXPERIMENTAL ANALYSIS OF A PASSIVE DEVICE TO REDUCE THE NOISE OF SUBSONIC JETS

Felipe A. F. Câmara
Victor H. P. Rosa
César J. Deschamps
POLO Laboratories, Federal University of Santa Catarina, Florianópolis, SC, Brasil, CEP 88040-900
felipe.camara@polo.ufsc.br

This paper presents an experimental analysis of a passive device to reduce the noise of subsonic jets which are typical of the engine exhaust of civil aircraft. The noise-reducing device consists of a thin tape glued to the inner nozzle surface near the nozzle exit. The tape covers the entire nozzle circumference, having a zigzag shape with thickness around 1% of the nozzle diameter. This device has also been studied elsewhere, so the objective of this work is to further explore its overall effect on the noise output and on the jet flow through measurements of velocity in the nozzle-exit boundary layer and in the jet plume with hot-wire anemometry. These flow measurements are used to quantify the thrust reduction caused by the device and to relate the noise reduction to changes in the flow turbulence levels. The results for a jet with acoustic Mach number of 0.5 showed that the reduction of the thrust output is small and that a net noise reduction remains even if the nozzle-exit velocity is increased to recover the thrust loss. It was also observed that the device reduces the turbulence kinetic energy in the jet plume, which can explain the observed broadband noise reduction.

Keywords: *jet mixing noise, noise-reduction device, hot-wire anemometry*

1. INTRODUCTION

Aircraft noise is a major concern in the aviation industry due to the environmental problems associated with it and rigid regulations that limit aircraft noise emissions. The mixing of the high-speed exhaust gases with the ambient air was the most significant noise source in the early subsonic aircraft powered by jet engines (circa the 1950s). Since then, the jet engines became significantly quieter as a result of the secondary stream in the design of the turbofan engines, which reduces the jet-exit speed whilst keeping the same thrust output. Theoretically, the thrust output scales with the jet speed to the 2nd power and the acoustic power of the mixing process scales with the jet speed to the 8th power (Lighthill, 1952). Hence the experimentally observed noise reduction of the turbofan engine can be explained by a reduction in mixing noise.

Recently, more subtle design changes to further reduce the mixing noise have been studied. Zaman et al. (2011) presented a historical and technical perspective on how early studies in the more intrusive tabs have led to the design of the chevrons, which effectively reduce mixing noise without much reduction in the thrust output. The noise reduction achieved using chevron nozzles can be explained by the qualitative explanation about the mixing noise process presented by Fazle-Hussain (1986). In this interpretation, most of the mixing noise is generated by the breakdown of azimuthally coherent structures that develop in the jet plume. With that in mind, it follows that the chevrons reduce jet mixing noise, hence the overall noise from subsonic jets, by reducing the growth rate of the azimuthally coherent structures. This growth-rate reduction is a result of the streamwise vorticity added to the jet shear layer by the chevrons. A negative aspect of chevrons is to increase the energy of smaller turbulent structures and consequently cause an increase of high-frequency noise emitted to the sideline direction. By carefully designing the chevron (number, penetration angle, length, etc.), however, a net overall benefit can be achieved (Saiyed et al., 2003).

Meyer et al. (2013) compared a few noise-reducing devices which could potentially replace chevrons. The most promising alternative was a tape with a zigzag shape glued to the inner nozzle surface near the nozzle exit. The thickness of the tape is approximately 1% of the nozzle diameter, being in the order of the boundary layer thickness at the nozzle exit. Schlieren photographs presented by Meyer et al. (2013) indicate that the noise-reduction mechanism of the zigzag shape is similar to the that of chevrons, i.e. reduction in the growth rate of azimuthally coherent structures by injection of streamwise vorticity.

This paper presents an experimental analysis of the optimum zigzag shape found by Meyer et al. (2013), exploring the influence of its thickness. Measurements are carried out for the far-field noise and velocity associated with the jet flow of the SMC000 nozzle geometry (Bridges and Brown, 2004). The measurements are then used to evaluate the reduction in the thrust output caused by the zigzag tape and to relate the broadband noise reduction with the turbulence intensity in the jet plume.

