THE UPDATE PROCESS AND CHARACTERIZATION OF THE SÃO PAULO UNIVERSITY WIND-TUNNEL FOR AEROACOUSTICS TESTING

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Abstract

The aircraft noise is one of the major environmental problems of the population living around big airports. In order to study this many aeroacustic test facilities have been constructed or adapted around world. The present paper shows the results of the update of a previous aerodynamics wind-tunnel into a wind-tunnel with capacity to execute aeroacoustics tests, while keeping its good aerodynamic qualities. In order to reduce the wind tunnel background noise level, melamine foam was applied on wind-tunnel walls, and an acoustic baffle was installed between corner vane sections. Also a treatment was applied to the tip fan to the tip fan blades and the noise generated by the electric motor was insulated. Results showed a reduction of up to 5 dB and a noticeable removal of spectral tones after the wind-tunnel treatment. Another positive effect of the noise reduction was the decrease of test section turbulence, from its previous level of 0.25% to 0.21%. As a minor penalty, the insertion of noise treatment caused a maximum flow velocity maximum reduction of 2% for the same electric power input. All this process, described by the present paper, resulted on a wind-tunnel with good flow quality and capacity for aeroacoustics measurements.

1 Introduction

With the aerial transportation increase the aircraft noise became a preoccupation to authorities and airport administrators of important cities. As a reaction, the authorities established noise stringent restrictions to aircraft certification and operations. In order to satisfy these restrictions, the aeronautic industry has developed means to reduce the engine noise. With the present state of art technology, the aircraft engine noise, mainly a high by-pass turbofan noise, reached the same level of the airframe noise. Therefore, the engine noise reduction is no longer the only preoccupation of the aeronautic industry, with the aeroacoustic optimization of aircraft components occupying the work table of design engineers and aeronautical researchers.

In order to develop aeroacoustics studies many wind-tunnels with capacities to execute aeroacoustics tests have been constructed around world [1], [2] and [3], or adapted from a pure aerodynamic wind tunnel [4] and [5]. As part of a major program to obtain knowledge on aeroacoustics and keep the Brazilian aeronautic industry competitive, the University of São Paulo wind tunnel (LAE-1) was upgraded to carry out aeroacoustic tests. There was a trend on the past, for the construction of very silent wind tunnels for aeroacoustics tests, with the models installed in an anechoic chamber to avoid reverberant effects of the wind-tunnel walls [6] and [7]. The philosophy adopted here for the LAE-1 wind-tunnel was to use a hard-walled circuit, with a reasonably low background noise level, and noise spectra with a small number of tones. This construction concept relies on the fact that with the use of advanced phased microphone array techniques, it is possible to measure model noise sources intensity and localization, using the beamforming technique [8], [9], [10]. In the present paper, the background noise is defined as the noise generated by the wind-tunnel functioning with an empty testing chamber.

The present paper is organized as follows: the section 2 describes the LAE-1 closed circuit wind-tunnel; the section 3 describes the wind-tunnel background noise reduction process; the section 4 presents the wind-tunnel background noise measurements results; the section 5 presents the effect of the wind-tunnel background noise reduction on the flow turbulence level and flow velocity for an identical power and finally the section 6 shows the conclusions.

2 The LAE-1 closed circuit wind-tunnel

The LAE-1 closed circuit wind-tunnel was designed originally as a 3/8 scale pilot wind-tunnel of a proposed automotive wind-tunnel to be constructed. The wind-tunnel construction started in 1997 and finished in 2002. Its predominant construction material is the naval plywood. With the automotive industries reduction of investments and the rebirth of the Brazilian aeronautic industry this wind-tunnel became a multi task wind-tunnel with instrumentation mainly focused on aeronautical tests for industry and academic research.
The Fig 1 presents a plan view of the LAE-1 closed circuit wind-tunnel.

