Noise from jets exiting from nozzles with chevrons: an experimental study

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Dedicated to my parents, sister and girlfriend, for their love and support
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Resumo

Desde o início do século XXI, os regulamentos de ruído em aeroportos têm vindo a tornar-se cada vez mais rigorosos devido ao impacto ambiental que a poluição sonora tem na sociedade. Vendo o futuro crescimento da indústria aeronáutica limitado pelas emissões sonoras das aeronaves, os fabricantes de motores têm vindo a trabalhar em novas soluções para reduzir este mesmo ruído.

O ruído do jacto, proveniente da exaustão do motor da aeronave, é um dos grandes componentes do ruído de uma aeronave. O actual estado da arte em tecnologias passivas de redução deste ruído passa pela utilização de tubeiras com chevrons. Estas tubeiras possuem recortes no bordo de fuga que promovem uma mistura acelerada do jacto com o ar ambiente em seu redor, resultando numa redução da pluma do jacto e consequentemente do seu ruído.

O objetivo desta dissertação passa por testar experimentalmente, no túnel de vento aero-acústico do IST, a capacidade de redução do ruído do jacto de uma tubeira com chevrons, comparando os seus níveis de ruído com os de uma tubeira circular. Os resultados revelaram que não há um benefício significativo na utilização de chevrons para a gama de velocidades testada. Apesar de no geral haver uma tendência para reduzir o ruído por parte dos chevrons, em certas gamas de frequência os chevrons tendem a aumentar substancialmente os níveis de ruído.

Uma oportunidade adicional surgiu para verificar experimentalmente o efeito que a camada de corte do jacto tem na transmissão de sons. Os resultados evidenciaram uma realocação de energia acústica da onda sonora para outras frequências próximas da original, expondo o fenómeno de ‘spectral broadening’.

Palavras-chave: ruído aeroacústico, redução ruído do jacto, túnel de vento aero-acústico, tubeira com chevrons, alargamento espectral
Abstract

From the start of the 21st century, noise regulations around airports have become more stringent due to the environmental impact that noise pollution has on society. As the future growth of the aircraft industry becomes constrained by its noise emissions, engine manufacturers have worked in new solutions to reduce the aircraft overall noise.

Jet noise, which radiates from the exhaust jet of an aircraft engine, is a major component of aircraft noise. The current state of the art in passive jet noise reduction technology is represented by chevron nozzles. These nozzles feature triangular serrations in the nozzle trailing edge, which enhance the mixing between the jet and the ambient air to yield a rapid decay of the jet plume and consequently to reduced jet noise.

The objective of this work is to experimentally test, in the aeroacoustic wind tunnel facility of IST, the noise reduction capacity of a chevron nozzle. This was done by comparing noise levels radiated from the jet with the chevron nozzle installed and a common circular nozzle. The results revealed that there is no significant benefit in using a chevron nozzle for the velocity ranges tested. Even though the general trend is to slightly attenuate noise across the entire spectrum, for some specific frequency bands the chevrons tend to highly increase the noise levels resulting in an overall prejudice.

An additional opportunity arose to experimentally verify the effect jet shear layers have on sound transmission. The results revealed a reallocation of acoustic energy of the sound wave into other frequencies, exposing the phenomenon of spectral broadening.

Keywords: aircraft noise, jet noise reduction, aeroacoustic wind tunnel, chevron nozzle, spectral broadening
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Notation

Acronyms

ADC  Analog to Digital Converter
AI   Analog Input
AST  Advanced Subsonic Program
B & K Brüel & Kjær
BNC  Bayonet Neill–Concelman
DAQ  Data Acquisition
DFT  Discrete Fourier Transform
EMOF Electric Motor Operational Frequency
EPNL Effective Perceived Noise Level
FFT  Fast Fourier Transform
FSS  Fine Scale Spectrum
GEAE General Electric Aircraft Engines
GND  Ground
IATA International Air Transport Association
IEPE Integrated Electronics Piezo-Electric
IST  Intituto Superior Técnico
LabVIEW Laboratory Virtual Instrument Engineering Workbench
LSS  Large Scale Spectrum
NASA National Aeronautics and Space Administration
NI National Instruments
OASPL Overall Sound Pressure Level
P& W  Pratt and Whitney
PCI  Peripheral Component Interconnect
PWL  Sound Power Level
RANS  Reynolds-averaged Navier-Stokes
RG  Radio Guide
SFN  Separate Flow Nozzle
SIL  Sound Intensity Level
SMB  SubMiniature version B
SPL  Sound Pressure Level
VI  Virtual Instrument

Greek symbols
\( \delta \)  Shear layer thickness
\( \gamma \)  Ratio of specific heat
\( \lambda \)  Wave length
\( \omega \)  Angular velocity
\( \rho \)  Density
\( \Delta f \)  Frequency resolution

Roman symbols
\( \bar{I} \)  Sound Intensity
\( \bar{u} \)  Sound particle velocity
\( A \)  Area
\( c \)  Speed of sound
\( C_p \)  Constant pressure specific heat
\( C_v \)  Constant volume specific heat
\( f \)  Frequency
\( F(\omega) \)  Frequency domain function
\( F(k) \)  Sample in the frequency domain
\( f(n) \)  Sample in the time domain
\( f(t) \)  Time domain function
\( f_c \)  Cut-off frequency
\( F_s \)  Sampling rate
\( f_{\text{bin}} \)  Frequency bins
\( h_{\text{wedge}} \)  Wedge length
\( l_e \)  Turbulence eddy length scale
\( Ma \)  Mach number
\( N \)  Number of samples
\( p \)  Pressure
\( p_{\text{din}} \)  Dynamic pressure
\( p_{\text{rms}} \)  Fluctuating pressure signal
\( R \)  Ideal gas constant
\( r \)  Radius
\( T \)  Temperature. FFT block size
\( t \)  Time
\( U \)  Wind tunnel jet velocity
\( U_c \)  Turbulence eddy convective speed
\( v \)  Airflow velocity
\( W \)  Acoustic Power

**Subscripts**

\( x, y, z \)  Cartesian components
\( 0 \)  Initial state
\( \text{ref} \)  Reference condition
Chapter 1

Introduction

Aircraft noise has become one of the major environmental constraints for the future growth of the aircraft industry. It is a significant political issue and remains a key environmental concern for many citizens. There are several ways in which noise could affect human health, including a physiological response via the autonomic nervous system leading to rises in blood pressure and heart rate, stress potentially mediated by annoyance, and disturbed sleep. There is evidence proving that exposure to high levels of noise at school or at home is associated with children having poorer reading and memory skills. [1, 2]

In order to work towards a greener future, noise standards around the world for aircraft have become more stringent. Engine manufacturers have directed part of their research towards noise reduction techniques, however, it has proven to be a difficult task due to the complexity of the noise generation mechanisms. A thorough understanding of aerodynamics is essential to accurately quantify the flow-induced noise, which remains the greater cause of aircraft noise in most flight conditions. In general, fluid flows are governed by a set of complicated equations named the Navier-Stokes equations, whose current understanding is very limited. The non-linearity of these governing equations makes fluid phenomena like turbulence, flow-induced noise, hard to understand.

1.1 Motivation

The increasing demand for transportation is resulting in skies filled with aircraft as air traffic becomes more and more congested. The International Air Transport Association (IATA) expects 7.8 billion passengers to travel in 2026, a prediction based on the 3.6% average annual growth rate [3]. However, a recent case study [4], has shown that the aviation sector might have to deal with a sudden increase in the number of passengers over the next decade. The authors believe that as people continue to migrate to cities for economic opportunity, the middle class will expand. The upsurge in middle-class households in major nations like China, Brazil, Russia and India (together hold 40 percent of the world’s population), combined with cheaper airfares, partly attributable to the aggressive growth of low-cost airlines, will create a boom in the number of passengers.

The fact that air transportation is growing so rapidly it is also being reflected in a huge increase in noise pollution in areas closer to airports. In cities, like Lisbon or London (Heathrow), where the airport is surrounded by residential areas this can turn out to be a very dangerous situation.
Over the last decades, aviation authorities have begun to impose stricter noise regulations and new proposals for aircraft noise certification standards [5]. This, in turn, has driven research in the area of aeroacoustics which deals with understanding aerodynamically generated sound. The peak noise from an aircraft occurs during its landing and take-off phase and it is predominantly caused by the engines and airframe noise [6]. The interaction between the high-speed flow exhausting from the engine and the steady outside flow surrounding the engine is the main cause of engine noise. On the other hand, airframe noise includes noise generated by high lift devices and landing gear.

For a long time, researchers have been investigating new noise reduction devices. Substantial progress was made with the introduction of turbofan engines with higher and higher bypass ratios as shown in Figure 1.1. Turbofan engines require lower exhaust jet velocity for the same level of thrust resulting in lower jet noise levels. The problem is that the noise levels remain too high and it has become difficult to further increase the bypass ratio in new engines.

While exploring various flow control methods to reduce jet noise, the solution found by engine manufacturers was to encourage the mixing between the surrounding fluid and the jet flow which would result in a reduction of the jet effective velocity. This velocity reduction would then translate to a reduction in noise levels. This faster mixing would be a result of a new design in the engine nozzle. The new nozzle, called a chevron nozzle, would feature a series of sawtooth-like patterns at the trailing edge of aircraft engines.

1.2 Objectives

Chevron nozzles are the current state of the art of passive noise reduction techniques in aviation. The main purpose of this work is to experimentally verify the effective noise level reduction of a chevron nozzle when compared to a baseline round nozzle. The tests will be conducted in the aeroacoustic wind-tunnel of the Aerospace Engineering Laboratory of IST.

The second main objective of the thesis is to experimentally test the phenomenon of spectral broadening. This idea came up while studying other closed section aeroacoustic wind-tunnel tests. This phenomenon is related to a frequency translation of a sound source located inside the jet flow due to the interaction with the jet mixing layer.
1.3 Thesis Outline

This final section of the introductory chapter presents an overview of the thesis layout. Chapter 2 presents the theoretical background with some basic concepts of acoustics and aeroacoustics, focusing mostly on jet noise. A review on aeroacoustic experiments in an open-jet wind tunnel is also presented. Herein the aerodynamics of a shear layer and the effects of a shear layer on sound waves will be outlined along with some basic concepts concerning signal processing. Chapters 3 and 4 complement each other with the presentation of the measurement system used and the experimental set-up of the tests. At last Chapters 5 and 6 present the results obtained and the conclusions of the work.
Chapter 2

Background

In this Chapter, a small introductory review of sound is first presented. Secondly, the fundamental aspects of aeroacoustics are discussed with particular emphasis on aircraft noise. Thirdly, the major theoretical aspects of wind tunnel testing are reviewed with specific emphasis on the aerodynamics of a shear layer and the influence of the shear layer on sound propagation. The chapter ends with a brief summary related to digital signal processing.

2.1 Acoustics

Originally, acoustics focused on the study of small pressure waves propagating through a transmission medium which can be detected by the human ear: sound. However, with time, the scope of acoustics has been extended to higher and lower frequencies: ultrasound and infrasound. Currently, acoustics is defined as the branch of physics that studies all mechanical waves in gases, liquids, and solids. [8, 9]

The present work’s focus is on the propagation of sound waves in fluids like air and water. In such a case, acoustics is considered a branch of fluid mechanics.

2.1.1 Introduction to Sound

As previously mentioned, sound can be defined as a pressure perturbation which propagates as a wave and which is detectable by the human ear. The audible human frequency range lies between about 20 Hz to 20 kHz, yet the human ear is more sensitive to sounds emitted in the frequency range of 1 kHz to 5 kHz [8]. Even though detectable, not all sounds are pleasant to the human ear. The term acoustic noise was introduced to characterize these unwanted sounds, yet, it’s definition is quite subjective and is not agreed by all researchers.

Besides the frequency range, sound involves a large range of power levels. The sound power corresponds to the rate at which sound energy is emitted from an object, independent of location or distance that the sound is observed. It is a characteristic of the source and is commonly specified in the noise regulations of many different kinds of products. As an example, a person whispering produces a $10^{-10}$ Watts power sound, on the other hand, a plane taking off produces a sound of about $10^5$ Watts [9]. In view of this large range of power levels, a logarithmic scale was created to measure the effective sound power relative to a reference value. The logarithmic unit used is called bel although, most usually, decimals of bel are used, decibels (dB). The Sound Power Level ($PWL$) is given
Another important measurement of sound is the sound pressure. It indicates the amplitude level of the acoustic pressure perturbations at a specific location in space and is a scalar quantity. The amplitude of a sound wave decreases with distance from its source because the energy of the wave is spread over a larger and larger area. This level is dependent on the location and distance the sound is observed relative to a sound source [10]. Similarly to the sound power, the sound pressure can also be logarithmically scaled by a reference value. The sound pressure level (SPL) can be calculated using the following expression, [8]

\[
SPL = 10 \log_{10} \left( \frac{p_{\text{rms}}^2}{p_{\text{ref}}^2} \right) = 20 \log_{10} \left( \frac{p}{p_{\text{ref}}} \right)
\] (2.1.2)

where \( p_{\text{rms}} \) (\( Pa \)) is the random mean square of the sound pressure perturbation and \( p_{\text{ref}} \) is the reference pressure whose conventional value corresponds to the threshold of human hearing for a 1000 Hz sound (\( p_{\text{ref}} = 2 \times 10^{-5} N/m^2 \)) [8]. Table 2.1 presents typical sound pressure levels in air for different sound sources.

<table>
<thead>
<tr>
<th>Sources (at 1 m)</th>
<th>Sound Pressure</th>
<th>SPL re 20 ( \mu \text{Pa} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rifle</td>
<td>200 Pa</td>
<td>140 dB</td>
</tr>
<tr>
<td>Threshold of pain</td>
<td>20 Pa</td>
<td>120 dB</td>
</tr>
<tr>
<td>Pneumatic hammer</td>
<td>2 Pa</td>
<td>100 dB</td>
</tr>
<tr>
<td>Street traffic</td>
<td>0.2 Pa</td>
<td>80 dB</td>
</tr>
<tr>
<td>Talking</td>
<td>0.02 Pa</td>
<td>60 dB</td>
</tr>
<tr>
<td>Library</td>
<td>0.002 Pa</td>
<td>40 dB</td>
</tr>
<tr>
<td>TV studio</td>
<td>0.0002 Pa</td>
<td>20 dB</td>
</tr>
<tr>
<td>Reference sound pressure</td>
<td>0.00002 Pa</td>
<td>0 dB</td>
</tr>
</tbody>
</table>

The last important sound measurement that relates to the previous two is the sound intensity. It is defined as the energy flux (power per surface area) corresponding to sound propagation and is measured in \( W/m^2 \) [10]. Sound intensity is a vector quantity - it has magnitude as well as direction. In an acoustic free field, the sound intensity and the sound pressure are directly related by the following equation,

\[
\vec{I} = p \vec{u}
\] (2.1.3)

where \( I \) is the sound intensity, \( p \) is the sound pressure and \( u \) is the particle velocity. And, as can be seen from equation 2.1.4, it is equivalent to the power per unit area definition given earlier.
\[ \text{Intensity} = \text{Pressure} \times \text{Velocity} = \frac{\text{Force}}{\text{Area}} \times \frac{\text{Distance}}{\text{Time}} = \frac{\text{Energy}}{\text{Area} \times \text{Time}} = \frac{\text{Power}}{\text{Area}} \quad (2.1.4) \]

Like the other two measurements, sound intensity can also be scaled logarithmically by the sound intensity level (SIL), defined by the following expression, [8]

\[ \text{SIL} = 10 \log_{10} \left( \frac{I}{I_{\text{ref}}} \right) \quad (2.1.5) \]

where \( I \) is the sound intensity and \( I_{\text{ref}} \) is a reference intensity value, being \( 10^{-12} \text{W/m}^2 \) the most used value. The reference intensity level used is related to the sound pressure reference value used in the SPL. The deduction of this relationship can be consulted in [9].

