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Validation of cold jet noise rig at Laboratory of Acoustic and Vibration (LVA), Federal University of Santa Catarina (UFSC)

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Abstract

Jet noise is one of the main noise sources in an aircraft, especially at take-off conditions. Considerable resources have been applied to the study of the noise sources mechanisms involved and ways to reduce it. Nevertheless, many questions still remain about jet noise generation and applicable noise mitigation techniques. In order to reduce the costs involved in jet noise studies, the use of experimental data obtained by means of measurements in small-scale models has been the norm. The so-called jet noise rigs aim at reproducing the noise generation phenomena present in real aircraft engine jets and, in order to be used with confidence, need to be properly design and its data validated. This work focuses on the acoustic validation of a jet noise rig recently built at the Laboratory of Acoustic and Vibration (LVA), Federal University of Santa Catarina (UFSC). To this aim, results from noise measurements in the new rig are compared with experimental data available in the literature and analytical models. Prior to the jet noise measurements, a detailed analysis was performed to investigate relevant parameters that could affect the measurements, such as the acquisition system, positioning of microphones and background noise due to machinery. The validation considered the jet noise from a smooth circular nozzle with 2” diameters, cold flow and subsonic conditions (Mach number 0.3 to 0.9), and a chevron nozzle in the same conditions. In both case, the nozzle geometries used are the same as the series of NASA Small Metal Chevrons. Results indicated that LVA/UFSC jet noise rig can be considered acoustically validated, since the sound field measured is in agreement with published data and expected trends.

Keywords: rig jet, aeroacustic, jet noise

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1 Introduction

The sound generated by the airstream coming from aircraft engine exhaustion is one of the main acoustic sources from modern jet airliners during take-off. This jet generated noise has been studied for decades in order to understand the physics phenomena associated to it, understand its characteristics and attempt to control it [1]. In general, advancements in the study of this noise have been achieved by means of noise reduction programs, which involved and partnerships between both of universities laboratories and industry.

In order to perform jet noise studies, experimental test benches have been developed so that better variable control and test conditions can be achieved. Due to the lack of standardization for designing such test bench, each research facility has come up with its on design in order to best meet its research necessities. In this sense, several aspects of the test rig can affect the measured data [2]. Therefore, a detail analysis of such aspects is needed to verify the rig operation capacity and to allow the comparison with results from other institutions. Ultimately, the acquired data from standard nozzles can be compared with known published results, and the rig may be considered validated if a good agreement is observed.

The objective of this paper is to present the validation procedure of a test rig dedicated to jet noise studies recently constructed at the Vibrations and Acoustics Laboratory of the Federal University of Santa Catarina. The validation process was carried out for the case of a single isolated subsonic cold jet, and the first step was the analysis of the Data Acquisition Device (DAQ), followed by the definition of the microphones positions so that a far field condition can be met. The evaluation of the background noise in different conditions was then performed. Subsequently, data repeatability was verified, and, finally, measured data was compared with results from analytical noise prediction and from published data.

2 Jet Noise Rig at LVA/UFSC

The jet noise rig at LVA/UFSC consists of the following elements: a compressed air line, a plenum, a discharge nozzle, an anechoic chamber, a flow control system and an acoustic data acquisition system. A schematic of the rig is shown in Figure 1. The compressed air line is constituted, in order, by: a compressor, filters for particulate removal, two-towers dehumidifier to guarantee a dry air flow, a first check valve to block air from returning in the line, pressure vessel for air stocking, a second check valve and a flow control valve. The air that exits the control valve is discharged in the plenum (a cylinder with large dimensions) containing chicanes and acoustic lining in its interior. The purpose of this device is to remove the noise generated by the downstream airflow, and it is also admitted as a stagnation condition for the fluid. Upon exiting the plenum, the air follows a 6” diameter line until it finds a convergent nozzle. The nozzle used at LVA rig in the validation procedure has its design published in the literature [3], and it is part of the Small Metal Chevron series – SMC000 from NASA. This nozzle was chosen so that the results could be compared in a direct manner with published data.

