Development and testing of an acoustic measurement system for the IST Aeroacoustic Wind Tunnel

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Abstract
Aviation authorities have begun to impose stricter noise regulations and penalties to airlines to address the effects of noise pollution on communities. This is a problem that is gradually becoming more evident in cities such as Lisbon where the airports is located near the city centre since the peak noise from an aircraft is during its landing and take-off phase. Historically, the industry investment has prioritized the reduction of noise originated by the engines but the vast development in the propulsion area has made the noise produced by the airframe to be more significant. The goal of this work is to produce the tools needed to acquire, process and visualize data captured by numerous sensors placed inside the Aeroacoustic Wind Tunnel located in the Aerospace Engineering Laboratory of IST, and to carry out the characterization of the facility. This dissertation covers a throughout explanation of the development of the program using the LabVIEW software, the equipment used, established procedures and the results of air flow and acoustic tests including the characterization of the flow and background noise levels. Flow uniformity tests revealed that flow profiles are generally consistent across all freestream velocities but there is a maximum 5.6% undershoot in freestream velocity near the centre of the jet which may pose a problem for future experiments. Background noise levels analysis showed the narrowband background SPL spectra in the anechoic chamber for various velocities in different conditions as well as the A-weighted sound pressure level measured during the studied scenarios.

Keywords: Aeroacoustic wind tunnel, LabVIEW, anechoic chamber, background noise, aeroacoustic performance.

1. Introduction
Human beings have only been flying for just over a century but have already filled the skies with thousands of aircraft. The fact that air traffic is growing rapidly means that there is a huge increase in noise pollution in residential areas closer to airports, a problem that is gradually becoming more evident in Lisbon, for example. Aviation authorities have begun to impose stricter noise regulations to address the effects of noise pollution on communities.

The peak noise from an aircraft is during its landing and take off phase. Historically, the industry investment has prioritized the reduction of noise originated by the engines and the ultra-high bypass engines and other low-noise propulsive technologies have greatly reduced the overall noise levels in the last few decades. Such development in the propulsion area has made the noise produced by the airframe to be more significant over the time. While the engines originate most of the noise during the take off, at approach conditions the engines have a low enough work rate that the airframe induced noise reaches the same order of magnitude. Airframe noise is dominated by the contributions from the high lift devices (leading edge slats, flap side-edge, trailing edge, etc.) and deployed landing gear systems. In general, the noise of larger aircraft is dominated by the landing gear while in medium aircraft it is mainly generated by slats and flaps.

The sources of airframe noise are seen as the barrier to overcome and this has motivated an increasing number of people in academia and industry to focus on aeroacoustic research. High quality aeroacoustic wind tunnels play a very important role in facilitating interdisciplinary research between airframe aerodynamics and aeroacoustics, and will continue to do so in the future.

The main purpose of this thesis is to characterize the Aeroacoustic Wind Tunnel of the Aerospace Engineering Laboratory of IST and produce the tools and procedures necessary for potential future studies using this facility. The first goal is to develop a program using LabVIEW that allows the acquisition and visualization of data captured by sensors placed inside the anechoic chamber. The second main objective is to run various tests and handle
all the data acquired in a way that the final results of the experiments can be compared between each other so one can evaluate the air flow and the acoustic performance of the aeroacoustic wind tunnel. Before this work, a characterization of the acoustic quality of this wind tunnel has never been performed.

2. Background

Aeroacoustics is a branch of acoustics that deals with the production of noise as a result of aerodynamic forces interacting with surfaces or turbulent fluid motion. Noise generation can also be related to periodically varying flows, such as the phenomenon referred to as the Aeolian Tones. In fact, this phenomenon is the main topic of aeroacoustics, steady tones that result from trailing vortices with oscillatory behaviour created when air passes over or through an obstacle [1].

The first publication of Sir James Lighthill [2] in 1952 originated the modern discipline of aeroacoustics, when attempts to understand and predict the noise generation associated with jet engine were beginning to be done in a thorough way. There is no scientific theory of the generation of noise by aerodynamic flows that is completely established, but most aeroacoustic analysis relies upon the often called "Lighthill's analogy", which gave a formal definition of an acoustic field in a flow. After Lighthill, other acoustic analogies have been formulated by Curle, Powell and Ffowcs Williams. They relate the wave like propagating pressure/density fluctuations to the hydrodynamic characteristics of the flow, by rearranging the Navier-Stokes equations [3].