### 2.1.2 Sound Waves

Sound propagates through the air as a series of longitudinal waves meaning the disturbance moves in the same direction as the wave. This waves, of alternating pressure deviations from an equilibrium pressure, result in non-stationary compressions and rarefactions of the medium. [8, 12]

The number of pressure variations per second is called the frequency of the sound, \( f \), and is measured in Hertz (Hz). The frequency of a sound produces its distinctive tone. A sound which has only one frequency is defined as a pure tone. Pure tones are rarely encountered in real-life situations, generally, most sounds are made up of different frequencies. The frequency of a sound defines its pitch, which is the subjective perception of a high or low sound by each person.

Another characteristic of a sound wave is its wavelength (\( \lambda \)) that is, the distance from one wave top or pressure peak to the next, as shown in Figure 2.1. The sound wavelength and frequency are related by the following expression, [9]

\[ \lambda = \frac{c}{f} \quad (2.1.6) \]

where \( c \) equals the speed of sound that, as shall be seen in subsection 2.1.3, is constant for a certain medium (constant conditions). In sum, the sound wavelength and frequency are inversely proportional being the speed of sound the proportionality constant.

![Characteristics of a sound wave.](12)
In general, the behaviour of sound waves is affected by the properties of the medium and its surroundings. Factors such as pressure, density and temperature can increase or decrease the sound wave speed. Obstacles in the sound path can lead to sound reflection, absorption, and transmission. How much sound is reflected, absorbed or transmitted depends on the properties of the object, its size and the wavelength of the sound.

2.1.3 Speed of Sound

The sound waves propagate at a certain speed depending on the medium it propagates through. Sound travels faster in liquids rather than gases and even faster in solids. In daily discussions, the term speed of sound is commonly referred to as the speed of sound waves in air. Sound propagates as a wave in a compressible medium at a speed given by,

\[ c^2 = \frac{dp}{d\rho} (\rho_0) \]  

(2.1.7)

where \(c\), previously defined as the speed of sound, will be used throughout this thesis to refer to the speed of sound in air, \(p\) is the air pressure, \(\rho\) is the air density and \(\rho_0\) is the air density in the medium before it was perturbed by the sound wave. The derivation of this equation can be consulted in [9].

Earth’s atmosphere can be approximated as an ideal gas, whose governing state equation is the following,

\[ p = \rho RT \]  

(2.1.8)

where \(R\) is the ideal gas constant that equals 287.058 \(J/kgK\) and \(T (K)\) is the air temperature.

Considering the process as isentropic, the following relation can also be used,

\[ \frac{p}{\rho^\gamma} = \frac{p_0}{\rho_0^\gamma} \]  

(2.1.9)

where \(\gamma\) is the ratio of specific heat of an ideal gas, \(\gamma = \frac{C_p}{C_v}\) that equals 1.402 for the atmosphere.

Using Equations 2.1.8 and 2.1.9, the sound wave speed equation can be simplified,

\[ c^2 = \frac{dp}{d\rho} (\rho_0) = \gamma \rho_0 \gamma^{-1} \frac{p_0}{\rho_0^\gamma} = \gamma \frac{p_0}{\rho_0} = \gamma RT \]  

(2.1.10)

For a temperature equal to 293 K (\(\approx 20 \degree C\)) the speed of sound in air is equal to 343 m/s. [8]

2.1.4 Sound fields

A region in space where there is sound is called a sound field. Sound fields depend not only on the sound power and directional characteristics of the sound source but also on the properties of any medium it passes through, is reflected, absorbed or diffused by. Even though there are numerous different possible sound fields, this section presents four of the most important ones. [13, 14]
Near-Field and Far-Field

The distinction between the two acoustic fields presented has to do with the physical distance from the sound source. The acoustic energy produced by the sound source will behave differently depending on how far away the observer is from the source.

When sound power radiates from a point source, the power is distributed over larger and larger spherical surfaces as the distance from the source increases [9]. The area of a sphere of radius $r$ is,

$$ A = 4\pi r^2 \quad (2.1.11) $$

then the sound intensity of radiation at distance $r$ is,

$$ I = \frac{W}{A} = \frac{W}{4\pi r^2} \quad (2.1.12) $$

therefore, the energy or intensity decreases by a factor of 4 as the distance $r$ is doubled, meaning in dB it decreases 6dB per doubling distance. This rule is called the inverse square law.

At a certain distance away from the source, the spherical shape of the sound waves have grown to a large enough radius making it possible to approximate the wave-front as a plane-wave. In this region, called the acoustic far field, the source is far enough away to essentially appear as a point in the distance, and the sound pressure level is governed by the inverse square law. A single microphone sound recording will give reliable and predictable results. In practice, the far-field region is defined at a distance of 2 wavelengths away from the sound source and extends towards infinity.

On the other hand, closer to the source, the sound waves behave in a much more complex way, and there is no fixed relation between pressure and distance, meaning the sound pressure level does not obey the inverse square law. This region is called the acoustic near-field, which is characterized by an inner zone where the sound energy circulates back and forth with the vibrating surface of the source, never propagating away, and an outer zone where part of the sound field continues to circulate, and some propagates away from the object. Eventually, the threshold distance of 2 wavelengths is reached, where the sound field strictly propagates. Typically, measuring in the near field requires the use of more than one microphone in order to accurately capture the energy borne by the circulating and propagating waves. [14]

Figure 2.2 illustrates the presence of the two acoustic fields near a source.

Figure 2.2: Illustration of the acoustic near and far fields. [14]
Free-Field and Diffuse-Field

The acoustic field can also be characterized by the path taken by the sound waves when reaching an observer. In daily situations, sound waves are reflected in the walls, floor, ceiling, as well as other objects in the area. The sound waves that reach an observer are a combination of waves travelling directly from the source and waves already reflected.

The extreme ends of this experience characterize the free and diffuse fields. In an acoustic free field, there are no reflections, the sound waves reach the observer travelling directly from the source. The waves pass the observer exactly once and do not return. An anechoic chamber is a classic example of a free field. The chamber’s walls, ceiling, and floor are covered with special materials to absorb sound waves before they can be reflected.

In opposition, in a diffuse field sound is reflected so many times that it travels in all directions with equal magnitude and probability leading to a zero net intensity. As a result, it does not appear to have a single source. This field is approximated in a reverberant room whose walls are designed to have reflective walls built at oblique angles so no walls are parallel to each other, causing the sound waves to be reflected a maximum number of times.

2.1.5 Sound Weighting

In acoustics, weighting is a process that involves emphasizing the contribution of a certain set of data, giving it more weight in the analysis. This is a very important tool when dealing with sound perception, that has resulted in several alternative sound measurement scales.

The human hear reacts differently to different sounds, depending on their frequency and intensity. A continuous sound can be more perturbing than an intermittent one. The noise level is then considered a subjective measure that depends on the observer. In response to this situation, a series of weighting filters were created that correlate measured sound pressure levels with the subjective human response.

The most commonly used filter is the A-weighting filter. It is a standard weighting of the audible frequencies designed to reflect the response of the human ear to noise. The filter covers the entire audible frequency range, however, it highlights frequencies between 1 kHz and 5 kHz to whom the ear is much more sensitive, as shown in Figure 2.3.

The A-weighting curve has been widely adopted for environmental noise measurements and is standard in most sound measurement devices. Measurements made using A-weighting are usually shown with dB(A) to show that the information is ‘A’ weighted decibels. Over the years other filters have been created such as the B-, C-, D- and Z- weightings although most have fallen into disuse. [16, 17]
2.2 Aeroacoustics

Aeroacoustics is commonly portrayed as a branch of fluid dynamics that deals with the theory of noise generation in unsteady flows. However, in reality, the field of aeroacoustics is concerned with the general interaction between a background flow and an acoustics field. [18]

Aeroacoustic phenomena are responsible for the grand majority of noise generation from an aircraft for example. For this thesis it is important to understand what are the main causes of aircraft noise, with a particular interest in jet noise, and how they are generated. The most recent aeroacoustic studies on sound generated aerodynamically have focused on how this noise can be reduced, which is exactly the main subject of study of this work.

2.2.1 Aircraft Noise

There are two main sources of noise in an aircraft flying at subsonic conditions. The first is the airframe noise and the second is the engine noise. Both cases involve various types of noise generating mechanisms including noise due to turbulent flow, structural vibrations and the interaction between flow and aircraft structures [6, 19]. The next items summarize the sources and causes of the two groups.

- Airframe noise - Caused by the interaction of airflow with all aircraft structures. The main sources of noise are the aircraft landing gear (when down) and lift/control surfaces (including the wing and tail).

- Engine noise - Created by the sound from the moving parts of the engine (including fan, turbine, compressor), but mostly from the interaction of high-speed exhaust or jet behind the engine as it mixes with the air around it.

The degree to which people experience aircraft noise on the ground has a lot to do with atmospheric conditions. Temperature, wind speed, direction, humidity, rain, and cloud-cover all have a part to play in the way we hear aircraft noise. The reverberation of sound waves caused by the weather can make noises seem louder. Sometimes aircraft flying at altitudes that would not normally produce noise may be heard in certain atmospheric conditions.

2.3 Jet Noise

Jet engines produce noise in different ways, but mainly it comes from the high-speed exhaust stream that leaves the nozzle at the rear of the engine, this type of noise is normally referred to as jet noise. Planes are loudest when they move slowly, such as at takeoff or at landing, causing severe noise pollution problems in areas surrounding airports. As the exhaust stream meets relatively still air, it creates tremendous shear that quickly becomes unstable. The turbulence produced from this instability becomes the roar of the engine. [20, 21]

The theory and study of jet noise started more than 50 years ago following the introduction of turbojet propulsion on civil aircraft, after the Second World War. The first universal theory of noise generated aerodynamically was proposed by Lighthill [22, 23] and his theory still remains an important tool in the understanding of jet noise. Other theories were developed based on Lighthill’s theory, Lilley [24], Ffowcs Williams [25], Goldstein & Rosenbaum [26], and many others. The current understanding of jet noise suggests that for free jets relevant
to aero-engines working at subsonic conditions, there exist two distinct jet noise sources, leading to two different noise spectra \[20, 21, 27\]:

- **Fine-scale spectrum (FSS)** - According to Tam & Auriault \[28\], fine-scale turbulence exerts an effective turbulence pressure on its surroundings. The fine-scaled turbulence is distributed throughout the mixing layer of the jet and its intensity is equal to 2/3 of the turbulence kinetic energy. Noise is generated when there are fluctuations in the turbulence pressure arising from fluctuations in turbulence kinetic energy.

- **Large-scale spectrum (LSS)** - This second mechanism is attributed to large turbulent structures that are spatially coherent in the axial jet direction. This allows the radiated sound from different parts of the structure to reinforce or cancel each other. This effect results in highly directional noise radiation. These structures’ behaviour has been characterized by researchers as similar to the growth and decay of linear instability waves. Starting out at very low amplitude near the nozzle exit, and growing rapidly as they propagate downstream. At some point downstream it reaches its maximum amplitude and from then on it becomes a damped wave.

Considerable progress has been made in the understanding of jet noise since the work of Lighthill. Yet, researchers are still unable to predict the noise spectra of the two basic components, mostly due to the limited understanding of jet turbulence at present time. Therefore, despite recent progress in jet-noise modelling and simulations, the effective mitigation of jet noise remains an open challenge for the future.

### 2.3.1 Jet noise reduction

The turbulent mixing noise is the main cause of jet noise and is originated by the turbulent mixing of jet flow and free-stream across jet shear layers. For separate flow exhaust designs, there are two such shear layers generating noise, the inner and outer shear layers. The first is the layer between the primary or core flow and the secondary or fan flow. The outer shear layer lies between the secondary flow and the free-stream. In the case of a single exhaust design, only one shear layer is present between the jet flow and the free stream. These shear layers are unstable and instabilities lead to vortex roll up and transition to turbulence. The structures and turbulent eddies generate non-equilibrium pressure fluctuations which are radiated as sound. \[29–31\]

In simplest terms, to reduce jet noise, the velocity of the jet plume must be reduced. To reduce the effective velocity exiting from the exhaust nozzle, the air must be encouraged to mix faster with the surrounding fluid and entrain more of this flow. The problem associated with encouraging a strong mixing of two flows is the generation of high-frequency noise. And so there has to be a careful balance between low-frequency noise associated with large-scale turbulence and high-frequency noise due to small-scale turbulence.

#### Chevron nozzles

Researchers have been exploring various passive flow control methods to reduce jet noise including chevron nozzles. These nozzles possess triangular serrations along the trailing edge and are capable of effectively reducing engine exhaust noise while imposing minimal engine performance penalty and a very small weight impact. The net effect of the chevrons is to introduce stream-wise vorticity into the jet shear layer, increasing turbulent mixing and decreasing the jet potential core length.
A chevron nozzle is normally characterized by three geometric parameters. The chevron count, penetration and length. The chevron count is the number of existing triangular serrations around the circumference of the nozzle. The chevron penetration is the difference between the tip and base radii of the chevron and is usually expressed as a penetration depth or taper angle. At last, the chevron length is the distance between the edge and tip of each serration.

The benefit of having chevron nozzles is recognized by the great majority of engine manufacturers, indeed it is becoming more common to see commercial aircraft equipped with chevron nozzle engines. The General Electric engine that powers the newest 747 and 787 Boeing aircraft has chevron nozzles as shown in Figure 2.4.

Acoustic studies on chevron nozzles

Studies on noise reduction concepts started with small protrusions at the nozzle tip, called ‘tabs’, that would suppress screech noise. The suppression of screech was desired in order to allow a clearer study of other components of jet noise. During the 80’s and 90’s, a more intensive study was done on tabs from which researchers concluded that the technique might have a potential for reduction of turbulent mixing noise. From these studies stand out the ones conducted at Lockheed Georgia [33] and later continued at NASA [34].

Due to the severe noise regulations that were expected to arise, NASA launched in 1992 the Advanced Subsonic Technology (AST) program to address engine fan noise. In response to that, several engine companies, including General Electric Aircraft Engines (GEAE) and Pratt & Whitney (P & W), expressed their interest on the subject and submitted proposals for conducting such tests in response to the solicitation.

GEAE and P & W were awarded contracts to design and build scale models of the separate-flow nozzle as well as a variety of noise suppression devices. This was the first important experimental work done with multiple tabbed and chevron nozzle models [35]. With regards to the geometry of the noise reduction devices, a distinction was made between ‘tabs’ and ‘chevrons’. Chevrons were basically extensions of the nozzle wall into a continuous serrated edge, in contrast, tabs were more incisive and were to have a more aggressive penetration into the flow, as shown in Figure 2.5.

