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WIND TUNNEL BACKGROUND NOISE ASSESSMENT FOR AEROACOUSTICS TESTS

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Abstract. *This work describes the investigation of noise sources in a low-speed wind tunnel originally design for aerodynamics measurements. Wind tunnel (WT) acoustic evaluation through noise source identification is a key point for remodeling the WT for making it available to perform aeroacoustics measurements through a set or array of microphones inside the test section. This noise source identification technique is named Beamforming. Based on this noise assessment the work was challenged to find feasible alternatives for implementing quick improvements in the wind tunnel which could reduce the noise levels inside the test section. Additionally, a literature review about characteristics of worldwide aeroacoustics wind tunnel is presented pointing out to improvements and alternative solutions that maybe considered for the current WT. Results are presented for single and multiple microphones (beamforming technique) placed at different locations in the WT.*

Keywords: *wind tunnel, background noise, aeroacoustics, instrumentation, beamforming*

1. INTRODUCTION

During the last decades it well known that many low-speed (subsonic) wind tunnels at aerospace industry and universities have been passed through an upgrade in their facilities to be able to perform aeroacoustics measurements as well as traditional flow characteristic assessment (aerodynamic flow-evaluation). Most of those facilities are large and relatively old and, therefore, an upgrade was more adequate despite the fact some of the wind tunnel circuit noise sources are difficult to cure without radical modifications. As the demand on aeroacoustics for the car industry is increasing in the last decades, most of the companies such Audi, Hyundai and Nissan have designed and built new facilities and documented the process – Wickern and Lindener (2000), Kim et al. (2001) and Ogata et al. (1987) and Duell et al. (2013), respectively. The University of Twente in the Netherlands and the University of Florida in the US also upgraded their facilities to aero-acoustic measurements capability – Santana et al. (2018) and Pascioni et al. (2013), respectively. The NASA LSAWT (Low Speed Aero-acoustic Wind Tunnel) in Langley Research Centre, Hampton VA, underwent an aero-acoustic conversion and the performance of the proposed modifications was assessed in 2005 as well as the Small Anechoic Wind Tunnel KAT at NLR – Soderman and Larry (1992).

An example of a low-speed wind tunnel designed for aeroacoustics measurements is the LSAWT (Low Speed Aero-acoustic Wind Tunnel) at NASA Langley, which is an open-circuit open-jet acoustic facility equipped for jet engine simulations. Besides the well-known LSAWT (Low Speed Aero-acoustic Wind Tunnel) at NASA Langley, several industry and universities have recognized the need to upgrade their facilities to be able to conduct aeroacoustic measurements as well as traditional flow characteristic assessment. Nissan, as well as General Motors, Daimler Benz, FIAT and other commercial automobile manufacturers have built wind tunnels with emphasis given on background noise reduction. The designers at Nissan choose a closed-circuit configuration of the so-called Goettingen-type, with a semi-open test section. The walls and ceilings as well as the corner vanes have been acoustically treated to reduce the emanating noise. The test section is lined with sound-absorbing wedges to create a semi-anechoic chamber, eliminating noise from the fan and wall reflections. The use of a honeycomb and two turbulence screens as well as a fine heat exchanger control the flow. Low turbulence is achieved by carefully designing the nozzle contraction (6.43 for the larger model and 12 for the smaller one, giving a respective maximal wind velocity of 50 m/s and 75 m/s). The Nissan wind tunnel has the particularity to be able to operate in open conditions for smoke streamline observation.

The new Audi facility is interesting regarding the collector design. It is an open-jet facility with closed return featuring a nozzle area of 11 m^2 and a top speed of over 80 m/s. The choice of such a test cross-section was dictated by low jet noise generation and general accessibility. An important survey of existing facilities and the incorporation of the latest findings contribute to the cost-effectiveness of the design, allowing similar experimental accuracy to facilities with jet cross-sections 2-4 times greater. The wind tunnel is equipped with two external balances for full and model scale measurements. This allows for a fast change between configurations. A large moving belt is installed between the wheels to simulate ground effect. To ensure belt flatness, a special suction system was developed. Additional individual belts were installed to drive the wheels since the large belt cannot be used for this purpose. An adjustable boundary layer suction system is implemented ahead of the test model. At the time of the first operational experience in spring 1999, the Audi wind tunnel had the lowest background noise level for an automotive application. Audi have installed an active resonance control system (ARC) to suppress the wind tunnel low-frequency pressure fluctuations known as "wind tunnel pumping". Hyundai's new facility was built to improve aerodynamic characteristics and meet the new fuel consumption regulations. The need for aero-acoustic testing was also recognized and the new wind tunnel was developed as a Goettingen-type closed circuit with a ¾ semi-opened jet test section surrounded by an acoustically treated plenum. The boundary layer can be removed using a suction system installed in front of the test section. The facility is treated with acoustic panels and the plenum is lined with acoustic wedges. The first and third corners have acoustically treated vanes. The fan (9 rotor and 8 stator blades) housing has acoustic insulation further reducing the noise level and vibration sensors were installed to detect any vibration of the shaft.