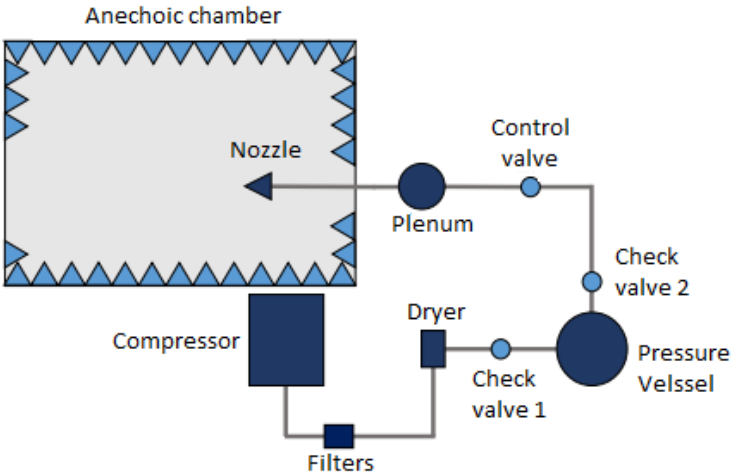

Figure 1: Schematics of the jet noise rig at LVA/UFSC.

The flow control system was developed in the *LabVIEW* platform, and it is based on isentropic relations of the airflow using pressure and temperature values from both the plenum and the anechoic chamber measured at a 10 Hz acquisition rate. The acoustic data acquisition system is composed of 10 ¼" free field microphones (G.R.A.S. Type 42BE) with working frequency range of 10 to 100 kHz, and a PXIe platform model 1082 from *Nation Instruments (NI).* Allocated to the PXIe platform are two PXIe 4499 data acquisition cards and a PXI 6723 static and waveform analogue output card, both manufactured by NI. The commercial data acquisition and signal processing software *Signal Express* (NI) was used. The microphones are allocated over an arc of 2.1 m radius and covering 60° to 150° angles from the jet axis, with 150° being upstream the nozzle and 60° downstream. The anechoic chamber in which the jet is discharged has approximately 60 m² with two openings in its walls to allow airflow. Acoustic measurements last around 20 s with a sampling frequency of 120 kHz and the results being an average of 200 samples for 1/3 octave bands and 1,000 samples for narrow-band. Both averages are linear and utilize Hanning window, while the narrow-band spectra also using a 50% overlap, which gives a 50 Hz band spacing.

3 Analysis of the experimental set-up

3.1 Data acquisition system (DAQ)

This subsection intends on analysing the data acquisition system in order to define the frequency range in which the system response is planar within acceptable errors. A similar methodology to the one adopted here was described in [3]. The methodology consists in generating a white noise in the same spectral frequency used by the data acquisition, and measuring the frequency response of the DAQ. The PXI-6723 card plugged to the PXIe platform and controlled by the Signal Express software is used to generate the white noise. The PXI-6723 is plugged to a connector block SCB-68A (NI), which directly sends the signal to the PXI-4499 (NI) data acquisition board. The PXI-4499 (NI) data acquisition board is the same used in the acoustics measurements and uses the same configurations: 20 s measurements with a 120 kHz sampling frequency and 50 Hz frequency resolution.

Figure 2 displays the measured data in blue and a fitted curve in red. Without the oscillations found in the measured data, the fitted curve is utilized for analysis. It can be seen that the DAQ system has a practically flat response with deviations lower than 0.3 dB up until 55 kHz. Higher deviations above 55 kHz can be found, with values as high as 4 dB in 60 kHz. Distortions up to 0.3 dB are accepted, so that data will be acquired up to 50 kHz in narrow band, and the 1/3 octave band spectra will extend until 40 kHz (central frequency).