On this program, a total of 54 Separate-Flow-Nozzle (SFN) configurations (Figure 2.5) were tested by modifying the core nozzle alone, the fan nozzle alone, or both nozzles simultaneously and tested on their jet noise reduction capacity using a phased microphone array. A selection was made on the suitable SFN’s for further development and verification. The five SFN’s chosen included both chevron and tabbed nozzles.
Researchers working on the program concluded that several designs provided an ideal jet noise reduction of over 2.5 EPNdb for the effective perceived noise level (EPNL) metric. The designs where both core and fan nozzles were modified simultaneously provided the greatest EPNL reduction, being the one with chevrons on both nozzles the best. In comparison with chevrons, tabs appeared to be an inefficient method for reducing jet noise.

In 1998, in a follow-up of the previous work, Saiyed et al. [36] studied the impact on thrust performance of the majority of the tested nozzles while evaluating the EPNL benefits. The authors recommended an even more reduced list of particular SFN’s that were thought as good candidates for further development via static engine tests and flight tests. The impact on thrust was evaluated to be less than 0.25%, and it was at this point that the industry started to invest heavily in product development programs on the topic. The AST program ended with a series of flight tests in 2001 on NASA’s Learjet 25 and Honeywell’s Falcon 20 as shown in Figure 2.6.

From this point on, several different studies were made on the benefit of chevrons for jet noise reduction. Bridges and Brown [38] studied a parametric family of chevron nozzles and investigated the relationship between the geometric characteristics of the chevron, the flow characteristics, and far-field noise. A total of ten different models were tested, varying chevron count, penetration, length, and symmetry. The results were used as subjects for four comparative studies. The authors concluded that the chevron length did not have a major influence on the results. On the other hand, chevron penetration increased high-frequency noise and reduced low-frequency noise, especially for low chevron count. High chevron count resulted in low-frequency reductions without high-frequency penalty.

Engblom, Bridges and Khavaran [39, 40] presented numerical predictions for single-stream chevron nozzle flow performance and far-field noise production and compared those results with experimental data. The results showed a correct far field noise reduction trend, although there were some evident discrepancies with the numerical
predictions.

Khirtov [41] presented in his work, experimental and computational results related to turbulent jet noise for baseline nozzles, chevron nozzles and coaxial nozzles with chevrons on both fan and core nozzles. The results showed that the chevrons produced longitudinal vortices that changed the structure large-scale turbulence inside the jet and reduced the noise level by about 2.7 dB.

A series of tests were also conducted at the University of Cincinnati in collaboration with GEAE. In their work, Callender et al. [42], experimentally investigated single and dual flows for a baseline inner nozzle and different designs of chevron nozzles. Tests were performed with varying number of lobes and levels of penetration to study the effect of the different chevron characteristics on far-field acoustics. The acoustic results presented, that included both overall sound pressure level and directivity data, showed the chevron nozzles were most effective at lower frequencies and aft angles. In terms of geometric characteristics, the chevron penetration was concluded to directly influence the shear-layer mixing, and eventually, the higher penetration led to high-frequency noise generation. The data also confirmed that the noise reduction of specific chevron configuration strongly depends on the velocity difference between the inner and outer flow streams of the nozzle. Which is reasonable, chevron nozzles are designed to increase the efficiency of shear-layer mixing, if the shear layer becomes weaker their ability to do this diminishes.

\begin{table}
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Nozzle ID & N & Length (mm) & Angle (°) & Penetration (mm) & D (mm) & Γ \\
\hline
SMC000 & 0 & 8 & 5.0 & 0.085 & 50.8 & 0.089 \\
SMC001 & 6 & 22.6 & 5.0 & 0.085 & 52.2 & 0.089 \\
SMC002 & 4 & 32.0 & 5.0 & 1.395 & 53.6 & 0.089 \\
SMC003 & 10 & 14.0 & 5.0 & 0.099 & 53.9 & 0.089 \\
SMC004 & 5 & 26.6 & 5.0 & 1.160 & 53.6 & 0.089 \\
SMC005 & 5 & 22.6 & 0.0 & -0.005 & 54.5 & 0.000 \\
SMC006 & 6 & 22.6 & 18.2 & 3.525 & 47.7 & 0.292 \\
SMC007 & 6 & 32.0 & 13.3 & 3.681 & 49.9 & 0.297 \\
SMC008 & 10 & 19.3 & 13.0 & 2.175 & 48.4 & 0.288 \\
SMC010 & 10 & 15.2 & 9.8 & 1.299 & 52.6 & 0.490, 0.130 \\
\hline
\end{tabular}
\end{table}

Figure 2.7: Chevron nozzle models used by Bridges and Brown [38] on their work and respective characteristics, being Γ the vortex strength parameter defined by the slope of the chevron edge in the plane normal to the jet diameter.

Callender et al. [42], also conducted detail investigations into the effect of chevron characteristics on the near-field acoustics of a separate flow system. Chevrons were found to be most effective at lower frequencies, reducing the peak noise by 5-7 dB. Chevron penetration was found to be more significant than the chevron count for noise reduction in the near field.

Birch [43] employed RANS-based jet noise prediction model to a series of chevron nozzle flows and the predictions were compared with experimental data. The results showed that the axial vorticity coming from the chevrons causes a very rapid increase in the width of the mixing layer, contributing to a noise reduction at the lower frequencies. A second effect due to the use of chevrons was identified. Although more complex it appeared to involve an interaction between the axial vortices and the jet turbulence that causes the high-frequency noise.

Tide and Srinivasan [44] presented a couple of new chevron concepts, including a sinusoidal design, and evaluated their noise reduction performance. The main objective of having sinusoidal configurations was to reduce the strength of the stream-wise vortices when compared to the regular triangular shaped ones. Although this change is expected to reduce mixing at lower pressure ratios and thereby reducing the acoustic benefit, they concluded to be advantageous at higher pressure ratios. At higher pressure ratios, more aggressive mixing takes
place with stronger vortices that result in higher level of turbulence immediately downstream of the nozzle, which significantly increases noise. Acoustic characteristics such as Overall Sound Pressure Level (OASPL), directivity spectra, acoustic efficiency, broadband shock associated noise, and so on were measured. The experiments were conducted for Mach numbers ranging from 0.75 to 1.70. They concluded that both symmetric chevrons provided a reduction in OASPL of 2.5dB, however at higher values of pressure ratios the sinusoidal chevron shows better noise reduction benefits for all emission angles due to the influence of the smooth chevron lobe profile.

The same authors presented in 2010 an experimental study [30] focusing on the effect of different chevron parameters like chevron count and penetration on the noise from both subsonic and under expanded flow. Multiple acoustic characteristics were measured, and experiments were conducted for underexpanded sonic conditions corresponding to fully expanded jet Mach numbers in between 0.75 and 1.70. They concluded that a higher chevron count with a lower level of penetration yielded the maximum noise reduction. Chevron count was agreed to have a more significant influence for noise reduction at low nozzle pressure ratios and the same for chevron penetration at higher ratios.

More recently Depuru Mohan and Doty [29] studied the possibility of using piezoelectrically-activated chevrons for jet noise reduction. Circular nozzles, static chevron nozzles, and piezoelectrically-activated chevron nozzles were tested. The authors observed that low excitation frequencies and amplitudes were good operating conditions for piezoelectric actuators. They also concluded that the nozzles with piezoelectrically-activated chevrons reduced jet noise up to 2 dB beyond the static chevron benefit, over a wide range of frequencies and observer angles.

The major experimental studies performed on chevron nozzles up to date were just presented. Other important works were done on computer simulations that were used to predict the noise of different nozzle configurations. [45–48]

2.4 Wind Tunnel Testing

Computer simulation has reduced the amount of wind-tunnel testing necessary, but the latter remains an important part of the development process in the aerospace industry. Mostly used for aerodynamic research, a wind tunnel can be combined with an anechoic chamber for aeroacoustic research. Hence wind tunnels have become an important research facility for the study of aircraft noise, in a way that it can accurately reproduce wind flow around model-scale objects under controlled conditions to study their aerodynamic or aeroacoustic performance.

2.4.1 Wind Tunnel Characterization

There are three main characteristics that define a wind tunnel: its speed regime, the tunnel geometry and the configuration of its test section. The speed regime is quantified by the maximum velocities that the flow can reach inside the test section relative to the speed of sound. Compressibility and thermal effects must be taken into consideration when working with speeds higher than the speed of sound.

In terms of geometry, there are two common designs, open-circuit and closed-circuit, as shown in Figure 2.8. In the closed return tunnel, air is conducted from the exit of the test section back to the fan by a series of turning vanes keeping a continuous flow of air inside the ductwork of the tunnel. On the other hand, in an open return tunnel, the air that passes through the test section is gathered from the room in which the tunnel is located. Even though
the closed return tunnel has a higher construction cost because of the vanes and ducting, it assures a superior flow quality in the test section and a quieter operation relative to the open return, which is a valuable asset for acoustic measurements.

![Image of wind tunnel geometries](image)

Figure 2.8: Most common wind Tunnel geometries. [49, 50]

The test section is the part of the tunnel where the model is placed. Wind tunnels can have open test sections, where there is an open throat and the flow temporarily meets an outside steady flow or it can have closed test sections with a complete closed circuit duct having no encounters between tunnel flow and steady outside flow. The two different test section configurations make it possible to perform acoustic measurements both in the air stream and out of the air stream.

### 2.4.2 Anechoic Chamber

The purpose of having open-jet tunnels is to have the chance to position the sensors for acoustic measurements outside the flow region and so, avoid the reverberant environment of hard-walled closed section wind tunnels and the self-noise produced by the microphones when located in the air stream region.

However, it is essential to guarantee that when positioned at a far field position the sensors will not be affected by unwanted outside noise. The solution is to enclose the test section within a large chamber, acoustically isolated, called an anechoic chamber.

To create the non-reverberant environment the chamber is covered in all surfaces with clusters of wedge-shaped sound absorbing material, usually polyurethane foam or rock wool. The material has the shape of a wedge to guarantee that it effectively dissipates all the energy coming from incident sound waves so there is no echo and the room becomes extremely quiet. The size of the wedge foam is directly related to its capacity to absorb a sound wave with a certain wavelength by the quarter wavelength ‘rule’. The rule states that the height of the wedge must be at least \( \frac{\lambda}{4} \) to absorb a wave with wavelength \( \lambda \). [51, 52]

Remembering from wave properties, [51, 52]

\[
f = \frac{c}{\lambda}
\]  

(2.4.1)

and in a given medium under fixed temperature and humidity, \( c \) is constant. The higher the frequency, the shorter the wavelength of a sound wave. Using the quarter wavelength rule \( h_{wedge} \geq \frac{\lambda}{4} \) and combining the limit situation with Equation 2.4.2 it is possible to obtain a constant wedge dependent theoretical cut-off frequency.
Even though it is only an approximate value of the cut-off frequency, it becomes an important parameter in the design phase as it provides an idea of the wedge foam size as a function of the lowest frequencies that researchers want to study. In general, the cut-off frequency should be made as low as possible but increasing wedge depth increases the installation cost and decreases the usable volume of the chamber, which sometimes might not be a possibility.

To obtain correct acoustic measurements in a wind tunnel it is also necessary to know the background noise levels in the facility. Only then it is possible for the researcher to estimate the signal-to-noise ratio (ratio of signal power to the noise power corrupting the signal) for test planning and to identify possible contaminations of data due to background noise. Common background noise comes from the wind tunnel drive fan, some type of in-flow support, strut noise and other possible sources outside the chamber as air conditioning systems. According to [53] the desired signal should be at least 10dB greater than the background noise level in the frequency range of interest to be considered accurate.

2.4.3 Aerodynamic characteristics of an open-jet shear layer

The aerodynamic characteristics of the jet will strongly affect the acoustic measurements performed. In that way, it is important to understand what type of flow is present in an open-jet wind tunnel and its characteristics.

The jet flow is discharged from a nozzle into the test section/anechoic chamber where it encounters and interacts with steady air. This kind of flow where the jet spreads through a medium at rest is known as a free jet [54]. A velocity shear is created between the entering and ambient fluids, causing turbulence and mixing. Disregarding very low flow velocities, it is found that the jet becomes completely turbulent at a short distance from the point of discharge. The emerging jet becomes partly mixed with the surrounding fluid at rest. Particles of fluid from the surroundings are carried away by the jet so that the mass-flow increases in a downstream direction. Concurrently the jet spreads out and its velocity decreases, but the total momentum remains constant. Abramovich [55], Rajaratnam [56] and Schlichting [54] present an extensive treatment of the aerodynamics of turbulent jets and the free shear layer.

The thickness of the fluid layer affected by this exchange of momentum is known as the mixing layer or a free shear layer. This region, that adopts a nearly conical shape, starts developing in the upstream positions and is fully developed in downstream positions. Due to this interaction with the quiescent flow, the velocity profile of the jet changes along the stream-wise positions. In an initial region, the jet leaves the nozzle or orifice with an approximate uniform velocity profile, as shown in Figure 2.9. For further downstream positions, due to the growth of the turbulent mixing layer, the velocity profile flattens and stretches ending up with a nearly Gaussian shape.

Shear Layer Thickness

There are many theoretical models that can accurately predict the evolution of velocity profiles, shear forces and shear layer thickness in a free jet. For the present study, the most relevant parameter is definitely the size of
the shear layer that will directly influence the spectral analysis of sound waves.

In Göttler’s [58] solution the shear layer thickness means a certain finite distance between two points, where velocity at one point is close to zero, and at the other close to the jet velocity [55]. In order to find an approximation that is independent of the arbitrary choice of the boundaries of the shear layer, the momentum thickness $\delta_m(x)$ is introduced:

$$\delta_m = \int_{-\infty}^{+\infty} \frac{U}{U_0} \left( 1 - \frac{U}{U_0} \right) dy \quad (2.4.3)$$

where $U$ denotes the time-averaged axial velocity in the shear layer and $U_0$ the uniform axial velocity in the potential core.

This is a measure of the momentum loss within the shear layer as a result of the reduced velocities. For the simple case of linear velocity distribution across the shear layer, the shear layer thickness ($\delta_x$) is equals 6 times the momentum thickness [54]. Using the Göttler’s solution for the axial velocity profile and defining $\delta_x = 6\delta_m$, the following expression can be obtained:

$$\delta_x(x) = \frac{6}{\sqrt{2\pi}} \frac{x}{\sigma} \quad (2.4.4)$$

where $\sigma$ is the spreading rate and it has to be obtained by experiment. Different values of this spreading rate can be found in the literature. From a comparison with Reichardt’s experimental data, Göttler obtained a $\sigma$ of 13.5 (Abramovich [55]). Liepmann & Laufer [59] obtained a value of 11, and a value of 9 has been obtained by Wygnanski & Fiedler [60]. Thus, the shear layer thickness grows linearly with the axial distance in an open-jet wind tunnel. The quantity $\sigma$ is the only empirical constant left free to be adjusted from experiment.

Zana [57] concluded that the following expression was a good approximation for the shear layer thickness,

$$\delta_x = y_{0.05} - y_{0.95} \quad (2.4.5)$$

where $y_{0.05}$ and $y_{0.95}$ correspond to the locations where the axial velocity equals 5% and 95% of the jet axial velocity ($U_0$).
2.4.4 Sound Propagation Through Shear Layers in open-jet Wind Tunnels

As mentioned in previous sections, when aeroacoustic tests are performed in open-jet tunnels, the microphones are placed outside the tunnel flow while the model (source) is typically placed inside the core of the jet. However, before the sound from the model arrives at the out-of-flow microphones, it has to pass through the open jet shear layer.