2.1. Properties of Sound

In physics, sound is defined as a vibration that typically propagates as an audible wave of pressure, by means of a transmission medium such as air, water or other materials. That vibration propagates away from the sound source at a certain speed, thus forming a sound wave. In general, the behaviour of sound waves is affected by the density and pressure of the medium, as well as the temperature, by the motion of the medium itself and by the viscosity of the medium. These factors can increase or decrease the speed of sound and also the rate at which the sound is attenuated. Depending on the medium characteristics, sound can also be refracted, either dispersed or focused, thus increasing or decreasing sound levels.

Sound has two fundamental elements to it: pressure and time. Any sound can be represented as a mixture of its component sinusoidal waves of different frequencies. There is a group of generic properties that can be used to easily describe a sound wave: frequency, wavelength, amplitude, speed of sound and direction.

Sound travels most slowly in gases, it travels faster in liquids and even faster in solids. For an ideal gas:

\[ K = \gamma \times p, \]

\[ c = \sqrt{\gamma \times R \times T} = \sqrt{\frac{\gamma \times p}{\rho}} = \sqrt{\frac{K}{\rho}}, \]

Where \( \gamma \) is the ratio of specific heat of an ideal gas, \( R \) is the gas constant, \( T \) is temperature in Kelvin, \( p \) is pressure, \( \rho \) is the density, \( K \) is the bulk modulus and \( c \) is the speed of sound.

Speed of sound in an ideal gas is dependent nearly only on its temperature. The speed of sound (c) in air at 20°C and acoustic impedance (\( z \)):

- \( \rho_{20} = 1.204 \, \text{kg/m}^3, \quad z_{20} = 413 \, \text{N} \cdot \text{s/m}^3 \) and \( c_{20} = 343 \, \text{m/s} \)

Human beings can only perceive sounds that have frequencies from about 20 Hz to 20000 Hz and the peak sensivity is around 3500 Hz. There are six different qualities of sound perception. They are: pitch, duration, loudness, timbre, sonic texture and spatial location.

Noise can be described as unwanted sound that is seen as unpleasant, loud or disruptive to hearing, an undesirable component that obscures a wanted signal. Environmental noise caused by vehicles such as aircraft expose millions of people to noise pollution that creates not only annoyance, but is also associated with several negative health outcomes such as hearing loss, high blood pressure and sleep disturbances, depending on duration and level of exposure [4].

Sound Pressure Level is calculated in decibels (dB). The logarithmic scale is used because of the large range of rms values perceived by the human ear. The reference value was chosen conventionally to correspond to the threshold of human hearing (\( p_{ref} = 2 \cdot 10^{-5} \text{Pa} \)).

\[ SPL = 20 \times \log_{10} \left( \frac{p_{rms}}{p_{ref}} \right), \]

In acoustics, weighting is a process that involves emphasizing the contribution of a certain set of data, giving it more weight in the analysis. When measuring loudness, estimates of sound annoyance typically rely on weighting filters. The most used type of weighting is the A-weighting curve, it is a correction to the SPL spectra which results in units of dB(A) sound pressure level. It emphasises frequencies around 3000 Hz to 6000 Hz where the human ear is presumed to be most sensitive, while attenuating very high and very low frequencies to which the ear is less sensitive. The A-weighting curve has
been widely adopted for environmental noise measurement, and is standard in most sound level meters. It is used to measure environmental noise such as roadway noise, rail noise and aircraft noise.

Extensive research has been made in order to understand how to mitigate flow induced noise. Flow induced noise generation in presence of solid bodies can be classified into three dominant mechanisms: vortex shedding noise, turbulence and structure interaction, trailing edge noise.

2.2. Wind Tunnel

Wind tunnel testing is accurately reproducing wind flow around full-scale or model-scale objects in a tunnel-like construction under controlled conditions to study their performance for aerodynamic design and research purposes, within a test environment that is also suitable for measuring the acoustics generated by the interaction between the airflow and the models. Despite CFD getting ever more powerful and increasingly applied, it has not come close to replacing the wind tunnel and it will never be, irrespective of the availability of computer power [5].