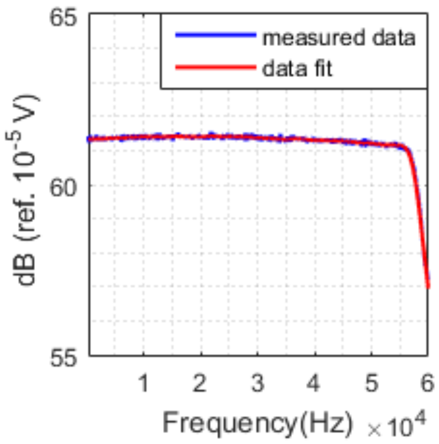

Figure 2: DAQ frequency response function for a 120 kHz sampling frequency and the fitted curve.

3.2 Acoustic far-field condition

The position of the microphones is a vital aspect of the measurements, since the microphones may be positioned either at near field or the far field generated by jet noise. The interest lies in evaluating the source at the far field, where the particle velocity is in phase with the sound pressure and there is a 6 dB decay in the sound pressure level (SPL) per doubling of distance (assuming spherical propagation). A similar methodology to that used by [4] was chosen to verify the far field condition. The analysis was carried out at 4 angular positions (60°, 90°, 120° and 150°) and 6 distances from the nozzle center, ranging from 1.60 m to 2.10 m. For a 2" (0.0508 m) diameter nozzle the radial position to effective nozzle diameter ratio $\left(\frac{r}{D_e}\right)$ is ranging from approximately 32 (1.60 m) to 42 (2.10 m) diameters. The procedure was done at several Mach numbers (acoustic Mach number). Measurements were conducted 5 times for each Mach condition and an atmospheric attenuation function (ARP 866 [6]) was used to correct the data due to atmospheric absorption. More details about the procedure can be found in [5].

The farthest position is assumed to be in the far field, and the inverse square law is drawn from this point as show in Figure 3 (blue curve). A $\pm$0.5 dB margin of error is also included and it is show in red in Figure 3. It is then verified if there is alignment between the measured SPL in other positions with the predictions from the inverse square law within the error margin. For example, Figure 3 shows the far field condition test for 0.9 Mach number and a 90° angular position. If there is consecutive alignment from the measured SPL and the last data point from the inverse square law, including the margin of error, it is assumed then that the far field condition has been met, otherwise the initial assumption is disregarded and even the last position is not accepted as being in the far field.

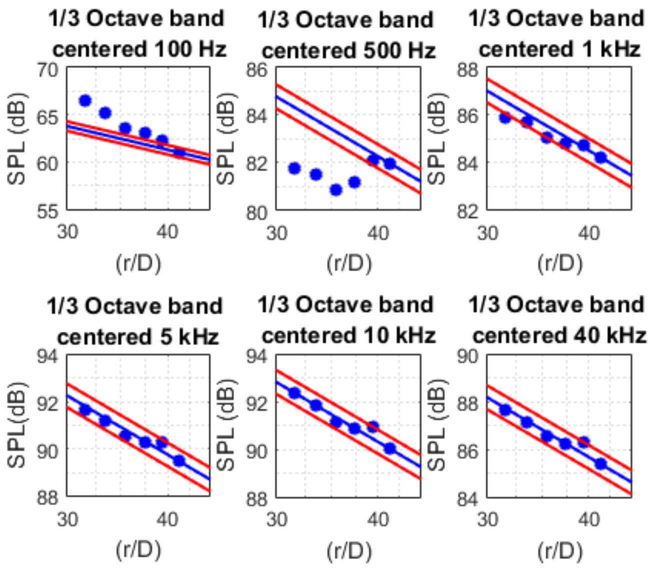

Figure 3: SPL x distance with 0.9 Mach number in 90° angular position.

In the case showed in Figure 3, the far field condition (accordingly to the adopted procedure) is not achieved for the 100 Hz band, and it is only possible to obtain a far field condition from frequencies higher than the 500 Hz band for the farthest microphone position (2.00 m). For frequency bands higher than 5 kHz, the far field condition is met at the first radial distance evaluated. Table 1 summarize the data for all tested Mach numbers and angular positions.