The shear layer influences the transmitted sound in two distinct ways. Firstly the sound is refracted due to the change of mean flow speed across the shear layer. This effect is analogous to the well-known phenomenon of light refraction upon passage through materials with different indices of refraction. Acoustic measurements done outside the jet flow must be corrected for this effect. Over the past years, several shear layer refraction theories have been developed to determine which parameter are important for an open-jet shear layer refraction correction. This phenomenon was first studied by Amiet [61] with the free-jet shear layer modelled as an infinitely thin cylindrical vortex sheet. The author derived a correction procedure to be added to the measured data. The author validated his theoretical work with a series of experimental investigations. Since then other theoretical and experimental investigations have been made on the same topic. [62, 63]

The second effect that must be taken into account when interpreting acoustic measurements obtained outside the flow in a free jet wind tunnel is that due to turbulence in the shear layer, the sound can be scattered. Suppose that a sound source, such as a loudspeaker, inside the open-jet, sends out a signal with a known frequency. Before this signal arrives at the microphones outside the open-jet, it has to pass through the turbulent shear layer, which causes distortion in phase and amplitude [64]. This phenomenon occurs due to a time delay caused by the encounter of sound waves with turbulent eddies. Although the amplitude distortion is time dependent and not constant, it is normally assumed that the effects of the time delay variations (resulting in frequency distortions) are the most important [64]. Therefore, in most situations, the amplitude is considered as a constant. Subsection 2.4.4 will provide a deeper insight on this subject.

Sound Scattering in Open Jet Turbulent Shear Layers

Experimental results have been published which show that when discrete tones propagate through the turbulent free jet shear layer, they are broadened in the frequency domain accompanied by a reduction in the amplitude of the tone. The changes in the spectral shape under various conditions were then concluded to be a direct cause of the presence of turbulence in the shear layer.

Consider the following experimental setup, adapted from [65]. The sound source is located in the jet center line and the microphones are located outside the flow, as shown in Figure 2.10. The source emits a wave that is convected due to the parallel flow until the turbulent shear layer is reached. Part of the incident waves are reflected (illustrated by the solid red arrow) while other are refracted when propagating through the shear layer (black arrows). Focusing on the sound wave path represented by the black arrows, if no turbulent eddies cross the wave path while it propagates through the shear layer, no scattering occurs and the correct tone is measured by the microphones. However, if there is a turbulent eddy moving through the wave path it will cause directional scattering (red dotted arrow), and so the measured amplitude is decreased in the spectrum at the tone frequency. If the proportion of scattered energy is very large when compared to the total acoustic energy, this phenomenon can
lead to the disappearance of the tone itself.

The sound waves originally emitted in other propagation directions (blue arrows), which would normally not be captured by the microphones, will interact with the turbulent eddies in the shear layer and be redirected to the microphones due to scattering. Due to convection at various speeds, the turbulent eddies will additionally subject the sound waves to a frequency shift resulting in two low amplitude lobes near the tone frequency.

![Image](image_url)

**Figure 2.10: Effect of turbulent shear layers on sound propagation in open-jet wind tunnels.** [65]

This reallocation of acoustic energy of the sound wave into other propagation directions and frequencies is best known in the literature as 'spectral broadening' or 'haystacking'. The typical broadened spectrum yields two side lobes around the main spectral peak and a reduced peak level as shown in Figure 2.10.

Candel, Julliene & Julliand [62] were the first to present preliminary results for turbulence scattering by the jet shear layer on their work on the refraction theory for a circular jet. They found that a test source emitting a monochromatic tone in the interior of a jet was received over a frequency range which is broader the higher the frequency of the original tone. Later on, Ahuja, et al. [63] also included an exploratory study of turbulence scattering at low jet Mach numbers and low acoustic source frequencies. Moreover, thorough theoretical studies have been carried out by Campos [66, 67] and Cargill [68]. More recently, a series of experimental investigations on the subject were carried out by Kröber et al [65] and P. Sijtsma et al [64], both investigations done within the same GARTEUR group. A series of computational aeroacoustics studies were performed by Erwert [69] and a derivation of a weak scattering model by McAlpine [70] that correctly predicted the general trends observed in experiments, but did not provide a simple correction method for shear layer broadening. Even though extensive work has been done on the subject, the physical mechanisms behind the spectral broadening phenomenon are still not totally understood.
Previous experimental works on shear layer induced spectral broadening

This section covers in more detail, two of the above-mentioned studies, as they become more relevant for being experimental ones.

Candel [62] was the first to conduct experimental tests at the von Karman Institute using a 3 m diameter open-jet wind tunnel. A sound source was positioned at the centerline of the jet producing pure tones of varying frequencies, from 4 kHz to 20 kHz. A microphone located at a polar angle of 90 degrees was used to measure the propagating sound. Jet velocities tested ranged from 20 m/s to 60 m/s.

From the experimental results, the author concluded that the spectral broadening increases with increasing wind tunnel velocity, source frequency and the shear layer thickness associated with varying microphones and source positions. In terms of the appearance of two side lobes on the sound spectrum, Candel concluded that their location on the frequency axis \( \Delta f \) is independent of source frequency, but increases with increasing wind tunnel velocity and decreases with increasing shear layer thickness. The author also proposed that the location of these lobes could be approximated by,

\[
|\Delta f| \approx \frac{U_c}{l}
\]

(2.4.6)

where \( U_c \) is the convective speed of the eddies in the shear layer and it can be approximated by \( U_c = \frac{1}{2} U_0 \) and the eddy length scale \( l \) can be approximated by \( l \approx 3.2 \delta_x \), where \( \delta_x \) is the shear layer thickness.

Based on Candel’s results, McAlpine et al. [70] derived a weak-scattering model which they used to more accurately predict the position of the side lobes associated with spectral broadening. They concluded that the frequency shift could be given by the following equation, in which they considered that the eddy length scale is in the order of the shear layer thickness, \( \delta_x \).

\[
|\Delta f| = \frac{\sqrt{2} U_0}{4\pi \delta_x}
\]

(2.4.7)

More recently, another major experimental work was done on the subject by Kröber et al. [65] and Sijtsma et al. [64], both under the same group and with similar procedures but different installations. The work done by P. Sijtsma will be briefly detailed.

Sijtsma et al. derived a theoretical model to predict the scattering properties of sound transmitting through a shear layer and later performed experimental tests to validate that same model. Those tests were conducted at the DNW-PLST open-jet wind tunnel. The tunnel nozzle has a width of 0.8 m and a height of 0.6 m. Initial aerodynamic tests measurements were performed to characterize the jet’s shear layer using a hot-wire measurement technique. Additionally, acoustic measurements were performed using a speaker that was installed slightly recessed in the nozzle extension plate, as shown in Figure 2.11. The measurements were conducted at tunnel velocities of 20, 40, and 60 m/s, and the loudspeaker produced tonal sound with frequencies between 4 kHz and 30 kHz.

The results obtained, that can be examined in [64], are in accordance with the ones obtained by Candel. It was clear that the spectral broadening increases with increasing wind tunnel velocity and the side lobes next to the main peak move outward with increasing velocity. They also concluded that the spectral broadening increases with increasing frequency and that the location of the shoulders does not change with increasing frequency. And lastly,
an increase in shear layer thickness yields more spectral broadening and an inward shift of the side lobes.

2.5 Spectral Analysis of Sound

During data acquisition, transducers output analog signals. A computer cannot store continuous analog time waveforms as the transducers produce, so instead, it digitizes the signal, breaking it into discrete samples to store them. Data is usually recorded in the time domain, but often it is desired to study that data in the frequency domain and so a Fourier transform is performed. The time domain representation shows when something happens and the frequency domain representation shows how often something happens.

When studying sound related problems, it is more common to perform a frequency analysis, as it is indeed more important to study the frequency content of the signal rather than its evolution with time. Hence, this Section will focus on the basic principles of digital signal processing in the frequency domain, usually referred to as spectral analysis. More details about the subjects discussed in this chapter can be found in Refs. [71–76], which have been used for the preparation of this section.

2.5.1 Discrete Fourier Transform

The Fourier Transform is a general method for taking in a time domain equation and converting it into a frequency domain equation and is given by, [72]

$$F(\omega) \equiv \int_{-\infty}^{+\infty} f(t)e^{-i\omega t} dt$$

where $F(\omega)$ is the frequency domain continuous function, $f(t)$ is the time domain continuous function, $t$ is the time and $\omega$ is the angular frequency.

This transform is based on the idea that almost all signals can be decomposed into a series of cosine and sine waves, and for the ones that cannot, it can get so close that the difference between the two has zero energy. However, this transform is only defined for continuous signals, in other words, signals extending from negative infinity to positive infinity. It is impossible to use a group of infinitely long signals to synthesize something finite in length. [71]

In the case of the previously detailed experimental tests, the microphones will acquire finite samples meaning
the signals carrying the sound information are finite. It turns out to be impossible to obtain the frequency response of a finite length signal. The only chance is to make the finite data look like an infinite length signal. Imagine a signal formed from 1024 points, the imaginary samples can be constant copies of the actual 1024 points. In this case, the signal looks discrete and periodic, with a period of 1024 samples. For a set of discrete and periodic data, the Discrete Fourier Transform (DFT) can be used.

The DFT changes an N point input signal into two-point output signals. In the time domain, \( x[n] \) consists of \( N \) points running from 0 to \( N - 1 \). In the frequency domain, the DFT produces two signals, the real part, \( \text{Re} \{x[n]\} \) and the imaginary part, \( \text{Im} \{x[n]\} \). Each of these frequency domain signals are \( N/2 + 1 \) points long and run from 0 to \( N/2 \) as shown in Figure 2.12.

![Figure 2.12: Discrete Fourier Transform terminology.](image)

The frequency domain contains exactly the same information as the time domain, just in a different form. The frequency domain is a group of amplitudes of cosine and sine waves, this is called rectangular notation. Alternatively, the frequency domain can be expressed in polar form. In this notation, \( \text{Re} \{x[n]\} \) and \( \text{Im} \{x[n]\} \) are replaced with two other arrays, Magnitude \( x[n] \) and Phase \( x[n] \). With rectangular notation, the DFT decomposes an N point signal into \( N/2 + 1 \) cosine waves and \( N/2 + 1 \) sine waves, each with a specified amplitude. In polar notation, the DFT decomposes an N point signal into \( N/2 + 1 \) cosine waves, each with a specified amplitude (called the magnitude) and phase shift. Even though the polar and rectangular representations contain exactly the same information, there are many instances where one is easier to use than the other.

**Fast Fourier Transform**

The most efficient algorithm for calculating the DFT is called the Fast Fourier Transform (FFT) and is given by the following expression, [72]

\[
F(k) = \sum_{n=0}^{N-1} f(n)e^{-2\pi i k \frac{n}{N}} \tag{2.5.2}
\]

where \( F(k) \) is the sample in the frequency domain, \( f(n) \) is the sample in the time domain, \( n \) is the time index, \( f \) is the frequency index and \( N \) is the number of samples.

The number of samples in the time domain is usually represented by the variable N. While N can be any positive integer, a power of two is usually chosen, i.e., 128, 256, 512, 1024, etc. Like all discrete Fourier algorithms, the FFT assumes that the time domain continues forever. The FFT has an alias region that is a mirrored image of
the valid frequency region and it occurs above half of the sampling frequency value. The spectrum is normally represented without the alias region, having the name one-sided spectrum.

There are some important frequency and time domain terms that must be highlighted. Figure 2.13 will help going through these terms. Firstly, the time domain. The sampling rate \( F_s \) is the number of data samples acquired per second. This term was already covered in previous Chapters. The time interval from which data was collected to perform a Fourier transform is called the frame or block size \( (T) \). And the total number of data samples acquired during one frame is called the sample length \( (N) \), blue dots in Figure 2.13. In the frequency domain, the highest frequency that is captured in the Fourier transform is equal to half the sampling rate. The frequency bins \( (f_{\text{bin}}) \), red dots in 2.13, correspond to the total number of frequency domain samples, which, for a single-sided spectrum equals half of the time sample length. The most important term is the frequency resolution \( (\Delta f) \), that is the minimum change in frequency that the FFT can detect. It can be determined by the ratio of the sampling frequency and the time sample length. [72, 76] The following expressions summarize the previously explained relations between time domain and frequency domain terms.

\[
F_s = \frac{1}{\Delta t}; \quad T = N\Delta t; \quad f_{\text{bin}} = \frac{N}{2} + 1; \quad \Delta f = \frac{F_s}{N} \quad (2.5.3)
\]

Figure 2.13: Relevant terms for the time and frequency domain analysis. [76]

### 2.5.2 Data Processing

The FFT algorithm can be a useful tool for the post-processing of a digital signal. Furthermore, it is important to understand how the spectral results of the FFT can be improved. This section presents a series of techniques that can be used to obtain clearer spectral results.

**Data Windowing**

The FFT assumes that the time domain signal continues infinitely in time. However, practical real-world signals always contain a finite number of points in what is usually called a frame size or a record. The FFT copies and repeats each of these frames repeatedly. If the time domain signal frame is an integer multiple of the sampling frequency, then each record will connect smoothly to the next record as shown in the top image of Figure 2.14. On the other hand, when the signal time domain signal frame is not an integer multiple of the sampling frequency, the repeated waveform will not smoothly connect to the previous waveform, as shown on the bottom image of Figure 2.14, and there will be a discontinuity. [72, 74]
These discontinuities will lead to spectral leakage. That is, the frequency components of a sampled signal will be scattered around several frequency bins instead of being at just one bin. It is then crucial to understand how the effect of such discontinuities can be minimized. The solution is to use something called a 'window', which is nothing but a function.

There are several types of windows, each with its own characteristics and used for different applications. Typically, the window used for most general purpose data is the Hanning or Von Hann window, represented in Figure 2.15. [72, 74]

Let us consider an example, adapted from [74], for a better understanding of the advantages and disadvantages of using a window. In this case, a 9.5 Hz sinusoid is being sampled. It is known that this signal is non-periodic within the time record used to calculate the spectrum. Due to the discontinuities, the spectrum results in something like the right plot of Figure 2.16.

If the time domain signal is multiplied by the window function, the signal will be forced to zero amplitude at the beginning and end of each time frame (Figure 2.17 Left). This will eliminate all discontinuities as the signal is now forced to be periodic. However, the signal is no longer a perfect sinusoid which means that even though the spectral representation was improved it is not totally accurate.

As nothing comes with a given penalty, the fact that the window is used represents a loss in frequency resolution for periodic signals within the time domain frame. Also, there could be some small processing errors associated
Figure 2.17: Sinusoid multiplied by the Hanning window on the left. Frequency spectrum of the new signal on the right. [74]

with each window type, resulting in small amplitude adjustments. Despite that, data windowing is essential for this thesis’ results post-processing as shall be seen in Chapter 5.

**Overlapping**

The use of data windowing comes with another drawback. Consider that close to the end of each time frame used for the FFT, an additional impulsive component containing a 100 Hz sinusoid was added to the signal. Due to windowing, the signal amplitude would be forced to zero at that location and the new impulsive information would be lost. That is the reason why signal overlapping is used. By applying this technique, the events occurring at or near the beginning and end of the time records are enhanced by using overlap processing.