At the university side, the existing closed-circuit facility in the University of Twente was recently upgraded to enable aero-acoustic research. The primary objective was to develop and validate Computational Aero-Acoustic (CAA) methods for flow-induced broadband noise. The major tunnel components such as the test section, the collector, the anechoic chamber, the fan and the silencers were modified. An open test section was designed for sound measurements but experiments with a closed test section configuration still had to be possible. The collector design was an important part of the new wind tunnel. The location of the collector at the most rearward position (closed breather slot) is of 4.38 nozzle diameters. The cross-section area ratio was chosen to be AC/AN=2.39 based on free-jet increase predictions. This choice is a compromise between a larger area that would increase power losses and a smaller section that would require a breather slot to avoid pumping. Although no breather slot is desired to avoid high frequency noise, it is considered to overcome blockage issues.

The LAE-1 wind tunnel of the Aerodynamics Laboratory from Aeronautical Engineering Department of EESC, is used for testing both aerodynamics and aeroacoustics testing as part of the major program between Brazilian Aircraft Industry (EMBRAER) on aeroacoustics called Silent Aircraft. In order to perform such tests, in 2008, an upgrade was carried out to decrease background noise and the implementation of a microphone array as is described in Santana et al. (2010). Two-dimensional high-lift wing models has them been testing for slat and flap side-edge noise with success. Recently, a campaign was performed to test nose landing gears (NLG) such as a basic Lagoon model and a more complex B777 nose landing gear. When developed noise reduction technologies were applied to the models their noise spectra were very close to the wind tunnel background noise showing a poor model noise signal to background ratio. Therefore, this paper describes the LAE-1 wind tunnel (WT) acoustic re-evaluation and identification of noise sources in the LAE-1 at São Carlos School of Engineering (EESC-USP). The local team worked in finding noise sources in this WT during different development phases. Tests were carried out with single microphones placed at different locations inside the equipment (WT) and beamforming phased-array to characterize the background noise at the test-section for different flow speeds. More to identify the noise sources, it is also planned to incorporate acoustic improvements (acoustic treatment) inside the sections to reduce the background noise levels and to make it available to perform aeroacoustics measurements with high degree of fidelity and reliability.

2. METHODOLOGY

The LAE-1 wind tunnel (WT), as described in Fig.1, in the São Carlos School of Engineering – University of São Paulo, is a closed-circuit, closed-test-section WT and it was originally designed for aeronautical and automotive tests – Catalano (2004). The test-section is 3.0 m in length, 1.29 m in height and 1.68 m in the spanwise direction, the fan is driven by a 110hp electrical motor, allowing flow speeds at test-section around 40 m/s, as described by Catalano (2004).