2. EXPERIMENTAL SETUP

Acoustic and flow measurements have been performed in a dedicated jet rig facility. The facility, shown in Figure 1, consists of (1) conditioning unit; (2) external storage tank; (3) block and control valves; (4) stagnation tank; (5) test chamber; (6) jet collector; (7) acoustic muffler; (8) microphone array; (9) control room. The test section is a 5 m x 4 m x 3 m (60 m^3) chamber which is anechoic down to 400 Hz. The stagnation tank, in which the flow is assumed to decelerate to stagnation, has acoustically treated walls that allow the reduction of noise from the upstream line. From the stagnation tank, the air is accelerated through a pipe with 152.4 mm of diameter and 2 m of length that enters in the anechoic test chamber. The control software uses temperature and pressure measurements at the stagnation tank and in the anechoic chamber to actuate the control valve in order to regulate the flow rate from the external storage tank to the stagnation tank and reach the desired acoustic Mach number through an isentropic relation for compressible and unidimensional flows. More details about the facility are available in Bastos et al. (2018).

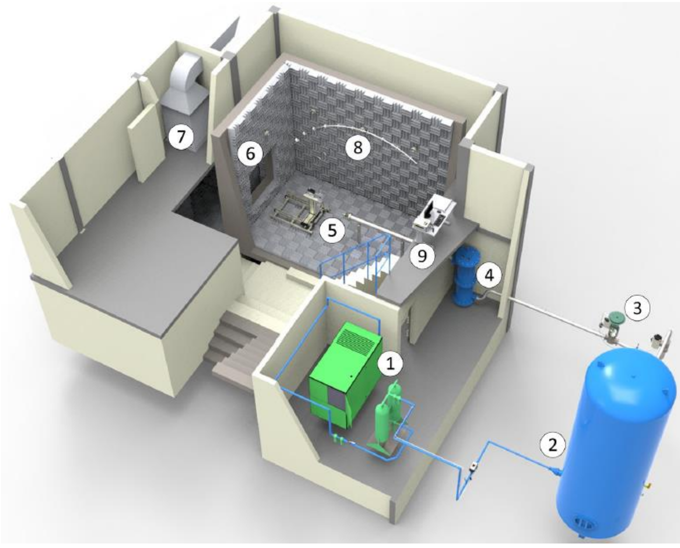
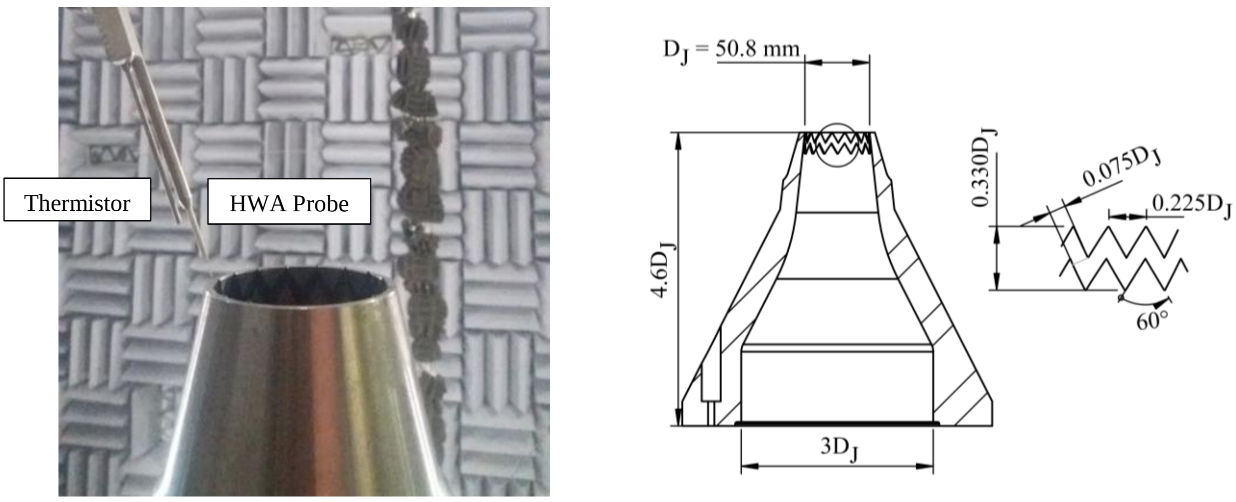


Figure 1 – Jet aeroacoustic rig facility. Source: Bastos et al. (2018).