![Figure 2.18: Representation of a 0% overlapping technique and a 50% one.][75]

As previously discussed, consider the additional impulsive sinusoid was added to the instant $t = 1\, \text{s}$ of Figure 2.18. With the 0% overlap situation, this information would be neglected due to windowing. However, with a 50% overlap, the information contained at this instance would be taken into account by the additional overlapping segment. In sum, when applying data windows to the time domain signal to improve its frequency resolution, it must be followed by the use of the overlapping technique.

**Averaging**

 Normally after using the FFT, the spectral results obtained are very noisy. This is due to the insufficient information that can be obtained from the number of time domain samples. The apparent solution would be to use a longer frame size (with more samples), however, this would only result in a better frequency resolution, the noise level would be the same. [75]

Consider the following example, taken from [71], where a 2048 FFT is being used. From previous sections, it is known that the frequency spectrum would become 1025 samples long. This would result in a very noisy spectrum (Figure 2.19 c). The alternative would be to use an averaging technique. With this technique, the 2048 samples input signal is divided into equally sized smaller segments, 256 samples each for example (Figure 2.19}
a). This would result in 8 different segments. The windowing and overlapping tools would be applied to each segment (Figure 2.19 b) and eight different spectra, with 129 frequency bins each, would be obtained. Only the magnitude of the frequency domain is averaged in this manner; the phase is usually discarded because it doesn’t contain useful information. To obtain a well-behaved curve, the eight different spectra could be averaged into one, eliminating most of the noise (Figure 2.19 d).

Figure 2.19: Example of a spectral analysis of a digital signal. [71]
Chapter 3

Measurement System

This chapter is the first of two that covers the experimental procedure used throughout the work. An overview of the measurement system is first presented. Thereafter, the fundamental aspects of the data acquisition system are discussed and the chapter ends with a listing of all the equipment used.

3.1 Data Acquisition

The complete system used to measure any physical phenomenon such as voltage, temperature or sound with the aid of a computer is usually referred to as a Data Acquisition System or DAQ. The system samples the signals of interest and converts them into digital numeric values that can be manipulated by a computer. Modern DAQ systems exploit the processing power, productivity display and connectivity capabilities of computers to provide a more powerful, flexible and cost-effective measurement solution.

A DAQ system can be divided into three major components as illustrated in Figure 3.1.

The following subsections will go into more detail on each of the DAQ components and make a parallelism with what was used during the work.

3.1.1 Sensors

The measuring system begins with a sensor. Sensors, also known as transducers, convert the physical phenomenon that is being studied into a measurable electric signal. The electrical output is commonly a voltage but can also be current, resistance or any other electrical attribute that varies over time. The type and quantity of sensors used is dependent on the experiment that is being performed.
Microphones

For the present experiments, the most important phenomenon to be measured is sound which is measured with microphones. As reviewed in Chapter 2 sound propagates as an audible pressure wave and microphones convert this acoustical waves into electrical signals.

There are a few different designs for instrumentation microphones, however, the most common type are condenser microphones. Condenser microphones are commonly called ‘capacitor microphones’ due to the similarity of its design to a capacitor. A stretched metal diaphragm acts as one plate of the capacitor and on the other end, there is usually a metal disk that acts as a backplate. Both plates are kept electrically charged due to a stable DC voltage applied through a high resistance. [78, 79]

When a sound wave reaches the microphone it causes an excitation of the diaphragm that moves back and forth relative to the solid backplate resulting in a change of capacitance. The change in capacitance generates an AC output proportional to the sound pressure. The charge of the capacitor is either done with an external power supply giving the name of externally polarized microphones or it can be done internally by the properties of the material itself, as in the case of prepolarized microphones that only need to be powered by pre-amplifiers with a constant current source. [78]

Depending on the field operating conditions, certain types of microphones might work better than others. A free-field microphone is designed to measure the sound pressure as it was before the microphone was introduced into the sound field. In theory, the free-field assumes that sound waves are free to expand forever from the source, meaning there is no reflections or reverberations. This is the reason why free-field microphones work better on anechoic chambers or large open areas. Additionally, pressure-microphones measure the actual sound pressure on the surface of the microphone diaphragm. They are designed to work in a sound field where the sound pressure has the same magnitude and phase at any field position. They are usually found in an enclosure or cavity to test the pressure exerted on walls or inside other structures. At last, random incidence microphones are designed to respond in a uniform manner to any signal arriving on its measuring surface from any angle. [78, 79]

Pitot Tube

Another measurement that is important in any wind tunnel experiment is the airflow velocity. With a Pitot tube, it is possible to measure the total and static pressure whose difference is the dynamic pressure that is directly related to the velocity.

Figure 3.3 shows a schematic of how a Pitot tube works. Small holes are drilled perpendicular to the surface of the tube called pressure taps. These taps are perpendicular to the local flow direction and are pressurized by the random component of the air velocity and so the pressure measured in the ducts coming from the taps is the
static pressure. On the other hand, the center tube is pointed in the direction of travel and is pressurized by both the random and the ordered air velocity. The pressure in this tube is the stagnation or total pressure. Each duct is connected to a different end of a differential pressure transducer that measures the difference between the two, the dynamic pressure [80–82].

![Figure 3.3: Schematics of the principle of work of a Pitot Tube. [80]](image)

The Pitot tube used is shown in Figure 3.4, the differential pressure transducer, coupled with a signal conditioning unit, measures the dynamic pressure. The voltage coming from the conditioning signal unit is measured and displayed by a voltmeter.

![Figure 3.4: 1 - Pitot Tube; 2 - Signal conditioner; 3 - Differential pressure transducer; 4 - Voltmeter.](image)

### 3.1.2 DAQ Device

The sensor outputs an electrical analog signal that contains the information on the phenomenon measured. An analog signal can not be read directly by a computer and so a device is needed to act as an interface between the sensor and the computer. This instrument is called a DAQ board or device and its primary function is to digitize the incoming analog signal.

The signal coming from the sensors can be very small and noisy, therefore a manipulation of the signal might be needed to amplify, attenuate, filter or isolate it before digitizing it. This process of signal manipulation before
the measurement system can effectively and accurately acquire the signal is called signal conditioning. Some DAQ devices include built-in signal conditioning designed for measuring specific types of sensors.

After signal conditioning, the signal is ready to be converted into digital form in order to be manipulated by digital equipment such as a computer. This conversion is done by an Analog-to-Digital Converter chip that digitally represents an analog signal at a certain time instant. It is important to understand in more detail how this conversion process is done and how it should be sampled to avoid incorrect measurements.

The signal coming from the sensor and after conditioning varies continuously over time, something similar to the one illustrated in the first plot of Figure 3.5. To digitize the signal it is necessary to sample it over a certain time interval dependent on the sample rate selected by the user. If the sampling rate is X Hz it means that the ADC converts X samples per second. Assuming that the sample rate is 12 Hz and that the time window on all plots of Figure 3.5 goes from 0 to 1 second, the twelve vertical lines on the second plot correspond to the points where the data is being converted. The amplitude of those twelve points is saved as a sequence of numbers (digital) and can be plotted over time as shown in the last plot of Figure 3.5. [83, 84]

![Figure 3.5: Illustration of Analog to Digital conversion. [83]](image)

Although it seems trivial to convert the signal from analog to digital there are a few problems that may arise when the wrong sample rate is chosen. Consider the 800 kHz sine wave represented in Figure 3.6 in grey tones. The dotted line indicates the aliased signal recorded at a predefined sample rate. It can be noted that the original 800 kHz signal now falsely appears as a 200 kHz sine wave due to the sampling that was done. This phenomenon is called aliasing that results in the appearance of false lower frequency components in the sampled data.

![Figure 3.6: Aliasing of signal due to low sample rate. [84]](image)

The Nyquist Sampling Theorem addresses the aliasing problem and explains the relationship between the sample rate and the frequency of the measured signal. Stating that the sample rate $F_s$ must be greater than twice the highest frequency of interest in the measured signal. [84]

$$F_s > 2f_{\text{max}} \quad (3.1.1)$$
The frequencies of interest in this particular case correspond to the threshold of audible sound frequencies to an average person that range from 20Hz to 20kHz. According to the Nyquist theorem, the sample rate should be at least 40kHz, however it is usually recommended to use a rate five times greater than the signal frequency and so the sample rate, $F_s$, used was 100 kHz.

### 3.1.3 Computer

The last major component of the DAQ system is the computer itself. The computer with a specific software controls the operation of the DAQ device and is used for processing, visualizing and data storage. The communication between the device and the computer is done by a computer bus. DAQ devices are offered on almost all computer buses such as USB, PCI, Ethernet or even Wi-Fi.

The computer has two major software components, the driver and the application itself. The driver software is what provides access to the DAQ device, once installed it is invisible in a way that it is only needed to provide the application software the ability to interact with the device. On the other hand, the application software is what facilitates the control of all the measurement system. It is normally a pre-built application with a programming environment. As shall be seen in the following sub-section the application used for the work was LabVIEW.

### 3.1.4 Data Acquisition Program

The three previous sections provided a general overview of the components of the DAQ system and how they interact with each other to obtain the desired measurements. As concluded in Section 3.1.3 it is the application software that controls the entire system and so that is the start of the system development.

To build a program capable of performing such measurements is something that requires a deep background in the application software where it is being developed as well as a long time to test everything. Fortunately, a previous work was done by Pereira [85] in which he developed and tested a measurement system for the aeroacoustic wind tunnel that will be used during these tests.

Although the development of the Data Acquisition program is out of the scope of this project it is essential to understand how it works and if necessary to adapt it accordingly to the necessities of the new experiments. Therefore the following paragraphs will provide an overview of the program developed in [85] to acquire the acoustic data.

LabVIEW is an application software that offers a graphical programming approach and is widely used for data acquisition and instrument control. A LabVIEW program consists of one or more virtual instruments (VIs), they are analogous to main programs, functions, and subroutines from popular programming languages like C. These VIs are hierarchical and modular and can be used as top-level programs or sub-programs. [86]

Each VI has three main parts:

- **Front Panel** - The interactive user interface of a VI. Simulates the front panel of a physical instrument (Left Image of Figure 3.7) and can contain knobs, push buttons, indicators and other controls.

- **Block Diagram** - The source code of a VI. It is the actual executable program constructed in Labview’s graphical programming language (Right Image of Figure 3.7). The components of a block diagram can be lower-level VIs, built-in functions, constants or others. Different objects are connected together through
wires defining the data flow. The objects on the front panel have corresponding terminals on the block diagram to pass data from the user to the program and the inverse.

- **Icon** - The pictorial representation of a VI. Each VI has its own icon to facilitate its use as an object in the block diagram of another VI.

![Figure 3.7: Front Panel and Block Diagram of a VI. [86]](image)

The VI developed in [85] starts by making the connection between LabVIEW and the DAQ device. This connection is made through a pre-built VI called DAQ Assistant Express VI. It is then necessary to select the measurement type (acquire or generate signals), the input type (voltage, temperature, resistance..) and the channels from which the data is being acquired. For each channel, the user may define the scaled units and the input range of the signal. The sample rate and the acquisition mode (continuous or N samples) of the device are also configured.

The output of the DAQ Assistant VI is a series of signals coming from the different channels configured in the VI. If the user is measuring data with X sensors, then the signal will combine data from X channels. To simplify the data treatment, each channel is then isolated with the help of a Select Signal VI. It accepts multiple signals as inputs and returns only the signal the user selects. Once all X channels are isolated, the block diagram of the program will now have X lanes with the exact same data treatment corresponding to each channel.

Note that this program was developed for acoustic measurements only, everything is configured to receive data from microphones and no other sensor. A few steps were made on the configuration of the pitot tube but it was rather not completed.

The procedure described from now on only covers the signal processing for one channel although it is the same for all other X channels. The time domain representation of the signal is first presented through a plot in the Front Panel. The signal contains voltage data that must be transformed into pressure units (Pascal) using the microphone sensitivity that can be found on the specification sheet of the microphones [87]. Once in pressure units, the frequency analysis of the signal may be done.

Before the Fast-Fourier Transform (FFT) is applied to convert the signal to the frequency domain, a weighting filter is applied through a pre-built VI. After the FFT a complete frequency analysis of the signal is made. The frequency spectrum in the narrowband and one-third octave are obtained as well as the equivalent continuous sound level (Leq). All frequency plots are presented in the Front Panel.

The final block diagrams of the VI gather the same type of data from each channel and use a Write to Measurement VI to save the data, chosen by the user, to a text file.
Also, note that the main function of the LabVIEW program is to control the acquisition of data and not to process the signal. It is indeed a good tool to display real-time data and to give the user an idea of the results obtained yet it lacks accuracy. For the current experiments, the important section of the program is the one that acquires the data and saves the time domain signal to a file. All the signal processing part will be done after the tests with a different software.

3.2 Instrumentation

The previous Sections provided a concise description of the Data Acquisition System components. The information on the specific devices, cables and other auxiliary items used is essential to the development of an organized system. In response to that, this Section presents a list of all the equipment used throughout the project followed by a brief description of each one.

- **Computer**

  A desktop computer with the latest Windows operative system running was used. The system had 8 GB of RAM memory and was run by an Intel i5 processor with 3.50 GHz.

- **DAQ Device**

  The ‘brain’ of the data acquisition function used in this project is the high-performance National Instruments (NI) PCIe-6353. It offers analog I/O, digital I/O, and four 32-bit counters/timers for PWM, encoder, frequency, event counting, and more. The device is well suited for a broad range of applications, from basic data logging to control and test automation. The driver and configuration utility included is the NI-DAQmx that truly simplifies configuration and measurements. The DAQ device is directly connected to the computer through a computer bus. [88]

- **Microphones**

  A total of seven sensors will be used in the tests. Six of them are Brüel & Kjær precision array microphones type 4958 that will measure the sound inside the anechoic chamber. Type 4958 is a ¼-inch pre-polarized microphone suited for use in systems requiring a large number of microphones. The microphones have excellent amplitude and phase-matching over wide ranges of temperature and humidity. With a frequency range of 10 - 20000 Hz and a sensitivity of 11.2 mV/Pa (-39 dB re 1 V/Pa). [87]

- **Pitot Tube**

  The Pitot tube is the last of the seven sensors that will be used. It will measure the flow seed inside the aeroacoustic wind tunnel. The sensor used was lent by Prof. Agostinho Fonseca, the Pitot tube is attached to a metal support with a height of approximately 1 meter. A differential pressure transducer measures the dynamic pressure with the help of a static pressure tap. The differential pressure transducer has a sensitivity of 0.001688 V/Pa.

- **Signal Conditioners**
Two model 482C15 signal conditioners from PCB Piezotronics will be used to power the pre-polarized microphones. The signal conditioner provides an adjustable current source to drive ICP sensors. Each unit has 4 ICP channels which means that for the experiments, two devices will be needed. [89]

A Thurlby Thandar TSX3510P high current laboratory DC power supplier was used to power the pitot tube. The device has a single output, 0 to 35V at 0 to 10A. [90]

- **Connector Block**

  The National Instruments CB-68LP is an unshielded I/O accessory with 68 screw terminals for easy signal connection to a National Instruments 68-pin DAQ device such as the PCIe-6353. In practice, it is the bridge between the sensors and the DAQ board. [91]

- **Signal Generator**

  A signal generator will be initially used to test the data acquisition program, as shall be seen in Chapter 4.