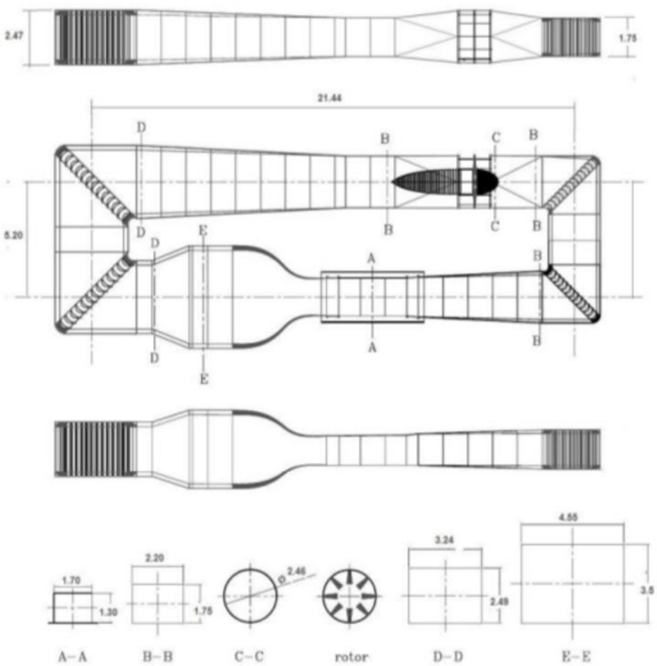
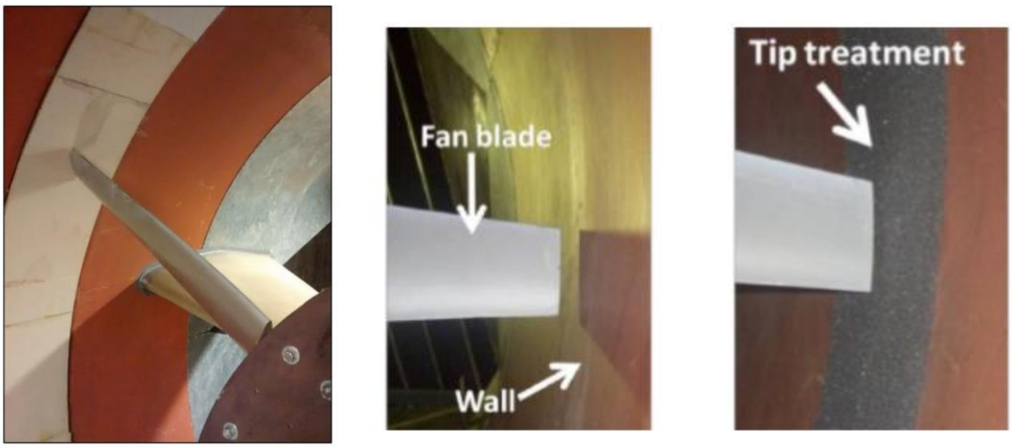


Figure 1. LAE-1 wind tunnel plan view, Source: Catalano (2004).

This current configuration of LAE-1 already has some acoustic treatment. The work of Santana et al. (2010) describes the application of melamine foam on some specific walls of the WT, installation of an acoustic baffle between the corner vanes sections. Additional small modifications on the wind-tunnel were performed aiming to reduce the wind tunnel background noise and increase its speed. Modifications included increases in the fan blade pitch removing the prior installed Gurney Flaps and blade tip treatments in order to reduce the blade tip to wall gap. Figure 2 shows the modifications described herein.



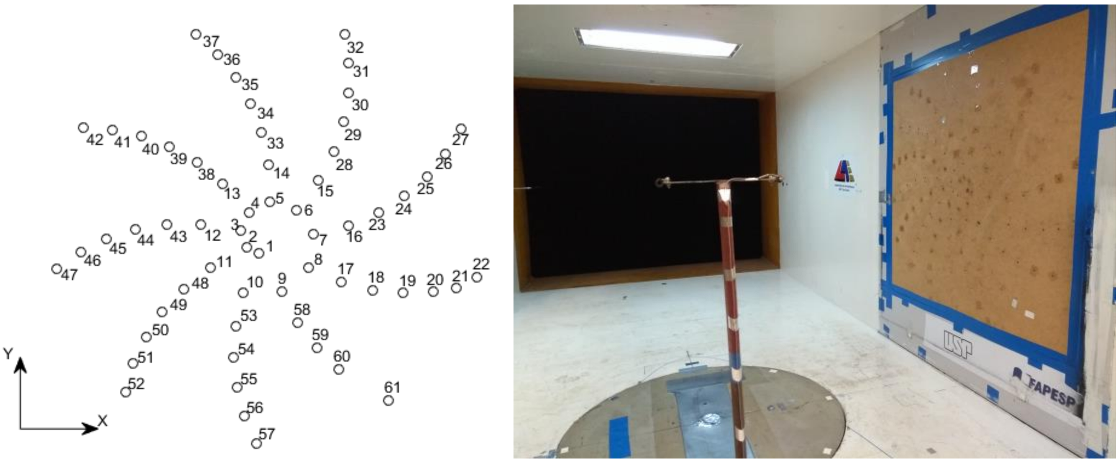
(a) (b)

Figure 2. Modifications applied to the drive-system (a) Increased blade pitch; (b) Blade tip treatment.