Almost every wind tunnel is a unique instrument. There is no mass production of wind tunnels, they are almost always custom-made. They can be open circuit or closed circuit, with an open test section or closed test section, with each configuration having its pros and cons. Although it is possible to conduct aeroacoustic tests inside a typical hard-walled wind tunnel, it is far from ideal. An anechoic open-jet wind tunnel is the most suitable to analyse noise intensity and directivity to predict full-scale far-field noise emission levels. The purpose of having an anechoic chamber surrounding the open-jet test section is to provide a non-reverberant, quiet, still-air environment for noise measurement. The theoretical frequency cut-off limit above which the chamber is considered anechoic is determined via the equation [6]:

\[ f_c = \frac{c}{4 \times L_w}, \]  

(4)

Where \( c \) is the speed of sound in the chamber, and \( L_w \) the height of the wedges.

The aeroacoustic wind tunnel of the Aerospace Engineering Laboratory of IST is a closed circuit, U-shaped wind tunnel with an open test section. The anechoic chamber is lined with foam wedges with tip-to-base depth of 0.285 m and has a theoretical anechoic cut-off frequency of 80 Hz. The chamber inner dimensions as measured from wedge-tip to wedge-tip are approximately 4.3 m \( \times \) 3.2 m \( \times \) 2.7 m (\( L \times W \times H \)). It is equipped with a 200 kW and 1500 rpm electric motor that powers a 7 blade fan. Airflow maximum velocity can reach up to 50 m/s.

3. Experimental Techniques

Acoustic diagnostics are usually done using microphones, they give us a good idea on where noise sources are located and how they sound. However, there are techniques that were developed in order to better understand the mechanisms of the generation of sound. A big investment has been made in advanced measuring methods for flow and acoustics, being two of those methods the PIV-based prediction of radiated sound and Acoustic Beamforming.

The Particle Image Velocimetry (PIV) method makes it possible to observe the source of the sound. This method measures movement of seeding particles between two laser light pulses, applies cross-correlation to interrogation areas and the velocity vector map of whole target area is obtained. The seeding particles used to accurately follow the fluid motion do not alter its properties or flow characteristics. Commonly, the PIV method is used to measure near-field data that serves as an input in various acoustic analogies that are then used to predict far-field acoustic pressure fluctuations.

Microphones convert acoustic energy into electrical energy. Acoustic beamforming uses arrays of microphones to investigate the sources of sound in difficult surroundings, and it has become a standard method. Microphones can be classified according to the type of their transducer, the most common type is the condenser microphone.

When sound waves hit the diaphragm, it moves back and forth relative to the solid backplate and the distance between the two capacitor plates changes. As a result, the capacitance changes according to the sound waves. That movement leads to the conversion of sound into an electrical signal. The variation in voltage that is measured can be
converted in terms of pressure fluctuations by calibration.

Beamforming microphone arrays consist of tens to hundreds of microphones. It is based on an averaging of sound signals from different receivers. For the system to be accurate each microphone must be calibrated to account for varying magnitude and phase frequency responses.

Figure 3: Principle of array beamforming [8].

4. Equipment and Approach
In data acquisition projects, in particular when developing a program in LabVIEW, knowing the equipment is essential to develop a simple and organized programme that meets all the requirements. What DAQ device is available, how many sensors will be used, cables needed, and most of all, what data is of interest and what measurements should the software display and save.

The main pieces of equipment used in this work consists on a computer with needed software installed, the DAQ device NI PCIe-6353 (with 16 differential or 32 single ended channels, ADC resolution of 16 bits and a multichannel maximum aggregate sample rate of 1.00 MS/s), six Bruel & Kjr microphones type 4958, a pitot tube sensor (used to measure the speed of the flow inside the aeroacoustic wind tunnel), two four channel ICP Sensor Signal Conditioners model 482C15 from PCB Piezotronics, one NI CB-68LP connector block and SHC68-C68-D4 NI custom cable connector, coaxial cables, a Sound Level Meter, multimeter and DC power supply, a speaker, an oscilloscope and other tools like adhesive tape, scissors, screwdrivers and measuring tape.

There will be two very different stages to this project: the first stage being the development of the software and testing of the equipment before moving on to the wind tunnel facility, and the second stage being the experimental activities, when experimental proceedings are designed so that all the tests are made following the same rules and ultimately proceed to the characterization of the aeroacoustic wind tunnel.