Table 1: **Correlation between radial distance and effective diameter for the SMC000 nozzle in which far field condition were met for 1/3 octave band higher than 500 Hz.**

Acoustic Mach number	$\frac{r}{D_e}$ **ratio where far field conditions were met**			
	θ = 60°	θ = 90°	θ = 120°	θ = 150°
0.30	≈ 39	≈ 39	≈ 37	≈ 37
0.50	≈ 39	≈ 37	≈ 35	≈ 35
0.70 and 0.90	≈ 39	≈ 39	≈ 32	≈ 35

Based on all test data, the far field condition is considered to be achieved at all angular positions for frequencies above 500 Hz and a radial distance of 2.00 m ($\approx 39D_e$). For precaution it was opted to allocate the microphones to a 2.10 m (42 D_e) radial distance. Apart from establishing the position of the microphones, this test also sets the lower frequency limit.

3.3 Rig and background noise

A methodology to assess the influence of rig and background noise is proposed. In this sense, background noise is assumed as the noise measured by the microphones when no flow is being released, while rig noise is the noise generated by the rig during its operation, excluding the jet noise. The proposed methodology is based on maintaining the same air mass flow rate in the compressed air line, while the discharge speed of the jet is considerably reduced by removing the nozzle. Therefore, the noise generated by the compressed air line is unaltered, while the jet noise is reduced so that the rig noise prevails. The SMC000 nozzle has an effective radius of 1” (0.0254 m) and the piping which this nozzle is connected to has a 3” (0.0762 m) effective radius, meaning that there is a 9 times increase in the original area without the nozzle. This larger area proportionally reduces the flow velocity, while the irradiated sound pressure level decreases in the order of 9^8, which means a significant reduction of the jet noise.

Figure 4 shows the measured SPL in 1/3 octave bands between 500 Hz and 40kHz for 60°, 90°, 120° and 150° angular positions with the SMC000 nozzle (blue) and the 3” pipe without the nozzle (red). It is easily noticed that rig noise is well below the jet noise measured with the nozzle. It is possible to state that rig noise does not significantly affects the measure jet noise within the frequency range of interest.