Acoustic measurements were made by using a polar array of 10 microphones in the acoustic far-field (at a distance of 41 nozzle diameters from the nozzle exit). The polar angles vary from 60° (aft-arc) to 150° (rear-arc), equally spaced in 10°. The measurements of acoustic pressure are post-processed digitally to compute the power spectral density (*PSD*) following the method proposed by Welch (1967). The 1/3 octave bands are acquired for the central-frequency bands of 400 Hz to 50 kHz. The spectrum is corrected for background noise and for atmospheric absorption following the SAE standard ARP 866.

Measurements of the velocity flow field were made with a Dantec StreamLine hot-wire system. This system is composed by a 55P11 single wire miniature probe and a 91C10 CTA (Constant Temperature Anemometry) module in the 91N10 Streamline Pro Mainframe. A thermistor was used to correct the measurements for changes in the fluid temperature. An A/D board NI PXIe 4499 was used to convert the analog output signal from the hot-wire system to digital signal that is send to a PC. At each measurement point 20000 samples were take with a sampling ratio of 20 kHz. The 55P11 probe uses a 5 µm tungsten wire, which is much small than the characteristic length of the problem (say, the jet diameter). Thus, the measurements can be considered as point measurements, and a 3D traversing mechanism was used to move probe in a measurement grid. The ISEL C142-4 3D traversing mechanism used for the tests can move the probe with 0.01 mm of resolution, allow measurements up to 100 points in the boundary layer in the nozzle-exit.

The thermistor and the hot-wire probe are shown in Figure 2a, near the nozzle-exit in which the zigzag tape is glued. Figure 2b shows a detail of the SMC000 nozzle of Bridges and Brown (2004) with the zigzag tape glued to its inner surface. The nozzle diameter is D_J = 50.8 mm. As can be seen, the tape is located very close to the nozzle exit.



(a) (b)

Figure 2 - (a) Hot-wire probe and thermistor near the exit of the SMC000 nozzle (Bridges and Brown, 2004) and (b) detail of the zigzag tape in the inner surface of the nozzle.

3. RESULTS

The acoustic and flow results were obtained for unheated jets at an acoustic Mach number of $U_J/a_0 = 0.5$. The *SMC000* nozzle with D_J = 50.8 mm was used without modification as the baseline case, whereas zigzag tapes have been glued to the inner surface near the nozzle exit to assess their effect on the acoustic and flow fields.

3.1 Acoustic far-field

The nozzle studied by Meyer et al. (2013) had a diameter of 24.5 mm. The authors studied different zigzag geometries, varying the thickness, width, jag width and jag angle. In the present analysis, the optimum geometry found by Meyer et al. (2013) was manufactured with thickness varying from 0.4% to 2% of the nozzle diameter. The objective was to find the optimum thickness for the optimum geometry of Meyer et al. (2013). This step was necessary because the optimum thickness is understood to be related to the boundary layer thickness in the nozzle exit, which could be different between the two facilities and nozzles. Figure 3 shows that the tape presenting the highest noise reduction has a thickness of 0.016 D_J, which is close to the value of $0.015D_J$ found by Meyer et al. (2013).