5. Development of the Data Acquisition Program
LabVIEW has been widely adopted throughout industry, academia, and research labs as the standard for data acquisition and instrument control software. A LabVIEW program consists of one or more virtual instruments (VIs) that can be divided into three parts: Front Panel (the interactive user interface of a VI), Block Diagram (VI’s source code, it includes terminals, subVIs, functions, constants, structures, and wires that transfer data among other block diagram objects) and Icon (VI’s pictorial representation).

5.1. First VI
The data that will be transferred from the sensors to the DAQ device and to the software is voltage converted by each sensor. The first VI was made to show a graph of the measured voltage and frequency value of a known signal using the oscilloscope. A signal of 0.6 V and 1000 Hz frequency were chosen, and when running the program the expected values were displayed. This proved that the DAQ device was working as intended.

5.2. Frequency Analysis and Sound Level Meter VIs
The microphones transmit voltage data and that voltage must be transformed into units that can be used in subVIs that are used to process and display sound measurements. The engineering units were set as Pascal, sensor sensitivity was set to 11.2 mV/Pa and the dB reference [Pa] was set to $20 \times 10^{-6}$. The signal conditioners will be operating with voltage gain set to x100 in order to amplify the signals captured by the microphones for better analysis translating into pregain settings of 40 dB. The SVFA FFT Spectrum VI was used to process the signal acquired and display the dB vs Hz graph. It computes the Fast Fourier Transform spectrum of the scaled signal, then returns FFT results as the magnitude and phase of the FFT spectrum.

An indicator of Leq value was also added using the SVT Sound Level VI. Leq is the sound level in dB, equivalent to the total sound energy over a given period of time, and can be described mathematically by:

$$L_{eq} = 10 \log_{10} \left( \frac{1}{t_2 - t_1} \times \int_{t_1}^{t_2} \left( \frac{p_A}{p_{ref}} \right)^2 \, dt \right), \quad (5)$$

Where the start time for measurement is represented by $t_1$ and $t_2$ is the end time for measurement, $p_A$ is the acquired instantaneous sound pressure of the sound signal and $p_{ref}$ is the reference sound pressure level of 20 $\mu$Pa.
5.3. Third-octave Analysis and Saving Data to Measurement Files
A VI called SVT Third-octave Analysis was used, it performs a 1/3 octave analysis on scaled signal in accordance with the IEC 1260:1995 and ANSI S1.11-2004 standards. One-third octave analysis is widely accepted in many industries, such as the aeronautical industry. Several Write To Measurement File Express VIs were coded to save the acquired and processed data to different measurement files in the LVM file format that can be used using other programs such as MatLab and Excel.

5.4. Weighting Filter and Other Considerations
The SVT Weighting Filter VI applies the selected weighting to the scaled signal and operates on time-continuous data. This VI complies with ANSI S1.4-1983, ANSI S1.42-2001, IEC 61672-1:2002, and JIS C 1509-1:2005 standards. When the the A-weighting setting is turned on the SVT Sound Level VI indicator displays the LAeq value. LAeq measurements are extensively used in environmental noise standards as well as many other regulations and documents.

A Trigger Loop was created to be run before the main While Loop, once the trigger conditions are met, an internal trigger signal is sent to initiate the acquisition. The Elapsed Time Express VI was used to indicate and control the amount of time that the program is set to run. Front panel controls and indicators were added to make it easier to customize each execution of the program. Finally, graphs that display the combined data of all the microphones together were implemented for a better understanding and evaluation of the results. SVT STFT vs Time VI was also added to perform a short-time Fourier transform on the scaled signal and return the colormap at the time specified.

6. Experimental Set-up
The aeroacoustic wind tunnel is located in the Aerospace Laboratory, while part of the work done until this phase was done in a small room outside the laboratory. It was crucial to transport all the equipment to the Aerospace Laboratory and prepare it to be used. A couple of desks were put right next to the entrance of the anechoic chamber. The computer, signal conditioners, block connector and cables were all mounted on and around these desks. The cables that link the microphones to the signal conditioners are long (10 meters), because of that they can be installed inside the anechoic chamber and easily connected to the signal conditioners outside that in turn are connected via coaxial cables to the block connector. The connections were made following the instructions on the NI PCIe-6353, ICP Sensor Signal Conditioners and NI CB-68LP user guides. Inside the anechoic chamber, the microphones were mounted on a support bar that exists for this purpose. Carbon sticks were used to secure the microphones in the desired positions. Each sensor uses 3 channels on the NI PCIe-6353 pinout, connector 0 (AI 0-15).