2.1 Instrumentation for Aeroacoustic Measurements

Aeroacoustic measurements are carried out with a 61-microphone array mounted on the tunnel side wall at two different possible locations for sideline and flyover measurements. The microphones are G.R.A.S. 46BD cartridges, combining a pressure transducer (40BD) and a pre-amplifier (26CB). The instrumentation is designed for a flat response from 7Hz to 40kHz (1dB loss) or from 4Hz to 70kHz (2dB loss).

The microphone array is designed with a modified spiral geometry - Fonseca et al. 2010 - in order to allow measurements at a large frequency band. The 61 microphones are positioned in a 0.8m × 0.8m wall for the sideline antenna. The flyover antenna has the same geometry but reduced to fit in the upper part of the turn-table system, with a diameter of 0.7 m, according to Fig. 3.



(a) (b)

Figure 3. (a) Description of microphones-array; (b) Actual microphone antenna – sideline position.

Acquisition is performed through a PXI system®, composed by four NI PXIe-4496 boards with capacity to hold simultaneously 64 analog inputs with 24 bits resolution and maximum of 204.8kS/s sample rate. The acquisition is controlled by a PXIe-8135 controller. RS-232 communications and regular Analog input and output are assessed via PXIe-8430 and PXIe-6341 respectively. This system allowed to perform the noise beamforming or noise source identification by an array of microphones, which will be summarized in the next section.

Additionally, during the background measurements a single microphone G.R.A.S. 46BD installed in a stand (mounting) at different WT sections was used. This complementary analysis was quite important to identify and locate the main noise sources in different locations inside the WT. To reduce the probe intrusion (interference) into the flow, two different stands (mountings) were tested in order to verify the one with minimum interference in the microphone measurements. The two tested mountings are presented in Figure 4. Moreover, as the microphones were exposed to the wind at high speeds, there was a need to protect the sensor and to reduce the wind flow noise (self-noise) in the microphone. To achieve such goal, two different nose cone or forebody were used – G.R.A.S ¼" Nose Cone type RA0022 and a B&K ¼". The microphone with the nose cone installed on it is also shown in Fig.4.

(a) (b)

Figure 4. Two microphone's stands tested. (a) with flat plate; (b) with advanced probe.

2.2 Beamforming Technique

According to Bolívar (2019), an array of microphones is used to record the pressure fluctuation over time for further calculating power spectra. Once microphones cannot reject interfering sources and quantify noise, a technique, called beamforming, is used for post-processing the acquired data. The method, developed by Boeing Company in 1994, creates a full array cross-spectral matrix for each frequency of interest using the microphones data – Dougherty (2002). A grid of a potential source location is then defined and a complex array steering vector is computed for each grid point, which considers the non-uniform flow, microphone imperfections and installation effects. Thus, the beamforming technique combines the cross-spectral matrices and steering vector to produce maps of the model acoustic distribution, and successively focuses the phased array for each point on a grid and measures the apparent source strength distribution (Bolívar 2019). Such a calculation depends on a mathematical model for the acoustic propagation from each grid point to each microphone. The mathematical model is based on the high-frequency wave propagation theory and will not be shown herein. During the array post-processing two beamforming algorithms were used namely Conventional Beamforming (CBF) and CLEAN-SC – Fischer et al. (2014). The beamforming algorithms were run in MATLAB scripts coupled to the PXI system ®. For post-processing of cross-spectral matrix (CSM) and plotting of beamforming maps an additional PC-workstation with multiprocessors were used due to time-memory consuming.

3. RESULTS

The results presented in this article is divided in two sections in accordance with the noise measurements performed to evaluate the WT acoustic signature. First, the noise data gathered with a single microphone at different wind tunnel locations are presented. Later, the noise data is presented by employing the 61-microphone antenna. These measurements allowed to identify the most prominent noise sources located inside the WT and to drive new conceptual designs to help reducing the noise levels inside the test-section.

3.1 Single Microphone Noise Measurements

In sequence the single microphone's data is presented. At first, two different stands (mountings) were tested in order to verify the one with minimum interference in the microphone measurements. It was decided to use the microphone with the advanced probe, as illustrated by Fig. 4(b).

A G.R.A.S. 46BD ¼" microphone with flat response up to 70kHz was used to assess the background noise in the middle of the test-section. Due to high total pressure fluctuations inside the flow, the microphone diaphragm was covered by a so-called "nose cone". As mentioned, two different nose cones were used, one from G.R.A.S. and other from B&K acoustic instruments – Fig. 5.

Figure 5. Example of a G.R.A.S. ¼" nose cone (forebody). Source: GRAS Sound and Vibration (www.gras.dk).