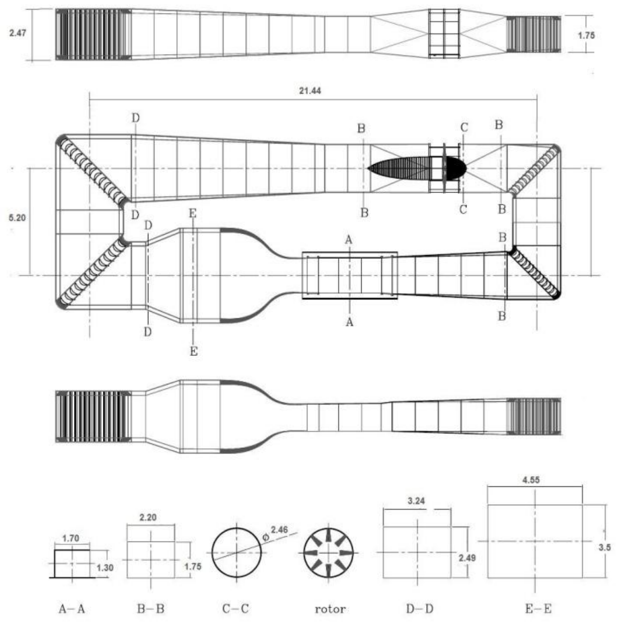

Fig 1: Plan view of the LAE-1 wind-tunnel

The wind-tunnel test section dimensions are 3.00 m long, 1.30 m high and 1.70 m wide. The maximum design flow speed was 50 m/s, with a turbulence level of 0.25%. Nowadays due to safety and component long range issues, this velocity is limited to 45 m/s. Its electric motor, with 110 HP, drives an 8 blades fan with 7 straighters localized downstream of the fan. On the flow stabilization section there are two 54% porosity screens followed by the 1:8 contraction cone designed using two 3rd order polynomials joined at 45% inflection point. It is remarkable to mention the relative low turbulence level considering the installation of only two screens, and no honeycomb. These standards were only obtained due to the care taken during the design of low angle diffusers, low-drag corner-vanes and high-efficiency propeller blades designed with a combination of CFD and semi-empirical techniques. The meticulous construction of this wind-tunnel was also a key factor for its performance, which explains the four years expended for its conclusion. More details about the design and construction of this wind tunnel can be found on [11].

3 The wind-tunnel background noise reduction process

To reduce the LAE-1 background noise a campaign were carried out in the following phases: a conceptual phase where several solutions were evaluated regarding efficiency, feasibility and budgetary constraints, followed by two phases of effective physical application of the solutions devised on the first phase. On the first phase the effect of foam insertions on the wind tunnel background noise and flow quality were evaluated. The results led to a final and deeper second phase of noise reduction. The directives adopted during the conceptual phase are presented on the subsection 3.1, the first phase of noise reduction is presented on the subsection 3.2 and the final phase of the process of noise reduction is in the subsection 3.3.

3.1 Preliminary concepts for the project

In order to delimit how much of the wind-tunnel background noise level should be reduced it was decided to define a target experiment that should be carried out after the wind tunnel modifications. As requirement, this experiment should be representative of further tests and also be well reported on the literature. Therefore, the noise sources identification results, to be obtained after the wind-tunnel update would be qualitatively and quantitatively validated. In order to accomplish these requirements, the ideal experiment found on literature is the measurement of NACA-0012 airfoil self-noise, described by [12].

The wind-tunnel background noise was measured in order to compare its noise level with the self-noise of the airfoil NACA-0012. In addition, it was decided to set the flow velocity at 31 m/s as a baseline condition of most of the results presented in this paper. This velocity was chosen due the existence of a structural resonance related with the fan rotation, which leads to a worse wind-tunnel noise condition relative the noise level that would be present without the resonance. Fig 2 shows a comparison of the LAE-1 noise level and the NACA-0012 airfoil noise level as the target experiment previously mentioned.