After mounting the equipment and having all microphones connected, the main VI was launched and run to try out the data acquisition system with a random sound source to have an idea of how everything would behave. This was the first time all the sensors installed were working simultaneously and the system was acquiring, processing, displaying and saving data at the same time. Unfortunately, the program was too big for the computer to handle as delays were clearly noticed when the Run button was clicked and the time set for the program to run was not being respected. It was concluded that the best way to solve this problem was to divide the main VI into two separate programs. One would consist on the VI that runs each microphone individually, and would be used when testing the microphones individually. The second one would be used in the main tests running all the microphones at the same time and displaying the combined processed data. During working hours there are numerous sources of sound that are unavoidable and may influence the results of the measurements inside the anechoic chamber. Machines like ventilation and equipment used in the surrounding facilities, produce sounds that were registered by the microphones during preliminary tests, as well as the fact that the laboratory is constantly being used by other students working on other projects. In order to try to make the interior of the anechoic chamber more sound proof, additional foam wedges were used to cover some key areas of the anechoic chamber.

6.1. Microphones: individual tests
Microphones were placed in a central position in the support bar, 1.45 meters high. A portable speaker, capable of producing sounds with frequencies ranging from 20 Hz to 20000 Hz, was placed 3 meters away at the same height and facing in the microphone’s direction.

![Figure 4: Frequency range test.](image)
quency range of the speaker and the microphones. A sound file that produces a sinusoidal wave going through the entire human audio spectrum, starting at 20 Hz and ending at 20 kHz, was played for 90 seconds. Note that the frequency increases exponentially during the test.

A test consisting on analysing pink noise was also made. Pink noise is often used as a reference tone to check frequency responses and becomes particularly useful when coupled with a 1/3 octave spectrum analyser.

This test was carried out because pink noise is used for acoustic applications, such as loudspeaker tests, and since pink noise has a flat spectrum when viewed on a third-octave spectrum analyser it was used to see if the developed VI would give the expected results.

Figure 5: Pink noise test result, front panel.

For the remaining tests pure tones of 500 Hz, 1000 Hz, 2500 Hz and 5000 Hz were played one at a time, for the duration of 1 minute. The same tests were made positioning the speaker at a distance of 2 meters and 1 meter from the microphones. The following figures present the results captured during the 1000 Hz pure tone tests.

Figure 6: Intensity chart for the pure tone of 1000 Hz.

Figure 7: Narrowband SPL spectra of the 1000 Hz pure tone test.

Microphones are usually calibrated by means of a professional microphone calibrator. The right way of doing it is using a calibrator that emits a 1000 Hz reference tone at 94 or 114 dB SPL, in order to determine the sensitivity of the microphone and preamplifier pairing. However, there is no unit like that available in the school and because of that there was the need of using a different approach here. After studying the numerous results obtained during the individual tests of the microphones, it was decided to pick up the 1000 Hz tests results at 1 meter distance between the speaker and the microphones and go from there. The mean value of the sound pressure levels measured was calculated and correcting pregain values were calculated in order to match all the microphones so they would read the same value in the exact same condition. The microphones were not calibrated having the results of a Sound Level Meter in mind but to approximate the behaviour of the microphones to each other.

6.2. Positioning of the sensors

The microphones were placed in a support bar installed in the far side of the anechoic chamber relative to the test section, but due to its dimension it was only possible to distribute 5 microphones in a span of 60 degrees. The 6th microphone was placed in the wall of the anechoic chamber, opposite to the entrance, oriented 45 to tunnel centreline.