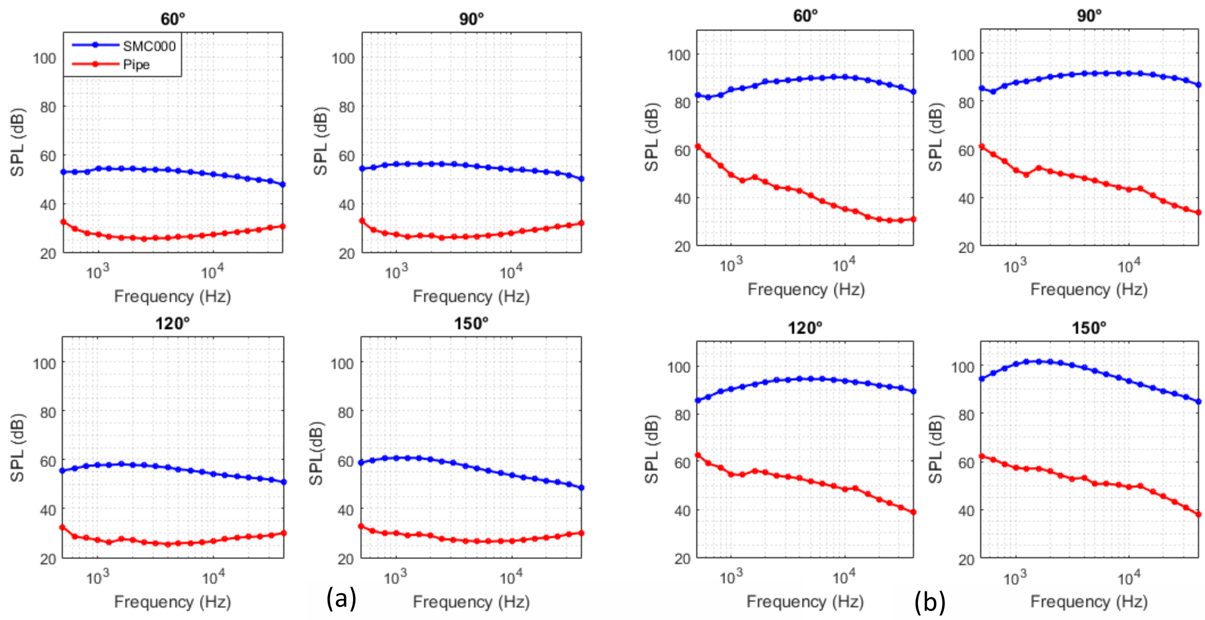

Figure 4: Comparison between SMC000 nozzle and piping without nozzle in two flow scenarios: a) 0.27 Kg/s mass flow and b) 0.80 Kg/s mass flow.

3.4 Repeatability

To verify the repeatability of the measurements, 5 identical measures were conducted in the same Mach number and the data distribution was analysed. Figure 5 shows the results of these measurements. For 0.3 Mach number flow condition there is a small deviation in the order of 0.5 dB between measurements, while a deviation lower than 0.2 dB was observed at Mach 0.9, which confirms the tendency proposed by the uncertainty analysis performed in [5]. In general, it is expected that in the worst case scenario differences in the order of 0.5 dB would be seen.

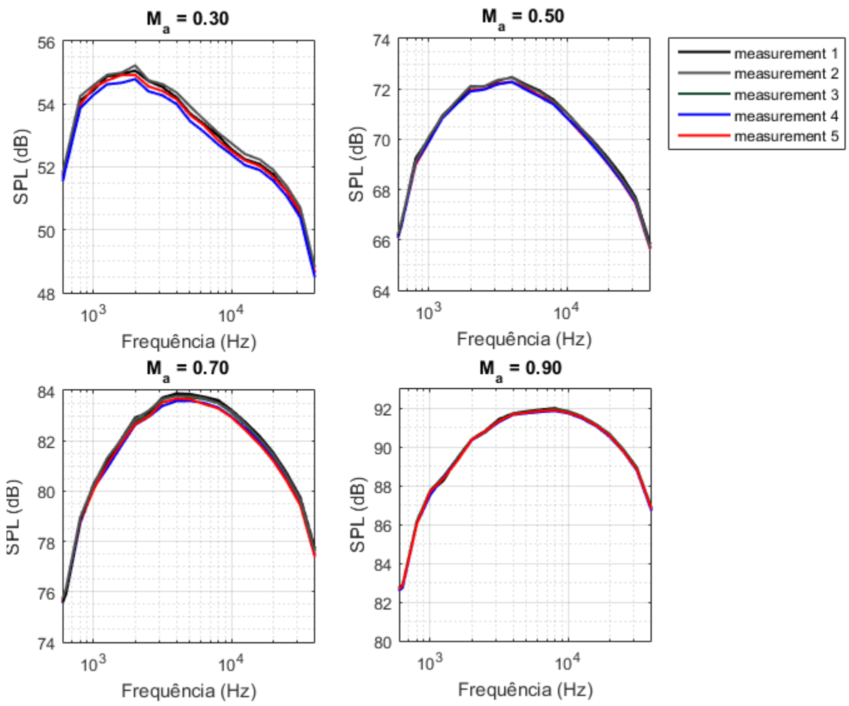

Figure 5: Analysis of the repeatability of the measurements at 90°.