- **Voltmeter**

  An HP 34401A Digital Multimeter is going to be used to measure the voltage outputted by the conditioning unit connected to the differential pressure transducer of the Pitot tube. The device has a 6½ digit resolution, a basic accuracy of 0.0035% DC and 0.06% AC, a maximum voltage input of 1000 V and a maximum current input of 3 A. [92]

- **Cables**

  A series of different cables will be needed to assure all connections. The microphones will be connected to the signal conditioning units through a special cable that was bought together with the microphones. At one end it has SMB coaxial plug that clips directly to the microphone and on the other end, it has a BNC connector that plugs in one of the conditioning units entry. Each microphone has its own cable.

  The conditioning devices will be connected to the connector block by RG-58 cables which are often used as generic carriers of signals in laboratories, combined with BNC connectors that are common on test and measurement equipment.

  A 10 meters long NI custom shielded cable for high-speed digital devices, model SHC68-C68-D4, will be used to connect the connector block to the DAQ device attached to the computer.

- **Speakers**

  Four different speakers will be tested to check which one is the most suitable for the final tests. A BOSE Soundlink Air was chosen as it was the one that reached higher sound levels.

- **Tools**

  A series of different lab tools will be needed such as small wires to connect the ground and negative terminals in the connector block, screw-driver for the screw terminal, adhesive tape, scissors, measuring tape, protective foam and others.
Chapter 4

Experimental Set-Up

The present chapter follows on from the previous one by providing a thorough description of the step-by-step approach used to set up and test all software and hardware needed for the tests. Firstly a brief characterization of the aeroacoustic wind tunnel used is presented, followed by the installation and testing procedure of all equipment. The chapter ends with a brief explanation of the experimental set-up used for each test.

4.1 Facility Characterization

The Aeroacoustic wind tunnel used for the tests is located in one of the laboratories of Instituto Superior Técnico, more precisely in the aerospace engineering lab incorporated in the Mecânica III building. The wind-tunnel program was financed by the Portuguese national funding agency for science, research, and technology as part of a scientific re-equipment program in 2005.

The U-shaped closed return wind tunnel (Figure 4.1) had originally an open-test section, however, a few years after the installation an anechoic chamber was built to enclosure the test section, as shown in Figure 4.2.

A 7 blade fan powered by a 200kW electric motor accelerates the flow to a maximum velocity of 50 m/s. The wind tunnel has a circular exit with approximately 1.5 meters.
The anechoic chamber is covered with foam wedges with a tip-to-base depth of 0.285m which theoretically provide a cut-off frequency of 80Hz. The usable volume of the chamber is approximately $4.3 \times 3.2 \times 2.7$ meters ($L \times W \times H$). To facilitate movement inside the chamber, a grid floor was installed. The main power panel of the wind tunnel is located at the entrance of the lab and the control panel is located next to the entrance of the anechoic chamber. It is in the control panel that the electric motor operational frequency is adjusted to vary the wind tunnel speed.

4.2 Installation

Taking into account the information presented in Chapter 3, the current section will describe the steps used to mount and install all the equipment needed for the experiments.

The first part of the installation procedure was to get to know and test the Data Acquisition Program developed by [85]. The DAQ board and the software needed to run the acquisition program were already installed on the computer. At this initial phase, it was essential to verify that the live-time results presented were correct and most of all, that the correct data was being saved in the computer.

Since the main objective was to test the DAQ program there was no need to complicate the process by connecting everything at once. And so, the connections were made step-by-step, started first with the essential devices and tested it and only afterwards the rest of the devices were incorporated. As a result, the first installation was done with a signal generator instead of the microphones and signal conditioning devices. There was also no need to start the tests inside the wind tunnel, and so these first experiments were done in a room next to the aerospace laboratory.

4.2.1 Tests with signal generator

The signal generator is connected to the connector block using a coaxial cable for each channel. The coaxial cable must be connected to the correct terminal within the screw terminal connector. Each terminal of the connector block is directly related to one pin of the DAQ board installed in the computer. To make these connections it is necessary to read the user’s manual of the connector block [91] and DAQ board [88]. Although it seems confusing, the connections are quite simple to make. Figure 4.3 shows a schematic of the screw terminal of the connector block and the pinout of the DAQ board. The connections are made based on these schematics.

Each pin on the PCI board (starting at 68) has a respective I/O Connector signal description [AI 0 (AI 0+)] next to it. The user manual provides information on these descriptions, for example, pin 68 is an analog input channel (AI). Also, note that each pin on the PCI board has a corresponding number on the connector block that simplifies the connection process.

All the present connections will be analog inputs operating in differential mode, meaning that the device measures the difference in voltage between two AI signals. The core of the coaxial cable, carrying the signal, connects to the positive analog input pin and the shield of the cable connects to the negative analog pin. The user manual recommends connecting the negative lead of the source to a AI GND pin, otherwise, the sensor may float out of the maximum working voltage range of the DAQ system and the device returns erroneous data. Table 4.1 summarizes the connections between the signal generator and connector block.
Table 4.1: Signal channels and respective screw terminal connections.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Screw Terminal/ Pinout number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[Description]</td>
</tr>
<tr>
<td>0</td>
<td>(+) 68 [AI 0 (AI 0 +)]</td>
</tr>
<tr>
<td></td>
<td>(-) 34 [AI 0 (AI 0 -)]</td>
</tr>
<tr>
<td></td>
<td>GND 67 [AI GND]</td>
</tr>
<tr>
<td>1</td>
<td>(+) 66 [AI 0 (AI 1 +)]</td>
</tr>
<tr>
<td></td>
<td>(-) 33 [AI 0 (AI 1 -)]</td>
</tr>
<tr>
<td></td>
<td>GND 32 [AI GND]</td>
</tr>
<tr>
<td>2</td>
<td>(+) 65 [AI 0 (AI 2 +)]</td>
</tr>
<tr>
<td></td>
<td>(-) 31 [AI 0 (AI 2 -)]</td>
</tr>
<tr>
<td></td>
<td>GND 64 [AI GND]</td>
</tr>
<tr>
<td>3</td>
<td>(+) 30 [AI 0 (AI 3 +)]</td>
</tr>
<tr>
<td></td>
<td>(-) 63 [AI 0 (AI 3 -)]</td>
</tr>
<tr>
<td></td>
<td>GND 29 [AI GND]</td>
</tr>
<tr>
<td>4</td>
<td>(+) 28 [AI 0 (AI 4 +)]</td>
</tr>
<tr>
<td></td>
<td>(-) 61 [AI 0 (AI 4 -)]</td>
</tr>
<tr>
<td></td>
<td>GND 27 [AI GND]</td>
</tr>
<tr>
<td>5</td>
<td>(+) 60 [AI 0 (AI 5 +)]</td>
</tr>
<tr>
<td></td>
<td>(-) 26 [AI 0 (AI 5 -)]</td>
</tr>
<tr>
<td></td>
<td>GND 59 [AI GND]</td>
</tr>
</tbody>
</table>

At the other end, the connector block is connected to the computer using the National Instruments custom shielded cable for 68-pin devices. It is important to verify that the connection to the computer is made through the correct connector port. The DAQ board has two connector ports associated, one for pins 0 to 33 and the second for pins 34 to 68.

Once all the devices were connected, the first test was performed. Using the signal generator, the frequency and amplitude of the signal were varied and the amplitude recorded in each channel was saved to a single file. The live results presented by LabVIEW matched approximately the values of frequency and amplitude pre-selected in the signal generator, having a small disparity probably due to interference on the coaxial cables. As expected, all channels presented the same signal. During the recording process, both frequency and amplitude selected in the signal generator were changed and the program had a fast response to the changes. Also, the file with the amplitude data (time domain signal) was being correctly saved in a single file. The maximum duration of the tests was 10
minutes to ensure there were no problems with running the program for a long time.

4.2.2 Tests with microphones

With the Data Acquisition Program working the next step on the preparation procedure was to incorporate
the microphones and the signal conditioning devices. The microphones are connected to the signal conditioners
through a special cable that comes with the microphones and the connection between the signal conditioners and
the connector block is made through the coaxial cables.

Two signal conditioning devices will be used having four channels each. Figure 4.4 shows the back of one of
the signal conditioning units, where the connections are made. The microphones are connected to the ICP entry
while the coaxial cable connects to the output entry.

![Figure 4.4: Back view of one of the PCB 482C15 Signal conditioners.](image)

Table 4.2 summarizes the connections between the three pieces of equipment: microphones, signal condition-
ers, and connector block. Note that each microphone cable is numbered from zero to five and that each signal
conditioner is numbered from one to two.

<table>
<thead>
<tr>
<th>Microphone</th>
<th>Signal C. [Channel]</th>
<th>Pinout number [Description]</th>
<th>Microphone</th>
<th>Signal C. [Channel]</th>
<th>Pinout number [Description]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 [Ch. 1]</td>
<td>(+) 68 [AI 0 (AI 0 +)]</td>
<td>3</td>
<td>1 [Ch. 4]</td>
<td>(+) 30 [AI 0 (AI 3 +)]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-) 34 [AI 0 (AI 0 -)]</td>
<td></td>
<td></td>
<td>(-) 63 [AI 0 (AI 3 -)]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GND 67 [AI GND]</td>
<td></td>
<td></td>
<td>GND 29 [AI GND]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(+) 66 [AI 0 (AI 1 +)]</td>
<td></td>
<td></td>
<td>(+) 28 [AI 0 (AI 4 +)]</td>
</tr>
<tr>
<td>1</td>
<td>1 [Ch. 2]</td>
<td>(-) 33 [AI 0 (AI 1 -)]</td>
<td>4</td>
<td>2 [Ch. 1]</td>
<td>(-) 61 [AI 0 (AI 4 -)]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GND 32 [AI GND]</td>
<td></td>
<td></td>
<td>GND 27 [AI GND]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(+) 65 [AI 0 (AI 2 +)]</td>
<td></td>
<td></td>
<td>(+) 60 [AI 0 (AI 5 +)]</td>
</tr>
<tr>
<td>2</td>
<td>1 [Ch. 3]</td>
<td>(-) 31 [AI 0 (AI 2 -)]</td>
<td>5</td>
<td>2 [Ch. 2]</td>
<td>(-) 26 [AI 0 (AI 5 -)]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GND 64 [AI GND]</td>
<td></td>
<td></td>
<td>GND 59 [AI GND]</td>
</tr>
</tbody>
</table>

These preliminary tests were still conducted in a room outside the laboratory. The complete layout of the
measurement system is shown in Figure 4.5, it can be seen that the microphones are positioned in a horizontal
array with approximately the same distance between each other. The sound source used was a laptop initially
playing a random sound and afterwards playing a pure frequency tone.
The results obtained matched what was expected taking into account the frequency tones played by the source. Note that in terms of amplitude no verification could be made since the sound amplitude coming from the source was unknown.

4.3 Flow velocity profiles: without nozzle

A series of tests were conducted with the final objective of obtaining the velocity profile and shear layer characteristics of the free jet inside the anechoic chamber, whose characteristics have been proved to affect sound propagation.

4.3.1 Experimental set-up

No nozzle was installed in the wind tunnel exit for these set of tests, as shown in Figure 4.6. The only equipment used was the pitot tube and its auxiliary devices as presented in Section 3.1.1. The voltage displayed by the voltmeter was read manually and with it, the flow speed was calculated using the procedure described in the next subsection. The voltage was also read before the wind-tunnel was turned on and after it was turned off, to use those numbers as a reference offset value.

The coordinate system defining x and y, is shown in Figure 4.7. The origin is located at the nozzle edge. The x-axis is the axial direction of the shear layer, the y-axis is normal to the x-axis and is in the direction of the width of the nozzle. In similar tests performed by [85] in the same wind-tunnel, the author concluded that the flow profile was generally coherent across all vertical positions. So, it was decided to only test the flow at different horizontal positions keeping the pitot tube always at the same height (approximately 1 m from the chamber’s grid floor).
Three different stream-wise positions were tested, \( x_{P1} = 0.75m, x_{P2} = 1.90m \) and \( x_{P3} = 2.70m \). For each position, the flow speed was recorded for more than 100 different points along the cross-stream direction (\( y \)) as illustrated by the three red dashed lines in Figure 4.7. The distance between each measurement point along the same position line varied between 1, 5 and 10 cm. In regions closer to the limits of the wind-tunnel exit, measurements were done with intervals of 1 cm to guarantee that the starting and ending points of the mixing zone were accurately identified. On the other hand, as the measurements started to go near the centreline of the jet, spacing was increased to 5 or even 10 cm.

![Figure 4.7: Schematics of the flow velocity tests set up.](image)

### 4.3.2 Data processing

As explained in Section 3.1.1 the voltage displayed by the voltmeter is directly related to the air dynamic pressure. Previously, for the calibration of the differential pressure transducer, multiple values of pressure were applied to the transducer, having acknowledged that its sensitivity is approximately equal to 0.001688 V/Pa. For this reason, knowing the voltage displayed by the voltmeter, that in turn is connected to the differential pressure transducer, it is possible to obtain the dynamic pressure by multiplying that voltage by \( \frac{1}{0.001688} = 592.406 \).

Consider the voltage data presented in Table 4.3 obtained directly from the voltmeter during a preliminary test. The data has units of millivolt, to convert it to dynamic pressure in Pascal it is necessary to first have the same data in Volt and then multiply it by 592.417. Note that these values are purely to illustrate how the velocity data was obtained from the pitot tube, more detailed measurements will be presented in Chapter 5.

<table>
<thead>
<tr>
<th>EMOF</th>
<th>7 Hz</th>
<th>14 Hz</th>
<th>21 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position 1</td>
<td>94mV</td>
<td>380mV</td>
<td>842mV</td>
</tr>
<tr>
<td>Position 2</td>
<td>94mV</td>
<td>373mV</td>
<td>830mV</td>
</tr>
<tr>
<td>Position 3</td>
<td>89mV</td>
<td>368mV</td>
<td>809mV</td>
</tr>
</tbody>
</table>

The Bernoulli equation defines the dynamic pressure as,

\[
\rho_{din} = \frac{1}{2} \rho v^2 \Rightarrow v = \sqrt{\frac{2\rho_{din}}{\rho}} \tag{4.3.1}
\]
where $p_{din}$ (Pa) is the air dynamic pressure, $\rho$ (kg/m$^3$) is the air density in the test location and $v$ (m/s) is the airflow velocity.

To obtain the flow velocity it is necessary to have a value for the air density which can be estimated using the ideal gas law, expressed as a function of temperature and pressure:

$$\rho_{dryair} = \frac{p}{R \cdot T}$$  \hspace{1cm} (4.3.2)

where $\rho_{dryair}$ (kg/m$^3$) is the density of dry air, $p$ (Pa) is the static pressure, $R$ is the specific gas constant for dry air that equals 287.058 J/(kg.K) and $T$ (K) is the air Temperature.

The idea was to acquire a small and precise temperature sensor for the tests. However, due to bureaucracy delays, the sensor was only available after a long time and so a small house thermometer was used to measure the air temperature inside the anechoic chamber. For the pressure measurements, the ideal situation would be to display the pressure measured by the static pressure tap of the Pitot tube. At the time of the tests it was impossible to accomplish this and so as an approximation, the atmospheric pressure measured in a station close to the university was used [94].