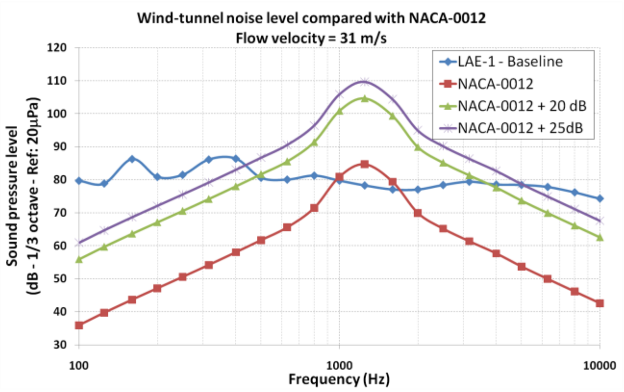

Fig 2: NACA-0012 noise compared with the wind-tunnel background noise

The blue line in Fig 2 represents the wind-tunnel background noise level for a flow velocity of 31 m/s, while the red line represents the NACA-0012 self-noise, calculated using the semi-empirical methods described by [12]. For these calculations, it was considered a model spanning the wind-tunnel test section, the same flow velocity and an angle of attack of two degrees.

From Fig 2 it is clear that, without post processing, it is only possible to measure 3 octave band frequencies (localized from 1 kHz to 1.6 kHz). This fact clearly justifies the necessity of some advanced far field noise measurement techniques like the *beamforming* technique (measurement approach adopted on this wind-tunnel).

Due the fact that the *beamforming* antenna to be constructed for the wind-tunnel after the background noise reduction would have 106 microphones, it would be possible to measure beyond the frequency band previously discussed. The Eq. 1, shows the noise reduction (ΔdB) that is obtained when using **M** microphones to synchronously measure a source.

$$\Delta dB = 10 \log_{10} M \tag{1}$$

Appling the number of microphones to be used (M=106) on Eq. 1, it was concluded that it is possible to measure a source with intensity 20.25 dB less than the wind tunnel background noise by only using ordinary post processing techniques, condition showed by the green line in Fig 2.

Another hypothesis considered, was the fact observed in practice, that when advanced deconvolution techniques are used on beamforming measurements, it is possible to subtract more 5 dB in relation the noise level estimated on the Eq. 1 [13]. Therefore, we can conclude that, with the gains given by the instrumentation and signal processing, it is possible to measure sources with intensity 25 dB less than the wind tunnel initial background noise level, condition represented by the purple line in Fig 2.

By adopting these two hypotheses, it can be concluded that it is possible to measure a NACA-0012 wing noise sources for all the region of the purple line of Fig 2, above the wind tunnel background noise level line.

With these considerations it was concluded that with a wind-tunnel background noise reduction of no more than 5 dB would make possible to measure all the range of frequencies of interest for the a NACA-0012 airfoil wing from 500 to

8.000 Hz. This would be quite enough for the purpose of this wind-tunnel.

3.1 The first phase of wind-tunnel noise reduction

The first phase of acoustic treatment for the LAE-1 wind-tunnel consisted of applying melamine foam on selected sections walls. Several regions of the wind-tunnel were considered for applying the foam. Sections with adverse pressure gradient where discarded due the risk of boundary layer separation induced by any imperfection on the foam surface finishing, or by steps between the foam plates. The settling chamber was also discarded due the risk of negative effects on the flow. Therefore, the remained regions A and B from Fig 3 were chosen as the best candidates for foam application.

The next step was to define the thickness of the sound absorbent layer. It was carried-out an analysis of sensitivity of reducing the transversal area, due the foam thickness on the testing chamber flow velocity. The calculations showed that the reduction of the tunnel cross-section on the region of the wall A (see Fig 3) had a stronger impact on the wind-tunnel flow speed, since this is a region with high flow speed and, consequently, considerable pressure loss. The reduction of the cross-section of the region of the walls B (see Fig 3) has a minor effect on the wind-tunnel flow velocity, once this area has a lower flow speed and greater cross-sectional area. In order to remain with the acceptable limit of 1.5% of reduction of the flow velocity on the testing chamber, it was decided to apply 2 cm thick foam on walls A and 5 cm thick foam on walls B.

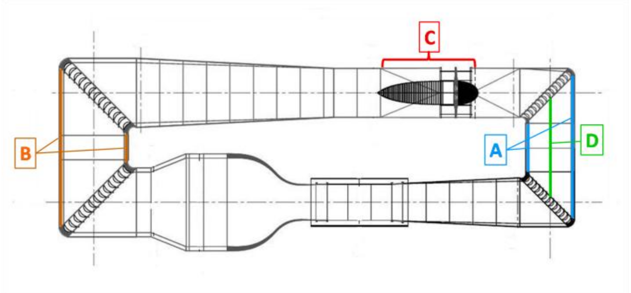

Fig 3: Wind-tunnel regions that received acoustics treatments.