4 Comparing results with analytical predictions and published data

4.1 Lighthill's eighth power law

Increases of the Overall Sound Pressure Level (OASPL) in regards to flow velocity (translated by the acoustic Mach number) has an analytical prediction through Lighthill's eight power law [7]. This proposed law informs that the sound pressure levels should grow with the flow velocity's eight power and, depending on the angular position, convective and refraction effects may affect the power exponent [8]. Figure 5 a) brings the increase of OASPL with flow velocity for angular positions of 60°, 90°, 120° and 150°, while Figure 5 b) shows the observed slope for different angular positions. It is important to stress that these coefficients are based on 1/3 octave band measurements from 500 Hz to 40 kHz, the same range considered in [3].

Figure 5 shows differences in the sound pressure level between measured values and Lighthill's eighth power law for positions upstream and downstream of jet nozzle. The angular coefficients displayed in Figure 6 b) shows a close tendency to the eight power law up until angular position 120°, from then on the data start to greatly diverge and a coefficient close to nine is achieved for angular position 150°. This is in total accordance to [3], [9] and [10].

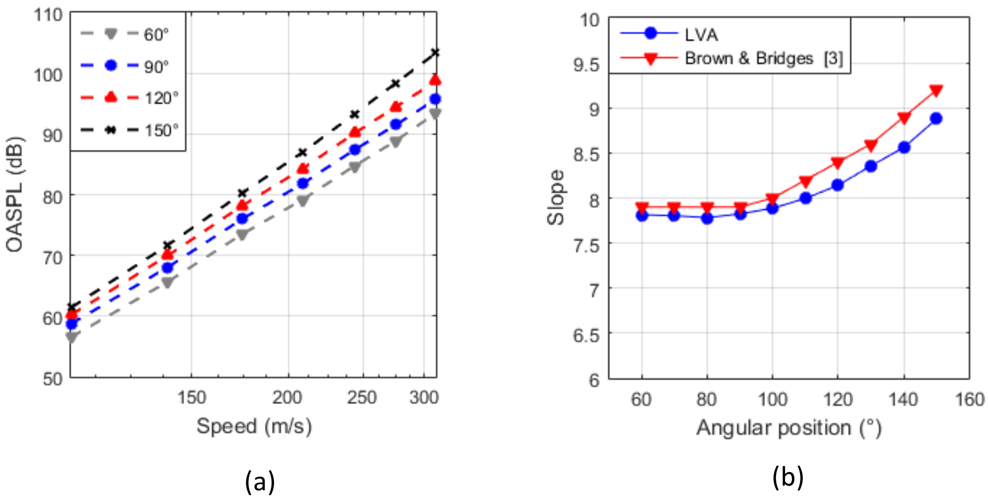

Figure 6: a) Increase of OASPL with flow velocity. b) Angular coefficient for each angular position.

4.2 1/3 octave band spectrum

Figure 7 shows 1/3 octave results obtained at LVA jet noise rig, together with measured data from Bridges & Brown [3]. Both data are shown from 500 Hz to 400 kHz 1/3 octave frequency band, without atmospheric absorption loss, following ARP 866 [9] procedures, and scaled to $100D_e$ for comparison. For angular positions 60° to 120° the maximum deviation found between the data sets is less than 2 dB. For the angular position 150°, a maximum difference of 2 dB can be seen for frequencies higher than 1 kHz, but between the 500 Hz and 1 kHz frequency bands it is possible to notice a larger difference amongst higher velocity curves, although not greater than 4 dB. It can be considered that the measured noise levels at the LVA/UFSC jet noise rig are in accordance with the literature and that the few discrepancies found can be associated to experimental errors such as imprecision in the microphones' angular position and/or physically associated to the piping extension before the nozzle.