It is known that nose cones could affect the measurement itself due to its forebody. The forebody protects the fragile microphone diaphragm and reduce flow-induced noise while the response becomes virtually omnidirectional at frequencies below 5 kHz. However, they could induce noise at higher frequencies mainly due to the shear layer developing at the forebody and cavity tones in the element-sensor – Mueller (2002). After measurements and data reduction, it was possible to identify that the nose cone started to affect the background noise measurements at St~0.7 (close to 5 kHz, as expected). What was surprising, was the effect of the design of the forebody in the measurements. For a wind speed of 35m/s, both measurements with the B&K and G.R.A.S. type nose cones were compared, as illustrated in Fig. 6.

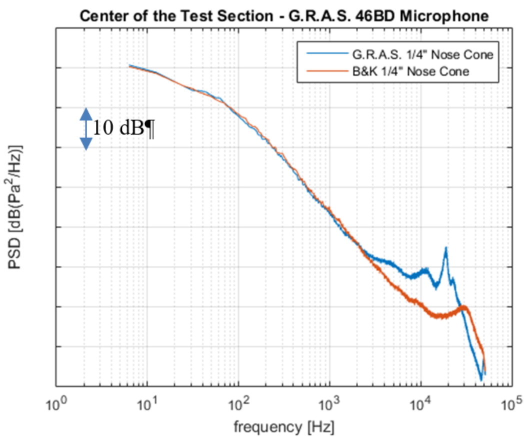


Figure 6. Nose cone influence in the background noise measurements at LAE-1.

As seen in Fig.6, with the use of B&K nose cone, the results were much better when compared to G.R.A.S. configuration. For the B&K nose cone the hump in curve started in 11kHz. Based on the results, the final background noise assessment was carried out with the use of B&K nose cones.

Figure 7 presents the background noise measurements for the G.R.A.S. 46BD ¼" mounted with the advance probe for different wind speeds at the test-section [9.8m/s, 15.3m/s, 20.9m/s, 26.7m/s, 35.2m/s, 40.9m/s and 46.4m/s]. The results in Fig 7 were consistent for wind speeds above 9.8m/s. Specifically at 9.8m/s some peaks were identified in the spectrum and in that case was some electrical noise present in the acquisition system.

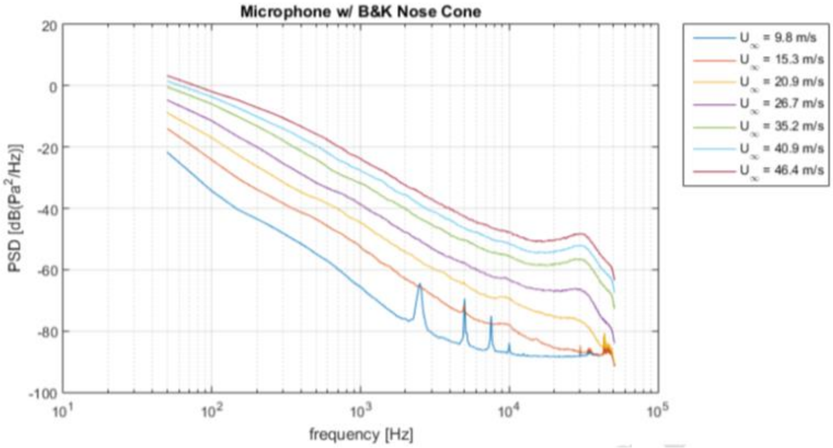


Figure 7. Background noise measurements at LAE-1 with single microphone.

Beamforming data by averaging 61 microphones was also acquired concomitantly with the single microphone measurement in the stand. The comparison between single microphone and beamforming is presented in Figure 8.

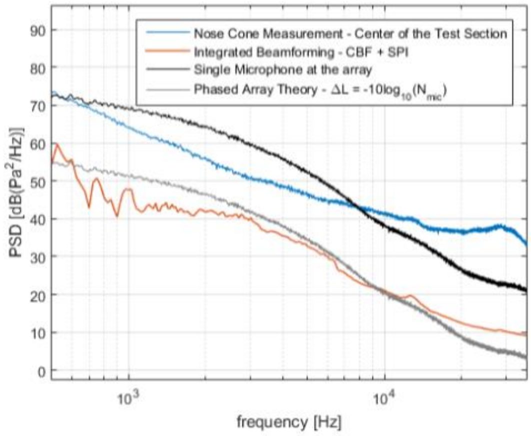


Figure 8. Background noise levels from single microphone versus beamforming data at the test-section