Figure 9: View of free-field microphone locations for tunnel noise measurements. Figure not to scale.
After getting all the sensors in the planned positions preliminary tests with the wind tunnel were made to ascertain that everything was correctly mounted. This opportunity was taken to test the microphones by measuring pure tones of 1000 Hz and 5000 Hz in two different tests, played by the speaker used in previous tests. This speaker produces a relatively clean sound when listening to it on axis, but when one gets 20 to 30 degrees off axis there is a slight loss in sound clarity and intensity. This test was intended to verify this fact.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>SPL (dB) 1000 Hz test</th>
<th>SPL (dB) 5000 Hz test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mic 0</td>
<td>60.11</td>
<td>66.30</td>
</tr>
<tr>
<td>Mic 1</td>
<td>59.10</td>
<td>63.44</td>
</tr>
<tr>
<td>Mic 2</td>
<td>59.08</td>
<td>63.61</td>
</tr>
<tr>
<td>Mic 3</td>
<td>58.57</td>
<td>62.83</td>
</tr>
<tr>
<td>Mic 4</td>
<td>58.38</td>
<td>62.95</td>
</tr>
<tr>
<td>Mic 5</td>
<td>57.50</td>
<td>61.25</td>
</tr>
</tbody>
</table>

Table 1: Pure tone tests with microphones placed in different positions.

7. Facility Characterization

Tests were performed with a slightly convergent nozzle mounted at the entrance of the chamber/test region, and were repeated after removing the nozzle using the same procedures.

7.1. Flow Speed

The flow velocity was measured using a pitot tube situated at the centre of the test section. This pitot tube was connected to a differential pressure transducer, that in turn was connected to a multimeter powered by a DC Power Supply. The signal was also acquired by the NI PCIe-6353 via a CB-68LP block connector. The values presented by the multimeter were compared to the values acquired by the LabVIEW program to be sure that the results were similar. The freestream velocity was calibrated against the frequency output of the tunnel motor control panel up to 12 Hz which means that the flow speed characterization was made using speeds between 0 rpm and 360 rpm.

The graphs displayed in Figures 12 and 13 show the results of the flow uniformity tests carried out in the horizontal axis, with and without the nozzle installed, respectively. The profiles at each streamwise location are generally consistent across all freestream velocities. Though, with the nozzle installed there is a difference between the minimum and maximum flow speeds measured in a profile that corresponds to a maximum of 5.6% undershoot in freestream velocity near the centre of the jet. After removing the nozzle, the difference between the minimum and maximum flow speeds measured in a profile corresponds to a 2.7927% undershoot in freestream velocity near the centre of the jet. These results show that without the nozzle installed the air flow is slightly more uniform, what points to the possibility that the nozzle influences the flow significantly mainly in its extremities. These deviations may have been more apparent because the...
wind tunnel was operated at low speeds which may not be the most efficiently way to use it. At higher speeds the flow may become more uniform in the nozzle exit. The measurements were also made close to the nozzle exit instead of being made in the middle of the test section in the anechoic chamber, as one moves away from the nozzle exit the flow may become slightly more uniform so further testing is needed. These deviations from the mean freestream velocity present in the different profiles tested may pose a problem for future experiments, and further testing in future projects is required.

7.3. Background Noise Levels
The first test was carried out in the quietest environment possible to achieve in the facility during the day. Data was acquired at a sampling rate of 50 kHz for 60 seconds each test.

Figure 13: Narrowband background SPL spectra in anechoic chamber in silent environment.

Some peaks in under 100 Hz frequencies can be seen and may originate from artificial sources of low-frequency noise such as ventilation or air-conditioning units and working equipment from nearby laboratories. In terms of evaluating the performance of the anechoic chamber in what concerns to its sound proof capabilities, the SPL values measured in a silent environment were around the 39 dBA mark although it should ideally be closer to 25-30 dBA. Considering the big size of the diffuser and nozzle exit, 39 dBA may be considered satisfactory since the test was carried out during busy hours but there is still room to improve the soundproofing of the anechoic chamber.

Background noise measurements were then carried out over the range of flow velocities from 7.58 m/s to 19.83 m/s with the nozzle installed. There are some noticeable peaks in the spectra at flow velocities of 7.58 m/s to 16.77 m/s, low frequency mechanical vibrations could be reduced through motor and fan blade balancing and bearing greasing. Shear layer impingement on the collector may produce low frequency broadband noise. Environmental sources are unpredictable and could contribute both broadband and tonal noise to the spectra, the main method of attenuating this type of noise is through acoustic baffles. There are also peaks around 2000 Hz and 4000 Hz frequencies characteristic of the motor. The background noise in the anechoic chamber mainly comes from the fan and motor, open-jet shear layer impingement on the collector, flow turbulence, and noise transmitted into the open-circuit tunnel. As the flow speed was increased, the data acquired showed more uniform results. The peak at 2000 Hz and 4000 Hz were not observed after the flow speed increase from 16.77 m/s to 18.30 m/s.