The effects of this acoustic treatment on the wind-tunnel background noise are presented and discussed on Section 4.

3.2 The second phase of wind-tunnel noise reduction

In order to increase the acoustics gains obtained by the treatment described by the previous section, a second and final phase of acoustic noise treatment were conducted in LAE-1 wind-tunnel.

Aiming a noise reduction at lower frequencies an acoustic baffle (element D from Fig 3) was installed between the walls **A**, dividing the inner sections from the first and second corner vanes. With the installation of this baffle, it was expected a total reduction on the wind-tunnel flow velocity of no more 2% regarding the wind-tunnel on baseline conditions. The construction scheme of this acoustic baffle is showed on Fig 4.

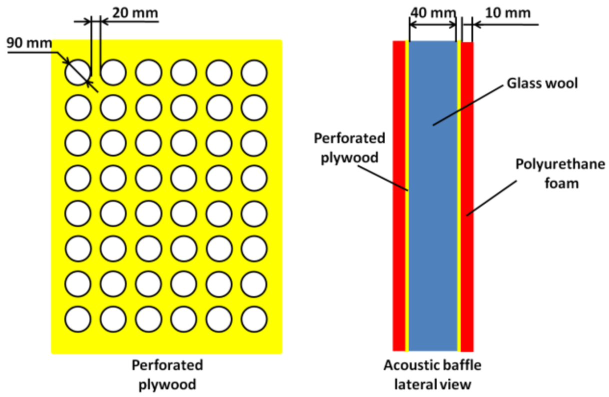

Fig 4: Acoustic baffle construction scheme

For the design of the baffle was considered the feasibility, efficiency and budgetary constraints. This baffle was composed of a sandwich assembly with glass wool inside as the acoustics absorbent material. As the mass element, a perforated plywood was adopted, with the hole diameter calculated in order to generate the better relationship of open area and mechanical strength of the baffle. The perforated plate was covered with polyurethane foam to assure a smooth surface. As an opportunity of improving of the wind-tunnel fan performance, and at the same time reducing its noise, it was decided to apply a treatment on the fan blades tips. Due to circularity defects of the metal shield that involves the fan, the tip to wall gaps varied from 1.5 cm to 3 mm. This gap generates a small tip vortex and a non-uniform loading on the fan blades which results in noise [14]. In order to avoid this, a polyurethane foam was applied on the fan regions with blade tip to wall distance greater than 3 mm. The foam leading edge and trailing edge were shaped to guarantee a smooth geometric transition. The Fig 5 (left) presents the region with greater fan tip to wall gap, and the Fig 5 (right) shows the same region after the tip treatment with polyurethane foam.

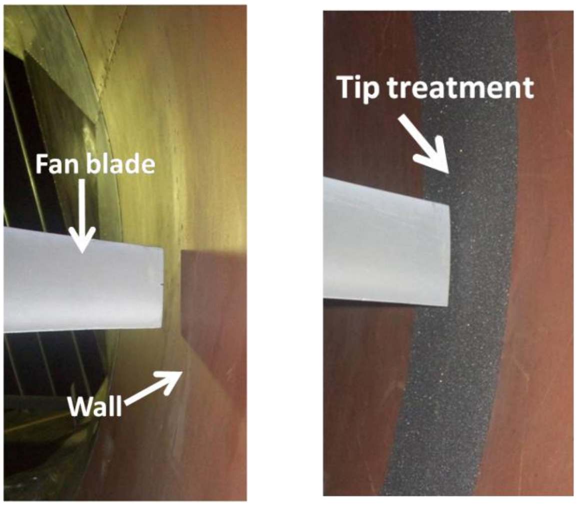

Fig 5: Region with higher fan tip to wall gap before (left) and after (right) the treatment.