According to Fig.8, beamforming seems to be predicting noise levels smaller that the phased-array correlation theory. One of the reasons for that could be associated to possible help from the spatial filtering applied at the BF post-processing. Single microphone with B&K nose cone measurements were presenting higher noise levels, especially for frequencies above 5kHz. At the end of these measurements, a noise source identification was taken in the test-section by covering any small holes, slits or breaches with silver-tape. Even the aperture between the turning-table and the floor of the wind tunnel was sealed. Additionally, the WT venting-windows were also sealed. Another test was taken for a wind velocity of approximately 35m/s and the final background noise levels were gathered, as presented in Fig.9.

Based on the results in Fig.9, it is possible to affirm that additional noise is not coming from the test-section. It is interesting to observe that with the ventilation windows closed the noise levels were slightly higher. Sealing the vents was probably causing leaking at different positions along the WT, possibly causing the increased levels.

Finally, to accomplish the background noise measurements with flow, the microphone with the B&K nose cone was mounted at three positions within the WT, upstream of the turning vanes (downstream of test-section), downstream of the fan and upstream of the screens, as illustrated by Fig.10.

As seen in Fig.10, the noise levels at the test-section are mainly due to the noise emitted by the drive-system (fan noise) which propagates towards the back (exit) of the test-section. The spectra upstream the test-section corroborate the fact that the fan's wake have lower levels. It is also possible to identify in the spectra the blade passage frequency (BPF) around 90Hz and its multiple tones. Just for clarification the Figure 11 illustrates some pictures of the single microphone mounted at different locations along the wind tunnel.

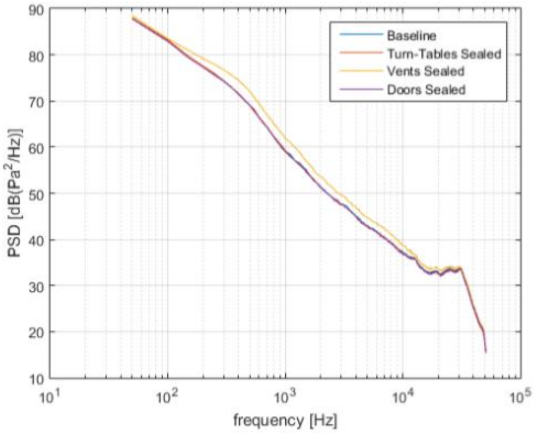


Figure 9. Background noise levels for different sealings at the test-section.

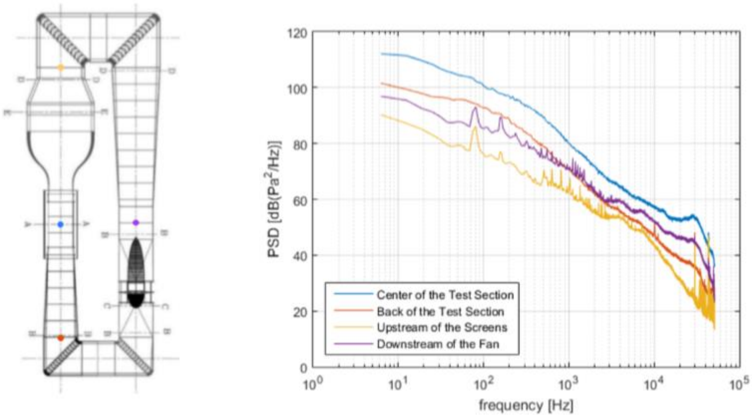
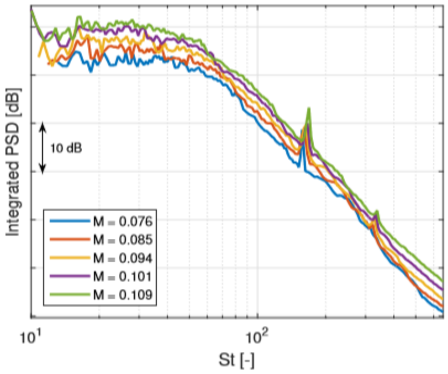


Figure 10. Background noise levels at different locations in the WT.