Taking into account the procedure just explained, the following air velocity was obtained from the data presented in Table 4.3.

Table 4.4: Air velocity calculated from the voltage data presented in Table 4.3.

<table>
<thead>
<tr>
<th>EMOF</th>
<th>7 Hz</th>
<th>14 Hz</th>
<th>21 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position 1</td>
<td>9.63 m/s</td>
<td>19.38 m/s</td>
<td>28.9 m/s</td>
</tr>
<tr>
<td>Position 2</td>
<td>9.60 m/s</td>
<td>19.16 m/s</td>
<td>28.63 m/s</td>
</tr>
<tr>
<td>Position 3</td>
<td>9.37 m/s</td>
<td>19.08 m/s</td>
<td>28.29 m/s</td>
</tr>
</tbody>
</table>

A few details were noted from these initial tests. The electric motor operational frequencies (EMOF) tested were the ones that were planned to be used in the final experiments and were believed to correspond, based on the correlation presented in [85], to 10, 20 and 30 m/s. However, the motor frequency settings used did not exactly match the expected air velocity. Instead of 10 m/s the frequency setting of 7 Hz resulted in velocities of around 9.5 m/s, the 14 Hz of around 19 m/s and the 21 Hz of 28.5 m/s. Although they did not exactly match those values, it was decided to keep these three frequency settings for the final tests in a way that it is easier to stabilize the wind-tunnel control panel at those frequencies rather than having decimal points in the frequency setting.

### 4.4 Acoustic experiments: without nozzle

Acoustic measurements are designed to assess the effects of the shear layer on the transmission of pure tones. In these experiments, a tonal sound is produced on one side of the flow using a loudspeaker, and a series of microphones on the other side of the flow receive the acoustic wave after travelling through the shear layer. By comparing the normalized spectra for different parameter variations, the effect that the shear layer has on the passing sound can be analysed. Variation of different parameters such as the axial position of the source, tunnel
speed, and source frequency will give an insight in the importance of each of them and to what extent this is in agreement with previous works.

### 4.4.1 Experimental set-up

The microphones were fixed in a support bar inside the anechoic chamber at different angles from the jet center line. The microphone array is capable of capturing data at jet directivity angles ranging from 60 to 120 deg, with the directivity angle being measured from the jet centreline such that the flow direction is defined as 180 deg. The speaker was positioned on the opposite side of the jet at the same axial positions as for the aerodynamic experiments. Figure 4.8 shows a schematic of the complete set-up and Figure 4.9 shows the support bar used and the speaker fixed between foam wedges.

![Figure 4.8: Plant view of the anechoic chamber with the microphone and speaker positions.](image1)

![Figure 4.9: Support bar used to fix the microphones and speaker position between foam wedges.](image2)

For each speaker position, pure tones of 0.5, 1, 2.5, 4 and 8 kHz were played. The acoustic measurements were performed at three wind tunnel speeds defined by the motor frequencies of 7, 14 and 21 Hz. In order to measure the tunnel background noise, which is the noise that is generated by the wind tunnel and the tunnel flow itself, measurements were done without a generated tone for each wind tunnel velocity.
4.4.2 Data processing

An online tone generator mobile app was used to create a pure tone which was then played by the loudspeaker. A sampling frequency of 100 kHz was used and each test had a measurement time of 60 seconds. The output of the data acquisition program was a text file with the time domain signal captured for each microphone. The time domain signal was then processed in MATLAB. For the computation of the frequency spectrum, a von Hann window was applied and the block size of the FFT was set to 100k samples leading to a frequency resolution of 1 Hz. An overlap of 50% was employed ensuring at least 120 spectral averages.

4.5 Flow velocity profiles: circular and chevron nozzle

A new set of tests was conducted with the purpose of obtaining and characterizing the velocity profile of the jet exhausting from two different nozzle designs. The tests were performed using the same procedure and data treatment as for the aerodynamic tests without any nozzle installed. However, the velocity profile was only obtained for the second position ($x = 1.90m$) as it was the most important for the further acoustic analysis. Ideally, the other two positions should have also been tested to obtain a more complete set of results for the shear layer thickness. Only the two higher motor operational settings were tested, 14 and 21 Hz. These were the ones to be used in the acoustic tests.

Figure 4.10 shows the two nozzles that were tested as part of the present experimental study. The first being a baseline circular nozzle and the second a nozzle with chevrons. Both convergent nozzles were mounted directly at the exit of the wind tunnel and had a length of 50 cm and an exit diameter of 1.40 meters. The chevron nozzle had 12 equally spaced chevrons, a chevron length of 34 cm and a chevron penetration of 3.4 cm.

![Figure 4.10: Circular and chevron nozzles installed in the wind tunnel exit.](image-url)

4.6 Acoustic experiments: circular and chevron nozzle

A set of acoustic experiments were performed with the two distinct nozzles installed in the wind tunnel exit. The purpose of these tests was to compare the effect each design had on jet noise reduction. The speaker was positioned at position 2 and the same microphone display was used.

Initially, the sound spectrum associated with the free jet noise was studied. Further, the same analysis was performed with the speaker playing pure tones of 0.5, 1, 2.5, 4 and 8 kHz. Frequency spectrums were obtained.
for each velocity and sound source frequency combination, along with other acoustic characteristics such as the overall SPL and one-third octave band analysis.
Chapter 5

Results and Discussion

With the complete measurement system mounted it was then possible to proceed to the experimental tests. A first set of tests were conducted to obtain the wind tunnel background noise. Secondly, a set of tests were conducted to analyse and characterize the wind tunnel flow. Thirdly, the phenomena of spectral broadening was experimentally verified. At last, the different nozzle configurations were tested and compared on their jet noise reduction efficiency. The present Chapter summarizes the results obtained for all conducted tests. A brief review of the set-up of each test is first presented followed by the results and a brief discussion.

5.1 Wind Tunnel background noise

5.2 Flow velocity profiles : without nozzle

The plots shown in Figure 5.1 summarize the results obtained for the axial velocity distributions of the 9 tests. Each row considers one motor frequency and each column a different position. The cross-stream locations are referenced to the jet centreline. Each plot is presented in a larger scale in A.1.

For each measurement point, three different voltage data were recorded, the maximum, minimum and the mean value. With that, three different flow velocity profiles were obtained, as shown in Figure 5.1. The mean value (in black) is the one that more accurately represents the flow velocity measured at each position. The two dashed lines indicate the maximum (red) and minimum (green) velocities registered for that point, making it is easier to understand in which locations there were greater fluctuations of speed. The temperature and pressure registered for each test are presented in each graph above the velocity profile plot.

From direct observation of the plots, it is clear that each case presents a similar velocity profile, characterized by a core region of approximately uniform velocity and two side regions with a significant velocity drop. The length of the core region varies for each case but is always centred in the jet longitudinal axis. The length of the side regions where the velocity decays also varies from case to case.

Focusing on the first column of graphs that show the velocity profiles for Position 1, note that for the three plots the size of the core region, where the flow speed is constant, is practically the same size as the exit of the tunnel, 150 cm. Additionally, the three lines coincide in all three graphs, meaning that there are no evident velocity
fluctuations at any measurement point. The proximity of Position 1 to the exit of the tunnel is the major explanation for these results. At such short distance, the flow is still in an initial region, where there is no interaction between the flow and quiescent air and so the mixing layer is very thin and there is a uniform velocity profile.

From observation of the results obtained for position 2 (second column), there are three trivial differences when compared to the previous one. Firstly, there is a reduction in the length of the profile core region. Considering, for example, the case with the motor frequency set to 7 Hz, the core region was very close to 150 cm in the first position and is about 127 cm in position 2. Secondly, there is an increase of the side regions. In the first case were practically straight lines and now have some inclination. And thirdly, there are evident velocity fluctuations in the side regions of the profile, the dashed lines no longer overlay the dark one. The results of the last position (third column) follow the same trend as the second case. However, for this last case, all three emphasised points become more evident.

These effects result from an expected growth of the turbulent shear layer as the jet interacts more and more with the steady air in the anechoic chamber. This phenomenon causes the air in the limits of the core region to decelerate, resulting in a reduction of the core region length. On the other hand, it also causes an acceleration of the steady air resulting in an increase of the side regions length, it takes a longer length for the jet flow to reach a steady condition as there is more mass-flow. The strong velocity fluctuations observed for the last positions, proven by the clear distance between the dashed and dark lines at each measurement point, are a result of the increasing turbulence levels in the mixing layer due to the intense shear.

In general, the results obtained are in accordance with the theoretical information presented in Section 2.4.3. To complement the results presented in the plots, Tables 5.1 and 5.2 present an estimation of the shear layer thickness for each case. This estimation was done by considering the approximation detailed in Section 2.4.3 that, as a reminder, is ruled by the following expression,
\[ \delta_x = y_{0.05} - y_{0.95} \]  

(5.2.1)

Table 5.1: Without nozzle : Estimation of the free jet shear layer thickness on the left boundary of the jet (downstream direction as reference).

<table>
<thead>
<tr>
<th>Velocity 1</th>
<th>Position 1 ((x = 0.75 , \text{m}))</th>
<th>Position 2 ((x = 1.90 , \text{m}))</th>
<th>Position 3 ((x = 2.70 , \text{m}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(U_0 = 9.5 , \text{m/s})</td>
<td>(y_{0.05} = +76 ) (\delta_x = 10 , \text{cm})</td>
<td>(y_{0.05} = +85 ) (\delta_x = 30 , \text{cm})</td>
<td>(y_{0.05} = +95 ) (\delta_x = 45 , \text{cm})</td>
</tr>
<tr>
<td>(U_0 = 19 , \text{m/s})</td>
<td>(y_{0.05} = +80 ) (\delta_x = 15 , \text{cm})</td>
<td>(y_{0.05} = +95 ) (\delta_x = 34 , \text{cm})</td>
<td>(y_{0.05} = +100 ) (\delta_x = 45 , \text{cm})</td>
</tr>
<tr>
<td>(U_0 = 28.5 , \text{m/s})</td>
<td>(y_{0.05} = +79 ) (\delta_x = 11 , \text{cm})</td>
<td>(y_{0.05} = +99 ) (\delta_x = 38 , \text{cm})</td>
<td>(y_{0.05} = +108 ) (\delta_x = 53 , \text{cm})</td>
</tr>
</tbody>
</table>

Table 5.2: Without nozzle : Estimation of the free jet shear layer thickness on the right boundary of the jet (downstream direction as reference).

<table>
<thead>
<tr>
<th>Velocity 1</th>
<th>Position 1 ((x = 0.75 , \text{m}))</th>
<th>Position 2 ((x = 1.90 , \text{m}))</th>
<th>Position 3 ((x = 2.70 , \text{m}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(U_0 = 9.5 , \text{m/s})</td>
<td>(y_{0.05} = -80 ) (\delta_x = 11 , \text{cm})</td>
<td>(y_{0.05} = -95 ) (\delta_x = 34 , \text{cm})</td>
<td>(y_{0.05} = -100 ) (\delta_x = 50 , \text{cm})</td>
</tr>
<tr>
<td>(U_0 = 19 , \text{m/s})</td>
<td>(y_{0.05} = -69 ) (\delta_x = 13 , \text{cm})</td>
<td>(y_{0.05} = -98 ) (\delta_x = 38 , \text{cm})</td>
<td>(y_{0.05} = -110 ) (\delta_x = 60 , \text{cm})</td>
</tr>
<tr>
<td>(U_0 = 28.5 , \text{m/s})</td>
<td>(y_{0.05} = -85 ) (\delta_x = 17 , \text{cm})</td>
<td>(y_{0.05} = -104 ) (\delta_x = 44 , \text{cm})</td>
<td>(y_{0.05} = -114 ) (\delta_x = 69 , \text{cm})</td>
</tr>
</tbody>
</table>

The shear layer thickness estimations suggest that there is an approximately linear downstream growth of the shear layer as shown in Figure 5.2. There also appears to exist a trend relating higher velocities with thicker shear layers at the same longitudinal position. This is proved by the increasing thickness obtained for higher velocities at all positions except in Position 1 from velocity 2 to 3 and in Position 3 from velocity 1 to 2, both situations in the left boundary of the jet. Additionally, the proximity of one of the jet’s boundary layer to the anechoic chamber wall seems to have a significant impact on the shear layer thickness on that side. This is suggested by the much larger lengths obtained in Table 5.2 when compared to Table 5.1.

An accurate method for determining the real size of each shear layer is out of the scope of this work, and so, even though it is not totally precise, these estimations will provide important information for the acoustic tests. In Figure 5.3, the theoretical shear layer thickness derived in Section 2.4.3 for three different values of \(\sigma\), namely \(\sigma = 11\), \(\sigma = 9\), and \(\sigma = 13.5\) together with the data of the present study have been plotted. It can be seen in this figure that, except a small deviation at \(x = 190 \, \text{cm}\), the present measured data show a good agreement with the theoretical shear layer thickness for a spreading rate, \(\sigma\), of 11.
5.3 Acoustic experiments: without nozzle

In this section, the results of the sound propagation across the wind tunnel jet without any nozzle installed are shown and discussed. The effect of different parameters such as wind tunnel velocity, source frequency, source and microphone positions on spectral broadening will be analysed. The amplitude reduction and the locations of the two shoulders on the frequency axis associated with spectral broadening will be treated as well.

Multiple spectra were obtained to study the different test conditions. The Sound Pressure Level (SPL) is plotted on the y-axis and the frequencies on the x-axis. The frequencies are centred on the pure tone frequency played for each test with a range of $\Delta f = \pm 250 \text{Hz}$. For similar analyses, different source positions, source frequencies and wind tunnel velocities were tested. However, only part of the results for one set of conditions are presented throughout this Chapter, other results can be consulted in Appendix section A.2.1.

5.3.1 Varying wind tunnel velocity

To study the effect of the tunnel velocity on spectral broadening, multiple spectra were obtained for different wind tunnel velocities, as shown in Figure 5.4. The spectra were acquired with the speaker positioned at a distance of 2.70 m (P3), source frequency of 1 kHz and tunnel velocities corresponding to 9.5, 19 and 28.5 m/s. The data was obtained from the microphone approximately aligned with the speaker (Mic 3 in Figure 4.8).
The frequency spectra obtained with the wind tunnel turned off, black line in Figure 5.4, is a single peak at the pure tone frequency, 1 kHz. With increasing velocity there is a clear widening of the peak and the appearance of two side lobes with a lower amplitude, giving the spectrum a symmetric appearance. The intensity of the peak broadening appears to increase with velocity as proved by the spectra of Figure 5.4. The green line is the one with the higher area under the graph, followed by the red and blue respectively. The frequencies at which the side lobes appears also seems to be affected by the wind tunnel velocity. As the velocity increases the lobes tend to appear at frequencies further away from the original source tone frequency. In terms of the original tone amplitude, no difference is observed, as all the different lines overlap at that particular region.

5.3.2 Varying source frequency

Figure 5.5 shows the spectra obtained for different source frequencies. The tests were performed at a wind tunnel velocity of 28.5 m/s with the speaker positioned at an axial distance of 1.90 m. Pure tones of 1, 2.5, 4 and 8 kHz were tested. The data was obtained from the microphone aligned with the speaker (Mic 2 in Figure 4.8).