Analysis of the wind-tunnel noise spectra measured on the testing chamber also shows the existence of a very intense tone localized on frequencies of 5 kHz and its multiples. Investigating the origin of those tones, it was concluded that they were generated by the motor inverter electric noise and related with the motor rotational speed control. It was possible to change the inverter set-up, by changing its carrier frequency to a limit of 10 kHz. Due the fact that the higher the frequency the better is the acoustic absorption by the medium, the highest achievable frequency was adopted as the carrier frequency for the inverter.

4 Wind-tunnel background noise measurements results and discussion.

A wind-tunnel noise is mainly of broadband and tonal nature from three main noise source mechanisms: the walls laminar/turbulent boundary layer, the corner vanes and fan noise and the noise generated by the electric motor that drives the fan. This former noise source is mainly related with the speed control that excites the electrical coil inside the motor producing acoustics noise.

It is quite difficult to identify and treat each noise source inside the tunnel separately. It is much more practical and efficient lining the acoustics waves propagation in order to acoustically isolate a given region of interest. That was the approach used on the present work. Since, traditionally, the main noise source on wind-tunnels is the fan (for low flow speeds) and the turbulent boundary layer (higher flow speeds), and on the author’s point of view for LAE-1 this rule was likely to be valid, it was decided to use acoustics absorbing foam downstream and upstream of the fan, in order to line the noise propagation generated by the fan and by the boundary layer of the region from the fan to the noise insulation. The upstream distance from the concentrated source (the fan) to the testing chamber is smaller than the downstream one; therefore, it was preferred to add, as much as possible, acoustic treatment on the region comprised by the walls A (see Fig 3). In other hand, for the acoustics waves, generated by the fan, propagating in a downstream direction need to follow a longer path to reach the testing chamber, consequently being more absorbed. Also, the screens of the settling chamber can be considered as a sudden increase of acoustic impedance, which tends to reflect the acoustics waves back, attenuating even more the noise generated by the fan and boundary layer. To better indentify and differentiate the noise sources generated by the fan from that one generated by the flow the noise spectra were analyzed on three different flow speeds: 15 m/s, 31 m/s and 37 m/s. The results are presented on Fig 6, Fig 7 and Fig 8, For low speed (15 m/s) it is expected that the fan plays a role of the main noise source, while for flow speeds up to 37 m/s is more likely that the turbulent boundary layer is main noise source. The velocity of 31 m/s is a special flow velocity due the occurrence of a structural resonance induced by the fan rotation.

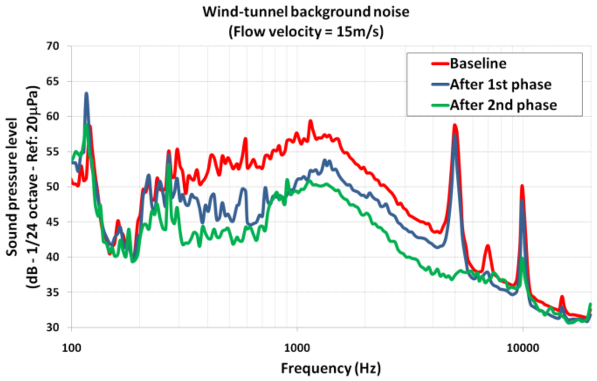

Fig 6: Wind-tunnel noise spectra measured on the testing chamber for a flow velocity of 15 m/s.

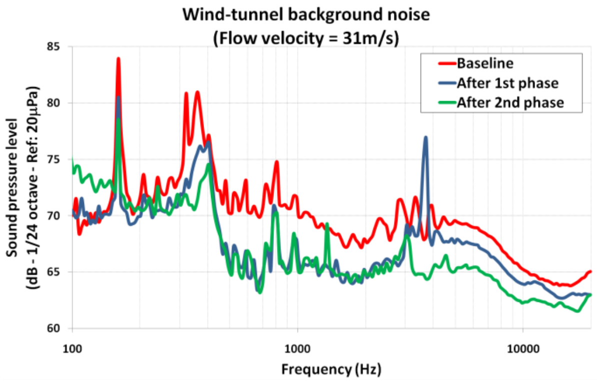

Fig 7: Wind-tunnel noise spectra measured on the testing chamber for a flow velocity of 31 m/s.