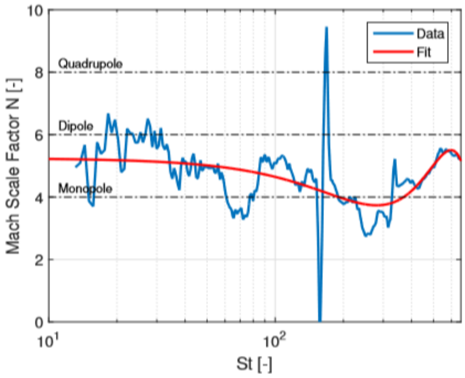
Figure 11. Single microphone measurements at different WT locations: (a) After the drive-system; (b) Upstream the screens.

3.2 Beamforming Noise Measurements

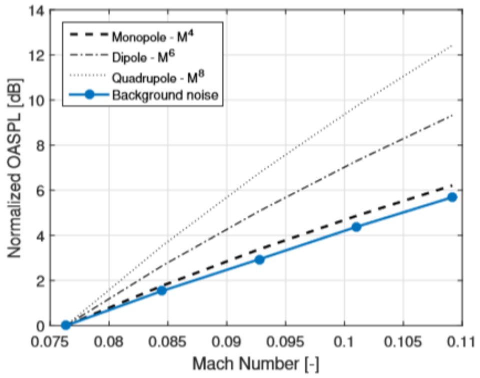
As identified by the single microphone measurements the LAE-1 wind tunnel presents some noise sources that could be addressed in future physical improvements. To complement the analysis, the background noise was investigated by assessing its influence on the measurements, regarding spectra and Mach scale factor – Giraldo (2019). Several measurements were performed for obtaining the background noise in the LAE-1 wind tunnel test-section. Figure 12 shows the wind tunnel sound pressure levels measured for different Mach numbers (usual to low-speed aeronautical configurations). The first spectral results in Fig. 12(a) is shown dimensionless as the Strouhal-number, provided an insight on the frequency scales with velocity. High-frequency peaks are caused by the Power inverter that rotated the fan of the wind tunnel. No peaks were detected between low to medium frequencies, which provided a broadband noise in all range with higher levels at low and mid frequencies.



(a) Background noise spectrum



(b) Mach scale factor



(c) OASPL (Filtered OverAll Sound Pressure Level)

Figure 12. 61-microphone array measurement of the background noise levels from LAE-1.

Mechanisms of background noise sources were investigated by the Mach scale factor (N). Fig. 12(b) shows the Mach scale factor as an average of the five velocities used and Fig. 12(c) displays a comparison between the OASPL obtained for the Mach numbers tested and expected curves. The scale estimated for the OASPL was found through the calculation of an average for the value of N. The results are in concordance with those expected as monopole scales were produced. Frequency and Mach scales are represented by Strouhal numbers calculated with the free-stream velocity. According to Allen et al. (2012) the main sources of wind tunnel background noise are the fan system (variables that contribute to fan noise are hub and tip diameter, rotational speed, number of blades and blade-pitch angle), wall boundary layer, test-dependent hardware, and microphone self-noise (boundary layer effect over the microphones, screen or cavity perturbations, electronic noise, and free-stream turbulence).

3.3 Proposed WT Improvements for Aeroacoustic Measurements

Based on the background noise measurements performed in this work and other development from previous works, it was possible to establish possible WT improvements to take place in further physical modifications. As illustrated by Fig.13, the potential noise reduction could take place in the regions (A), (B), (C), (D) and (E). Currently, acoustic treatment with melamine foam is already inserted in regions (A), (B) and (D).

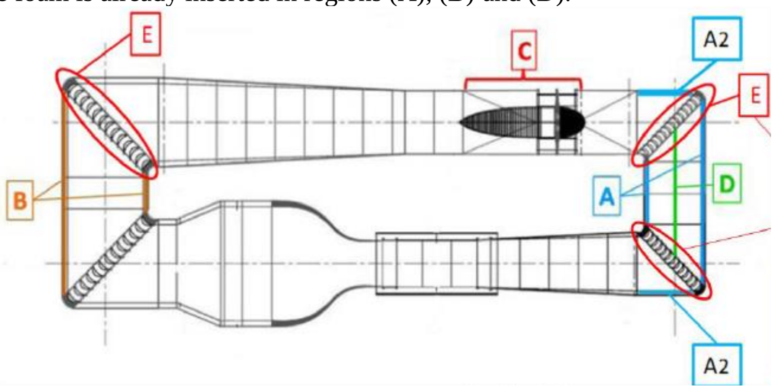


Figure 13. Potential noise-reduction areas within the LAE-1.