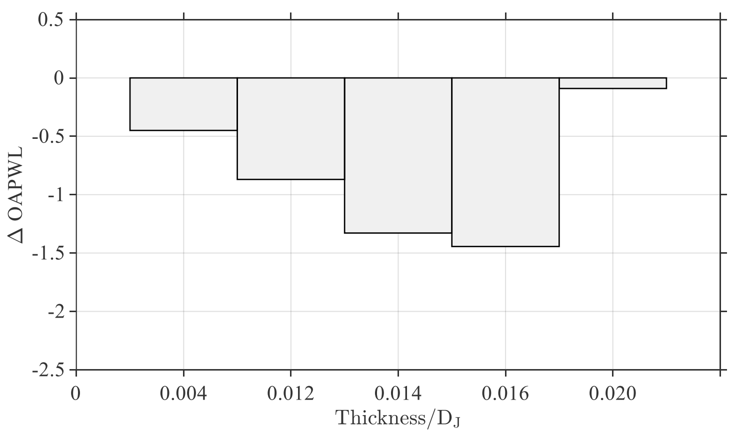
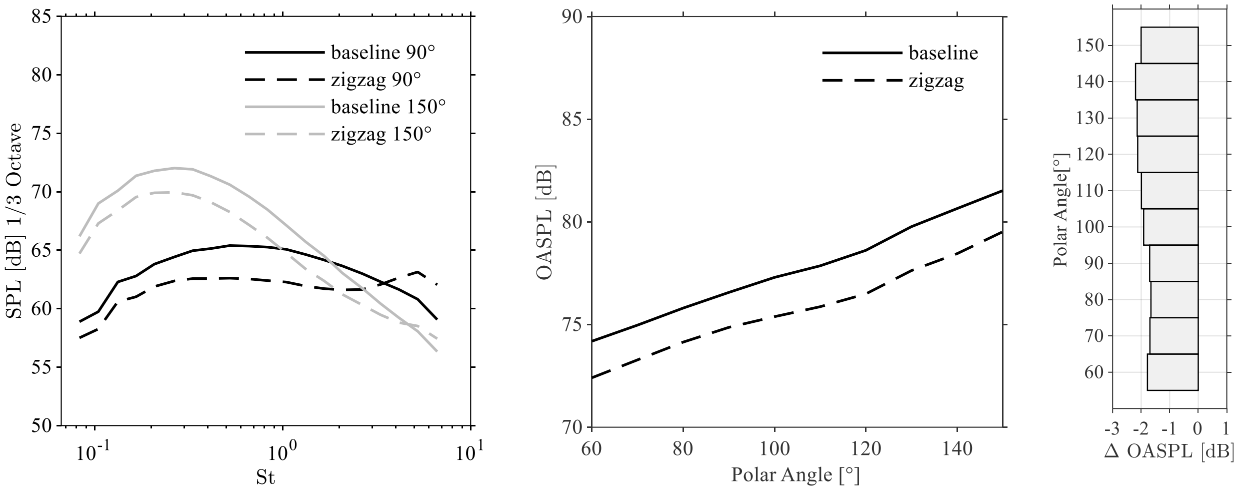


Figure 3. Reduction in the overall power level is maximum for the zigzag tape with a thickness of $0.016D_J$.

More detailed acoustic measurements for the zigzag tape with the optimum thickness of $0.016D_J$ are presented in Figure 4. The zigzag tape reduced the noise in most of the frequency range of interest, showing a noise increase only at the highest frequencies. In Figure 4a it is possible to observe that the zigzag nozzle presented lower sound pressure levels until approximately St ≈ 3.5 for 90° and St ≈ 4.2 for 150°, for frequencies above that the nozzle with zigzag presented higher sound pressure levels. The results show a reduction in OASPL larger than 1.5dB in all angles and larger than 2.0 dB for a few polar angles closer to the jet axis in the rear-arc. These results corroborate the results of Meyer et al. (2013)

in magnitude and trend. Alkislar et al. (2007) studied chevron and microjets as mixing enhancement devices, the authors also observed a reduction in levels of the low frequency spectrum content and an increase in levels of high frequency. Alkislar et al. (2007) suggest that the reduction in levels of the low-frequency spectrum content can be attributed to a reduction in the growth rate of the large-scale coherent structures in the jet plume and that the increase in the high-frequency SPL content can be attributed to an increase in turbulence energy of the small scales structures.



(a) (b) (c)

Figure 4. (a) SPL for an observer at the sideline (90°) and rear-arc (150°), (b) OASPL for polar angles from 60° to 150°, and (c) change in OASPL between the baseline and zigzag cases.

3.2 Turbulence intensity

Measurements were also made to assess how the zigzag tape affects the turbulence kinetic energy in the jet plume. Figure 5 shows that the turbulence intensity associated with the axial velocity component is significantly reduced by the zigzag tape in the first 10 diameters downstream of the nozzle exit, despite a small increase very close to the nozzle exit. These results explain the observed noise reduction for all measured polar angles and for most frequencies of interest. The noise increase at high frequency shown in Figure 4 (a) can be explained by the slight increase in turbulence intensity near the nozzle exit.

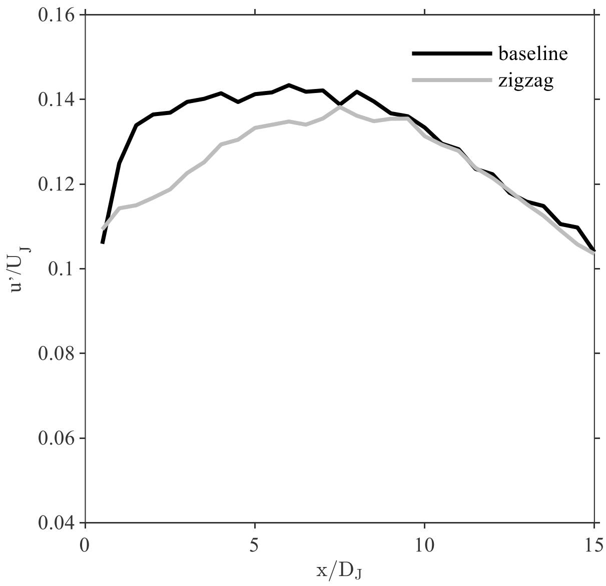


Figure 5. Turbulence intensity in the lipline.