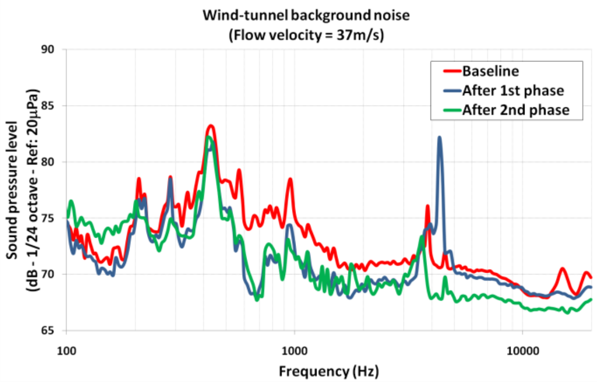

Fig 8: Wind-tunnel noise spectra measured on the testing chamber for a flow velocity of 37 m/s.

Analyzing the first phase of noise reductions, regarding the Fig 6, Fig 7 and Fig 8, it is noticed that for all flow speeds the foam treatment where effective on reducing the noise at frequencies from 300 Hz to 4 kHz. From Figures 6 to 8 it can be seen that the first phase of noise reduction was quite effective in absorbing the noise generated by the fan. For lower flow speeds the noise reduction reached 5 dB for the frequency of 1 kHz. In the other hand, when the flow speed increases to higher speeds (like 37 m/s) the boundary layer noise became a important noise source and its reduction reaches 2 dB for the same analysis frequency. With the final phase of noise treatment it can be noticed that the acoustic treatment was also very effective in reducing the noise from the fan at low flow speeds. Although, it also generated acoustics gains (up to 2 dB) for the high frequencies at high flow velocities. Regarding specially the Fig 7 and Fig 8 it is noticed that the final phase of noise treatment generated an undesired noise increment on frequencies below 200 Hz. In despite of all noise level increase be undesired, it will not affect the future noise measurement of models localized in the testing chamber, as this increase is localized in frequencies far below of that of interest for future tests.

Other remarkable result noticed mainly on Fig 6 is the vanishing of the frequency peak at 5 kHz after the second phase of the aeroacoustics treatment. This can be explained by the modification of parameters of the inverter that controls the fan rotation. Since this carrier frequency was moved to 10 kHz, it almost disappeared. The first phase of noise treatment acted mainly for low frequencies, while the second phase, worked well for high frequencies, providing noise reduction for all the region of interest of the acoustic spectra.

Fig 9 presents the Overall Sound Pressure Level (OSPL) variation with the flow speed. From Fig 9 it is remarkable that the first phase of noise treatment reduced the OSPL in an average value of 4 dB for all flow velocities. In other hand the second phase of noise treatment reduced the OSPL just for flow velocities below 20 m/s, and had no effect for high velocities flows. It can be explained by the fact that this treatment has reduced the noise for high flow velocities at high frequencies (frequencies of interest). Also, as a drawback, it has increased the noise at very low frequencies (out of the range of interest).

When the balance OSPL is calculated the losses at the non interesting regions of the spectra sums with the gains on the interesting region has resulted in a null effect on the OSPL.

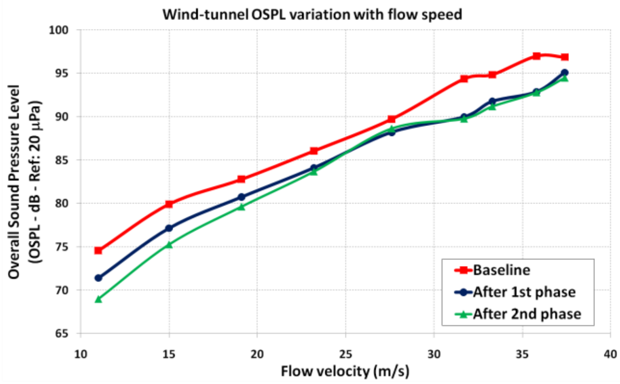

Fig 9: OSPL variation with the wind-tunnel flow speed

5 The effect of the acoustics treatment on the wind-tunnel flow

In order to verify the effect of the acoustic treatment on the flow quality, the flow turbulence, measured on the testing chamber, were analyzed. To measure the turbulence a DANTEC constant temperature hot wire anemometer was used. A single wire 55P01 probe was rigidly fixed on the center of the wind-tunnel empty testing chamber. The 55P01 probe was calibrated using a DANTEC calibration system described in [15] with a King's Law calibration [15].