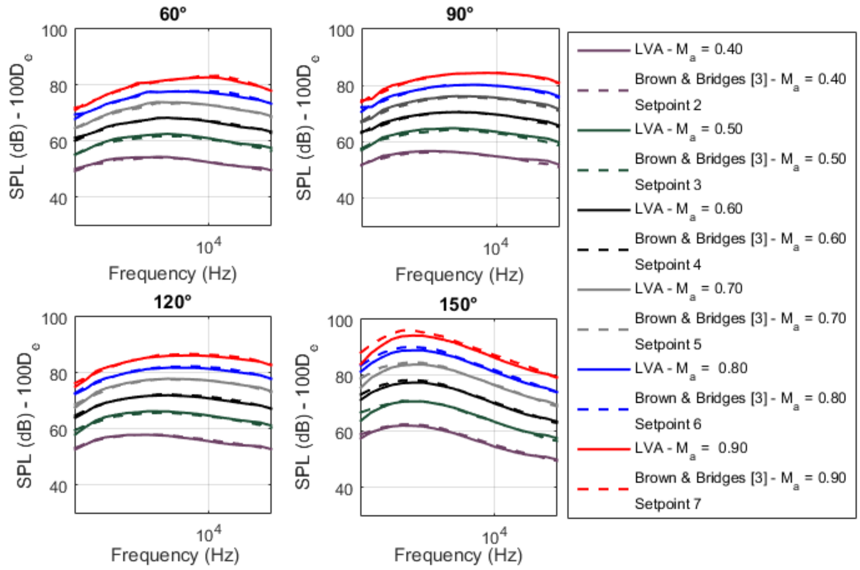

Figure 7: Comparison with published data by [3] and data measured at LVA/UFSC jet noise rig.

4.3 Narrow-band spectrum and similarity spectra

In order to analyse the data trends of narrow band spectrum, the similarity spectra F&G from ref. [11] were compared to measured data in angular positions 90° and 150°. Figure 8 shows the comparison between the measured and similarity spectra for M_a = 0.90. A very good agreement can be observed between the curves, reinforcing the confidence in the data acquire at LVA/UFSC jet noise rig.

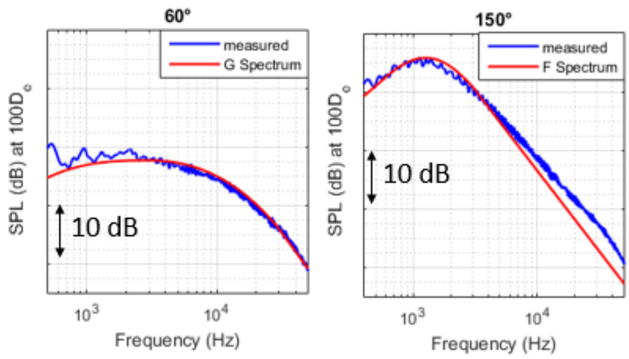

Figure 8: Comparison of measured spectra and similarity spectra for M_a= 0.90.

5 Conclusions

The procedure adopted for the validation of a recently constructed jet noise test rig has been presented, which included the analysis of the acquisition system and the test rig background noise and the comparison of measured data with analytical predictions and published results. The analysis of the data acquisition system defined 50 kHz as the upper limited of the valid frequency range (narrow band), or the 40 kHz 1/3 octave band, by assuming a maximum acceptable distortions of 0.3 dB. In order to ensure far field conditions, it was establish that measurements should be carried out for frequencies higher than 500 Hz and the microphones should be position at least 41D_e from the nozzle center. A data repeatability analysis, based on five measurements, indicated that the rig has deviations around 0.5 dB for Mach 0.3 (worst case scenario) getting values lower than 0.2 dB for Mach 0.9. The analysis of OASPL versus flow velocity measured at the rig showed a growth rate very similar to Lighthill's eighth power law for angular position smaller than 120° and closer to ninth power for position 150°, a behaviour very similar to that found by [3]. The 1/3 octave band spectra were compared to published data, and it showed differences lower than 2 dB for all Mach numbers considered, up until 150° angular position, where higher discrepancies were only found for higher Mach numbers as far as 1 kHz frequency. Nonetheless, discrepancies are attributed to the microphones' imprecision in angular positioning or to the piping length before the nozzle. Lastly, the LVA/UFSC jet noise test rig is considered valid, meaning that the noise generated and measured at the jet noise rig has characteristics and sound levels very similar to those found in the literature.

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