Figure 14: Background SPL spectra by microphone 0 in all different velocities. Nozzle installed.

Figure 15: Comparison of the results obtained for microphones 0, 3 and 4, in two different velocities.

There are considerable differences between the results from each microphone due to the angle that their diaphragm makes with the jet centreline.

Figure 16: Comparison of A-weighted SPL between three microphones and Sound Level Meter.

The same noise measurement tests were made after removing the nozzle since the absence of the nozzle may influence the data captured by the microphones. It should be noted that in the test without the nozzle no peaks around the frequency of 2000 Hz were seen, this is one characteristic of the electric motor and some times when turning on the motor it would produce a slightly different sound each time,
sometimes originating those peaks around the 2000 Hz that fade away when the velocity is increased. The biggest differences can be seen when analysing the results of microphone 4 that are a lot different from the results obtained with the nozzle installed.

Figure 17: Comparison between the results obtained for microphones 0, 3 and 4.

There are considerable differences between the results from each microphone due to the angle that their diaphragm makes with the jet centreline. In this case, microphone 3, that is oriented 60° to tunnel centreline facing upstream, clearly shows a substantial deviation from its counterparts.

Figure 18: Comparison of A-weighted SPL between three microphones and Sound Level Meter.

By observing the results, one should also highlight the fact that there is a significant fluctuation around the 15.5 m/s mark that overlaps with the intense 4000 Hz sound that could be heard during the test and that suddenly stops. During the previous tests with the nozzle installed the same sound could be heard but it faded away gradually until the wind tunnel velocity setting reached the 12 Hz.

Considering that the flow velocities tested are relatively low, in the future higher speeds should be used in order to obtain more diverse results.

Figures 19 and 20 present third-octave analysis using the data captured with microphones 0 and 3 respectively, with and without the convergent nozzle installed, \( U = 19.83 \text{ m/s} \).

7.4. Noise measurements with a Wind Turbine in the Test Section

There was also the opportunity to carry out the same noise measurement tests with a vertical axis wind turbine placed in the center of the test section. This object has a main component, the vertical axis wind turbine that is painted red, and secondary and smaller white turbine. Both of them will produce noise, as well as the remaining of the body structure. This experiment was made with the nozzle installed.

Figure 21: SPL spectra, comparison of the results obtained with wind tunnel turned off, with empty chamber and with wind turbine. \( U = 7.58 \text{ m/s} \).

Figure 22: SPL spectra, comparison of the results obtained with wind tunnel turned off, with empty chamber and with wind turbine. \( U = 18.30 \text{ m/s} \).
In the first case there are not many differences between the results obtained with and without the wind turbine placed in the test section, mainly due to the low speed of the flow. However, in the second case, due to a higher air flow velocity of 18.30 m/s, the wind turbine rotated faster and originated higher sound pressure levels across the frequency spectrum.

Figure 23: Comparison of A-weighted SPL measured in tests with empty anechoic chamber and with the wind turbine.

Figure 24: Third-octave analysis. Results obtained by microphone 0 in silent environment, and with and without the wind turbine placed in the test section, at speed of 7.58 m/s.

Figure 25: Third-octave analysis. Results obtained by microphone 0 in silent environment, and with and without the wind turbine placed in the test section, at speed of 18.30 m/s.

8. Conclusions
The tunnel characterization was performed, which addressed the flow velocity, flow uniformity uniformity, background noise measurements with and without the convergent nozzle installed and a test with a vertical axis wind turbine was also made. It is possible to observe, by looking through the results presented in this thesis, the influence of the noise that comes from the fan and motor, flow turbulence, open-jet shear layer impingement and noise transmitted by nearby machinery. There are characteristic frequency peaks produced by the electric motor and fan that show up in the acoustic tests.

The flow uniformity tests exhibit unwanted deviations that despite being small still are disappointing. Testing at higher velocities is essential in the future to confirm if the undershoot in freestream velocity near the center of the jet remains.

Unfortunately, the highest flow speed measured and used during the tests was about 20 m/s, only 40% of the theoretical maximum airflow velocity of up to 50 m/s, this happened due to limitations of the equipment, time availability and security reasons.

The work performed in this thesis is good starting point for future projects that can go further in the characterization and setting up of the wind tunnel to be used in diverse aeroacoustic research.

References