The hot-wire anemometer data was acquired on a sampling ratio of 51.2 kHz in 5 seconds of sampling. The measured turbulence raw data were processed with made in house software that calculates the turbulence intensity and its auto-power spectra. In order to calculate the wind-tunnel turbulence free of influence generated by structural vibration and electrical noise, it was decided to use a band-pass filter on the acquired time domain raw data. The high-pass and low-pass frequencies adopted for these measurements are 3 Hz and 1000 Hz, respectively.

The Fig 10 shows the evolution of the turbulence measured on the wind-tunnel testing chamber.

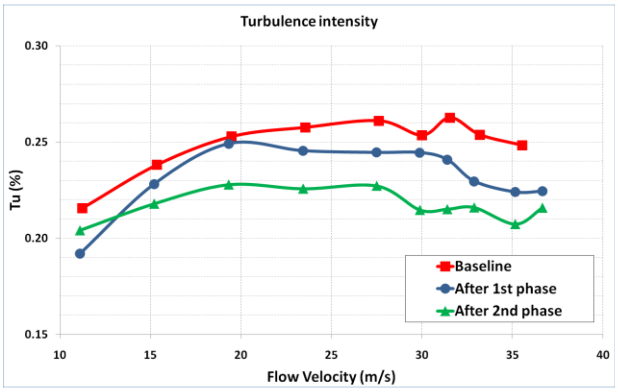

Fig 10: Wind-tunnel turbulence measured on the testing chamber

Observing the results presented on Fig 10, it is clear that with the flow velocity increment the wind-tunnel turbulence grows-up until velocities of approximately 19 m/s, reaching an approximately constant level from velocities up to 30 m/s to afterward decay again. This behavior is showed constant for all phases of the acoustics treatment. This comportment can be explained by the fact that the design condition of this wind-tunnel is for a flow speed of 50 m/s, what means that as the velocity increases in a first moment the flow pass from a low turbulence condition to an "on design" turbulence level with the fixed blade angle fan reaching its design point. Since for high velocities the large turbulence scales became smaller and viscous dissipation may occurs with the turbulence becoming isotropic at most of the wind tunnel section, so that turbulence level decreases, as noticed by Fig 10.

Another worth of discussion point, which comes from the analysis of Fig 10 is the fact that the acoustic treatment induced a positive effect on the wind-tunnel turbulence levels. This is explained by the fact that the acoustic noise contributes as an excitation source on the non-linear instabilities mechanisms that lead the flow to turbulence and this explanation is reinforced by the fact that for high Reynolds numbers the statistics of small scales are universally and uniquely determined by the viscosity and the rate of energy dissipation is not related with the noise.

The turbulence spectra is analyzed in Fig 11 and Fig 12 where are shown the turbulence spectra for 20 m/s and 31 m/s flow velocities respectively.

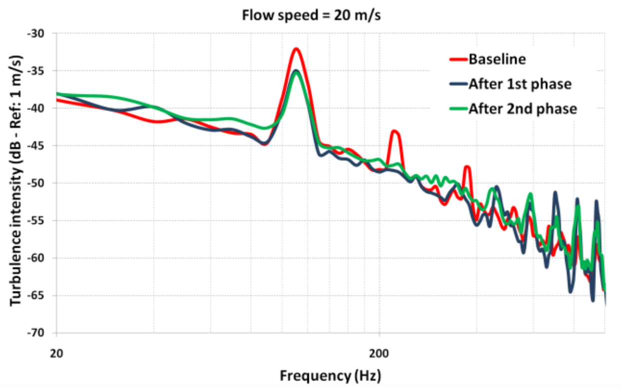

Fig 11: Wind-tunnel turbulence spectrum measured after background noise reduction process for a flow speed of 20 m/s.