3.3 Thrust coefficient

The boundary layer was measured at a streamwise distance of 0.008D_J from the nozzle exit plane with the aim to evaluate changes in the thrust coefficient caused by the zigzag tape. Zaman et al. (2003) relate the thrust coefficient to the momentum flux losses due to the boundary layer. Thus, the thrust coefficient can be calculated by comparing the momentum flux of the actual velocity profile with the momentum flux of a uniform velocity profile, i.e.:

$$C_T = \left[\int_0^{D_J/2} \rho\,(r) U^2(r) 2\pi r dr\right] / \left[\rho_J U_J^2 \frac{\pi D_J^2}{4}\right], \quad (1)$$

where $\rho(r)$ is the local density calculated from theoretical relations for isentropic compressible flows, $U(r)$ is the mean streamwise velocity measured with the hot-wire probe, ρ_J is the nominal jet-exit density and U_J is the nominal jet-exit velocity. Figure 6 shows the mean axial velocity profile of the boundary layer for the three cases tested and the average of zigzag-valley and zigzag-peak. It is shown that the zigzag tape increases the boundary layer thickness near the zigzag peak, but it reduces the boundary layer thickness downstream the zigzag valley. The average between the two profiles shows an overall growth in the boundary layer thickness when compared to the baseline case without the zigzag tape.

Table 1 shows that the zigzag tape reduces the thrust coefficient by 1.24%. Increasing the nominal jet-exit velocity (U_J) by 0.64% is enough to counteract this effect and recover the thrust coefficient to its baseline value. As the acoustic power of the mixing noise scales with the eighth power of nominal jet-exit velocity (Lighthill, 1952), the increase of the nominal jet-exit velocity would result in an increase of 0.21 dB OASPL at 90º. As the zigzag reduces the OASPL by 1.70 dB at the sideline (90º), a net benefit of 1.49 dB is still achieved.

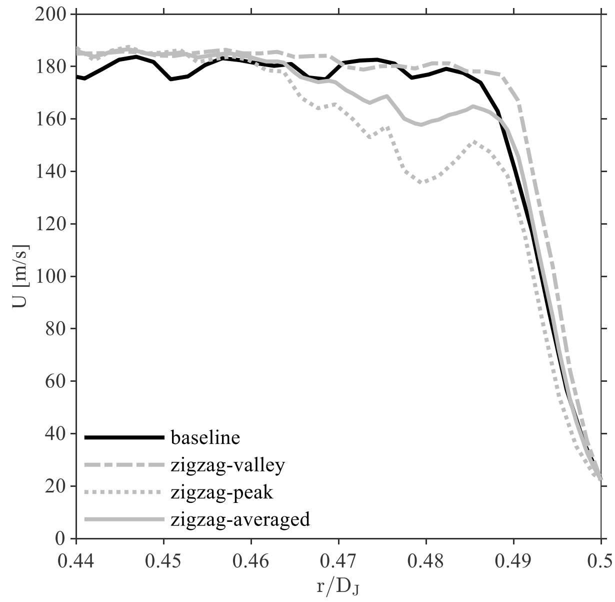


Figure 6. Boundary layer profile at the nozzle exit for different configurations and the resulting thrust coefficient (C_T).

Table 1. Thrust coefficient for different configurations.

Velocity profile	C_T
baseline	0.968
zigzag-valley	0.978
zigzag-peak	0.938
zigzag-averaged	0.956

4. CONCLUSIONS

The experimental analysis presented in this paper extends the work of Meyer et al. (2013) in two ways. First, the noise reduction achieved by the zigzag tapes are confirmed in a different facility and for a different nozzle geometry. Second, hot-wire measurements are carried out in the jet plume and used to evaluate the reduction in the thrust coefficient and to relate the broadband noise to the turbulence intensity in the jet plume. The reduction in the turbulence intensity observed in the hot-wire measurements can explain the broadband reduction in the noise output when the zigzag tape is applied to the inner nozzle surface.

5. ACKNOWLEDGEMENTS

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