Another important modification that is being executed is the acoustic-treatment in pressure side of the corner-vanes, as illustrated by Fig. 14. Corners (1) and (2) downstream the test-section will have this modification to reduce the mid-frequency content from the drive-system. Also, the melamine foam in the sidewall and splitter plate would be improved to help reducing the noise levels.

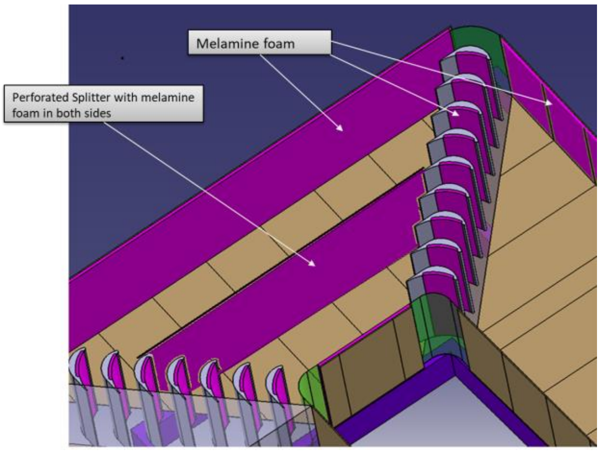


Figure 14. Acoustic-treatment in the corners (1) and (2) within the LAE-1.

Testing with no flow and with 10 mm acoustic foam applied to the corner vanes pressure side in both corner 1 and 2 showed promising results for the frequency range where the background noise is more relevant. The idea is to abate sound waves with lengths up to the corner vanes chord coming from the fan. Figure 15 show the twitter placed at the fan front fairing and the results for foam at the second vanes only and at both 1 and 2 corners vanes. The acoustic treatment applied at the turning-vanes appears to be very effective in reducing noise levels in the range of frequencies higher than 1000Hz (for wavelength smaller than corner vane chord).

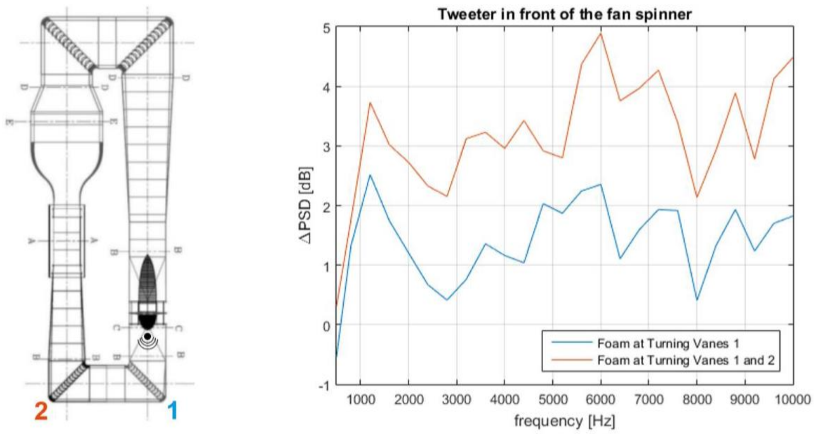


Figure 15. Results for the effect of foam placement at corner vanes 1 and 2

4. CONCLUDING & REMARKS

Background noise measurements were carried out in a low-speed wind tunnel with the purposes to find a way to reduce the noise sources inside the WT and to make it available for aeroacoustics measurements. Background noise with and without flow, data from accelerometers and tests with more sophisticated techniques such as beamforming (array of microphones) were employed to gather reliable results that could indicate what could be the level of WT modifications. The results showed in this work were consistent and revealed potential for improvements in the LAE-1 wind tunnel at São Paulo School of Engineering (EESC-USP). During the year of 2019, it is establish a third-phase of acoustic improvements for this WT, which will be based on the insertion of acoustic treatment in the corner-vanes at the turns (1) and (2), improvement of the melamine covering for the sidewall and splitter plater and possibly a major modification in the 61-microphone array with the inclusion of a Kevlar top-covering over the recessed microphones. It is believed that all these modifications in the WT will reduce the noise levels in the working section by an amount of 3 up to 6 dB, allowing a satisfactory background noise reduction. Thus, the WT could be used to investigate more detailed aeronautical configurations such as complex landing gear, high-lift and even different flap side-edge configurations. Additionally, fundamental research also will gain focus which could bring the development of future products (patent) or configurations for use in the aeronautical industry.

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