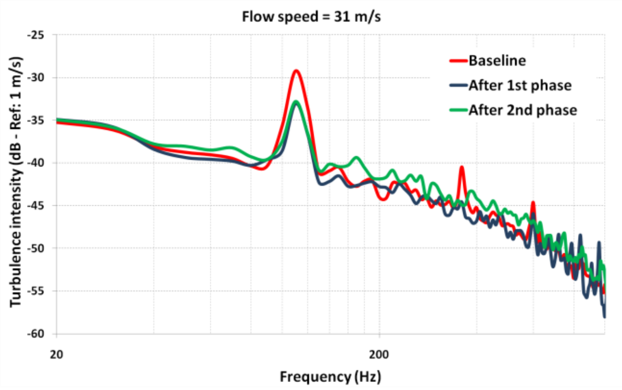

Fig 12: Wind-tunnel turbulence spectrum measured after background noise reduction process for a flow speed of 31 m/s.

It is desirable, for good quality wind-tunnels, that its turbulence spectra be free of several tones. It is noticed from Fig 11 and Fig 12 that the acoustic treatment does not introduce any effect on the turbulence spectra.

The last analysis of the influence of the acoustic treatment is its influence on the flow velocity for the same input power. Due to the characteristics of the electric motor that drives the fan, it keeps a constant torque for the same fan rotational speed. As the wind velocity is a function of the pressure loss if by any reason it increases, there will be a reduction of test sections velocity by the same input power. On this base, it is possible to compare the flow velocity reduction for the same input power after the wind-tunnel noise treatment phases. As pointed out before, the foam installation on the wind tunnel walls increased the local velocity by reduction of its cross section area. Therefore, a slightly increase on pressure loss at the treated sections are expected with a related decrease of test section velocity. Fig 13 shows the effect of the noise reduction phases on the test section velocity.

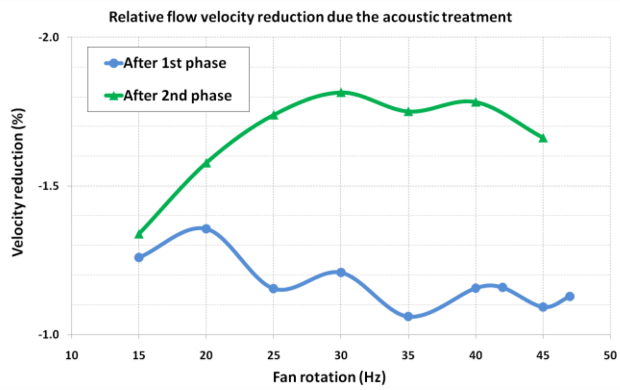

Fig 13: Wind-tunnel flow velocity reduction due the acoustic treatment.

Analyzing the results presented on Fig 13 it can be seen first that the measured flow velocity reductions were in agreement with the expected results, described on subsections 3.1 and 3.2. It is remarkable that the second phase of acoustic treatment caused a considerable reduction of the flow velocity, in comparison of the first phase. This fact is mainly due the hydraulic diameter reduction caused by the baffle installation. Since the pressure loss is proportional to the inverse of the hydraulic diameter, this diameter reduction of 2 times implies on an increase of the pressure loss of that section on 8 times. Since the local pressure loss of section B is small when compared with the rest of the wind-tunnel it also has a minor effect on the total wind-tunnel velocity reduction.

6 Conclusions

The present paper showed the process of background noise reduction on LAE-1 wind-tunnel. This process was divided on two phases, where a first phase evaluated the effect of small changes on the wind-tunnel noise and were more effective on frequencies from 400 to 4 kHz, while the second phase complementarily acted mainly on frequencies from 4 kHz to 8 kHz. These two phases produced a remarkable wind-tunnel background noise reduction of up to 5 dB and a desirable turbulence level reduction from the original 0.25% level to the after modifications 0.21%, with no addition of tones on the turbulence spectra, having only as a minor drawback the total reduction of 2% on the flow speed for the same electrical input power. The wind tunnel background noise reduction process resulted on a facility with the previous qualities for pure aerodynamics tests, and now also able to execute aeroacoustics tests.

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