From these results, it can be seen that for higher tone frequencies, there is a wider broadening of the peak. It is difficult to qualify the effect of the tone frequency on the amplitude of the side lobes as the results are inconclusive. However, the frequency location of these side lobes seems to remain unchanged with varying frequency sources, in contrary to what was verified for the varying wind tunnel velocity case.

Figure 5.6 shows the spectra obtained for different source frequencies under other conditions. The wind tunnel velocity was set to 19 m/s and the source was located at an axial distance of 2.70 m. The results are in accordance to what was previously described about the widen of the peak. It is more evident in this case that the frequencies at which the side lobes appear coincide for all the pure tones. Just like for the previous case there are no clear indications on the effect of the different tones on the amplitude of the side lobes. Although it seems that for higher
frequency tones, the amplitude of the side lobes tends to be higher. Unlike the previous case, for this one, the amplitude of the original tone seems to decrease for higher frequencies. Yet, that difference is not caused by the jet but by the speaker’s difficulty to reach the same amplitudes at higher frequencies. This was proven by comparing each tone amplitude with the one obtained without the jet.

Additional results, on the same study, under different conditions can be consulted in A.2.2.
5.3.3 Varying source axial position

The effect of varying the axial position of the source is illustrated in Figure 5.7. The tests were performed at a wind tunnel velocity of 28.5 m/s and a tone of 8kHz was emitted by the speaker. The microphone data used for each axial position corresponds to the microphone aligned with the speaker, hence, with position 1 microphone 1 was used, with position 2 microphone 2 was used and with position 3 microphone 3.

From observation of Figure 5.7 it can be concluded that axial locations farther downstream show a larger broadband contribution and a higher reduction of the peak amplitude. Which makes sense, increasing the axial source position means that the sound passes through a thicker shear layer before reaching the microphones. In reality what is being analysed here is the direct influence of the shear layer thickness on spectral broadening. Moreover, the side lobes seem to slightly move towards the main peak for downstream locations. Additional results, on the same study, under different conditions can be consulted in A.2.3.

5.3.4 Varying microphone position

A last set of tests was performed to evaluate the effects of varying microphone position on the spectral broadening phenomenon. The wind tunnel velocity was equal to 28.5 m/s and the source located at P3. The spectra obtained from all five microphones is presented in Figure 5.8.

The results presented in Figure 5.8 are quite inconclusive, as there is no apparent relationship between the microphone location and the spectral broadening phenomenon. Although there are evident differences from the various resulting spectra.

By varying the microphones, which are located at different positions there are two factors that must be taken under consideration. The first is that to reach the microphones located further downstream, the sound wave has to
Figure 5.8: Spectra for different microphone positions ($f_{\text{speaker}} = 8\text{kHz}$, $U_0 = 28.5\text{m/s}$).

take a longer path and cross thicker shear layers. Secondly, the angle under which the microphone is positioned with respect to the source causes an oblique sound wave transmission through the shear layers.

With the fact that the sound waves have to cross two shear layers and with the different oblique paths leading to the microphones, there are probably too many factors affecting the sound propagation, making it difficult to qualify the influence of the microphone position on the sound peak broadening.

5.4 Flow velocity profiles: circular and chevron nozzle

The plots of Figure 5.9 show the velocity profile obtained at an axial distance of 1.90 meters for two different electrical motor operational settings and with the different nozzle designs installed. Note that this 1.90 meters distance is relative to the exit of the tunnel without any nozzle installed.

The velocity profiles show a similar shape to the ones obtained without a nozzle. The approximately uniform core jet velocity obtained with the circular baseline nozzle installed is around 22 m/s for the 14 Hz setting and 33 m/s for the 21 Hz. For the same motor operational settings, the jet reaches 20 and 30 m/s when the chevron nozzle is mounted. There is a clear acceleration of the jet in comparison to the no nozzle situation (5.1). This was expected for both nozzles due to their convergent properties that result in a reduction of the cross-sectional area of the jet exit and so, to keep the same mass flow rate (conservation of mass) inside the duct, the velocity increases. Comparing the two nozzles, there is a greater increase in velocity in the case with the baseline circular nozzle installed. This is related to the fact that with the serrations, the chevron nozzle promotes an earlier mixing between the free jet and the steady air which in turn results in a higher deceleration of the uniform velocity jet.

In terms of the jet’s velocity profile length, the overall profile obtained with both nozzles is smaller than the one obtained without a nozzle. This reduction is associated with the smaller exit diameter of the nozzles. Comparing
the two nozzles, the one obtained with the chevron nozzle installed shows a slightly longer length, around 185 cm against 180 cm for the circular nozzle. This is also a result of the enhanced mixing caused by the chevrons. The higher levels of mixing accelerate more outer steady air leading to a higher mass-flow and subsequently, a lengthier velocity profile.

The shear layer thickness was once again estimated using the velocity data and is presented in Tables 5.3 and 5.4. The estimation method used is the same as described in Section 2.4.3. An isolated experiment was performed with the pitot tube placed very close to the nozzle exit aligned with the jet central position. The velocity was obtained to be used as a reference, \( U_0 \), when estimating the shear layer thickness. The thickness values obtained were lower than the ones obtained without the nozzle. The first row of Tables 5.3 and 5.4 shows the estimations obtained for the shear layer thickness for a motor operational setting of 14 Hz, from which can be concluded that the two nozzles show similar estimations at both boundaries of the jet. On the other hand, for a motor operational setting of 21 Hz, the estimation obtained with the chevron nozzle installed is higher than the one with the circular nozzle. Also, for both nozzles, the right boundary of the jet shows a much thicker shear layer when compared to the left boundary, a trend that was already observed in the previous case.

Table 5.3: Estimation of the free jet shear layer thickness on the left boundary of the jet (downstream direction as reference)

<table>
<thead>
<tr>
<th>Velocity 2</th>
<th>Circular nozzle</th>
<th>Chevron nozzle</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_0 = 22.2 \text{ m/s} )</td>
<td>( y_{0.05} = +80 ) ( \delta_x = 26 \text{ cm} )</td>
<td>( y_{0.05} = +80 ) ( \delta_x = 25 \text{ cm} )</td>
</tr>
<tr>
<td>( U_0 = 33 \text{ m/s} )</td>
<td>( y_{0.95} = +54 ) ( \delta_x = 24 \text{ cm} )</td>
<td>( y_{0.95} = +84 ) ( \delta_x = 29 \text{ cm} )</td>
</tr>
</tbody>
</table>

Figure 5.9: Velocity profile obtained at an axial distance of 1.90 meters from the exit of the tunnel for different operating conditions.
Table 5.4: Estimation of the free jet shear layer thickness on the right boundary of the jet (downstream direction as reference)

<table>
<thead>
<tr>
<th></th>
<th>Circular nozzle</th>
<th></th>
<th>Chevrons nozzle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$U_0 = 22.2$ m/s</td>
<td>$y_{0.95} = -90$</td>
<td>$\delta_x = 35$ cm</td>
<td>$y_{0.95} = -95$</td>
</tr>
<tr>
<td>$y_{0.05} = -55$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$U_0 = 33$ m/s</td>
<td>$y_{0.95} = -93$</td>
<td>$\delta_x = 33$ cm</td>
<td>$y_{0.95} = -60$</td>
</tr>
<tr>
<td>$y_{0.05} = -60$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.5 Acoustic experiments: circular and chevron nozzle

The results of the acoustic tests performed with the two different nozzles installed will be presented in this section. An analysis will be made to study the effect that the different nozzle designs have on jet noise reduction. Acoustic characteristics such as the overall SPL, spectra and one-third octave band SPL are compared for both nozzles.

The first section presents the results obtained for the free jet noise on its own and the following section presents the results obtained for the cases with the speaker playing a pure tone.

5.5.1 Jet noise only

Narrowband frequency spectrum comparisons at directivity angles of 60 to 120 deg are shown in Figure 5.9. The sound pressure level is presented in the y-axis and the frequencies are presented on a logarithmic scale in the x-axis. The motor operational setting selected for the presentation was the 21 Hz setting as this velocity was the highest tested. The trends observed for this operational setting were also observed for the 14 Hz case, whose results can be consulted in Appendix section A.3.

Figure 5.10: Spectral comparison for a motor operational setting of 21 Hz.
The plots show a very noisy spectrum, with the higher levels of noise coming from the lower frequencies and almost no noise from the higher ones. This is a consequence of the anechoic chamber background noise levels that are predominantly low-frequency sounds, previously studied in [85]. The intermediate frequency region, between 0.1 and 1 kHz, is characterized by a series of small single frequency peaks that are common to all directivity angles.

Disregarding the very low frequencies, the first plot shows an overall, even though very little, reduction of SPL for the majority of the spectrum when the chevron nozzle is installed. On the other hand, there is, for the other directivity angles, a frequency band where the chevron nozzle seems to increase the jet noise. This region starts to be observed at a directivity angle of 75 deg where it ranges from 40 to 200 Hz, as shown on the second plot of Figure 5.10 where the blue line is above the red one. This trend is carried on and even increased to the following upstream angles. For example, at the 120 deg angle, the band ranges from 40 to 600 Hz. On the other hand, for higher frequencies, the chevrons tend to reduce the noise coming from the free jet, especially at frequencies between 750 and 2500 Hz. For frequencies higher than 2500 Hz the signal captured becomes very noisy and it is difficult to compare the spectrum obtained for each nozzle, especially at the most forward directivity angles.

A one-third octave-band spectral comparison is presented in Figures 5.11 - 5.15 at the same directivity angles. The A-weighing filter was applied to the data to emphasise the results obtained taking into account the sensitivity of the human ear.

Figure 5.11: One-third octave-band A-weighted spectrum; directivity angle, 60 deg; motor operational setting, 21 Hz.

Figure 5.12: One-third octave-band A-weighted spectrum; directivity angle, 75 deg; motor operational setting, 21 Hz.
Figure 5.13: One-third octave-band A-weighted spectrum; directivity angle, 90 deg; motor operational setting, 21 Hz.

Figure 5.14: One-third octave-band A-weighted spectrum; directivity angle, 105 deg; motor operational setting, 21 Hz.

Figure 5.15: One-third octave-band A-weighted spectrum; directivity angle, 120 deg; motor operational setting, 21 Hz.

With the one-third octave-band analysis, the difference, in sound pressure level, between the two nozzle designs becomes more explicit facilitating the comparison between the two cases. From an examination of the graphs, it is possible to conclude that the 60 deg directivity angle is the only where the chevron nozzle provides SPL attenuation across the entire frequency range. Showing a maximum sound level reduction of 6 dBA for frequencies between 400 and 8000 Hz. As observed on the narrowband spectral analysis, there is a frequency range for low frequencies
where the chevron nozzle appears to have a negative effect on noise reduction at the other directivity angles. This frequency range seems to increase for the most aft-angles. For the 75 deg, it covers all bands below the 160 Hz band, for the 90 deg all bands below the 250 Hz band, for the 105 deg all bands below the 500 Hz band and for the 120 deg it covers all bands below the 630 Hz band. For frequencies higher than the previous bands, the chevron nozzle appears to provide little attenuation for all directivity angles except for the 90 deg angle. For this angle, the chevron nozzle does not bring any benefit at high-frequencies.

Figures 5.16 - 5.18 present a one-third octave-band analysis for directivity angles of 60, 90 and 120 degrees, and motor operational settings of 14 and 21 Hz. The results show that the trends discussed in previous paragraphs on the effect of chevron nozzles on jet noise reduction for the 21 Hz are observed for the 14 Hz motor operational setting, though for overall lower SPL values.

![Figure 5.16](image1)

Figure 5.16: One-third octave-band spectrum; directivity angle, 60 deg; motor operational setting, 14 and 21 Hz.

![Figure 5.17](image2)

Figure 5.17: One-third octave-band spectrum; directivity angle, 90 deg; motor operational setting, 14 and 21 Hz.
5.5.2 Jet noise plus pure tones

In Figures 5.19 and 5.20 the narrowband spectrum is plotted for the cases with pure tones of 1 and 8 kHz being played by the speaker. Once again, the sound pressure level is shown on the y-axis and the frequency, on a logarithmic scale, on the x-axis. In general, the noise reductions obtained for the different frequency tones being played followed the same tendency. As a consequence, only two of the tones were selected to be presented, the spectral results obtained for the rest of the tones can be consulted in Appendix section A.4.1. Likewise, the results obtained for the jet noise plus pure tones at an EMOF of 14 Hz can be consulted in Appendix section A.4.2.

It can be seen from these figures that the sound spectrum is very similar to the ones obtained without any tone being played. Also, for each directivity angle, the chevrons seem to increase the jet noise at the same specific frequency bands. In terms of the peak itself, for the 8000 Hz tone, the chevron nozzle tends to reduce the amplitude of the peak at all directivity angles. The same cannot be said about the 1000 Hz case, where the chevron nozzle at
some angles appears to be noisier.

Again, a one-third octave-band analysis was conducted to better analyse the noise level difference between the two nozzles. As it was seen in the previous case that the mid directivity angles, 75 and 105 deg, did not significantly vary from the ones obtained at the outer angles, they were omitted from this analysis. Although only the 1 and 8 kHz narrowband spectra were presented, for the one-third octave band analysis the results for the 4 kHz are also shown to better understand how the peak noise behaves. Figures 5.21 - 5.29 present the results obtained.

The peak associated with the tone played by the speaker is easily identified for each case as the highest sound level observed, around 50 dBA for the 1 kHz, around 35 dBA for the 4 kHz and 30 for the 8 kHz. This difference in SPL for the different tones is related to the fact that the speaker cannot reproduce sounds with very high frequencies with so good quality.

It is recognizable from Figures 5.21, 5.24 and 5.27 that the 60 deg directivity angle is the only that shows an overall benefit of using chevrons for the three cases. Differently, considering all plots, the chevron benefit at lower frequencies seems to diminish and even disappear for higher aft angles. For the highest frequencies, the chevrons show a slight attenuation for the outer angles, however, for the 90 deg angle it clearly brings no benefit, something that was already observed in the previous tests. In terms of the tone played and its surrounding frequencies, no direct conclusion can be drawn. For the 1 kHz case, the peak with and without chevrons have very similar noise levels. For the 4 kHz case, the chevron appears to decrease the peak sound level at all directivity angles. At last, for the 8 kHz there is a slight attenuation of the peak noise level for the outer angles but not for the 90 deg one.

By comparing these one-third octave-band sound levels to the ones obtained with the speaker turned off (5.16 - 5.18), one can observe that the chevron nozzle has the exact same behaviour for the same directivity angles. Even though there is an amplification of a specific frequency due to the tone played by the speaker, the difference in SPL is approximately the same as without the tone.
Figure 5.21: One-third octave-band A-weighted spectrum; directivity angle, 60 deg; motor operational setting, 21 Hz; frequency tone, 1 kHz.

Figure 5.22: One-third octave-band A-weighted spectrum; directivity angle, 90 deg; motor operational setting, 21 Hz; frequency tone, 1 kHz.

Figure 5.23: One-third octave-band A-weighted spectrum; directivity angle, 120 deg; motor operational setting, 21 Hz; frequency tone, 1 kHz.
Figure 5.24: One-third octave-band A-weighted spectrum; directivity angle, 60 deg; motor operational setting, 21 Hz; frequency tone, 4 kHz.

Figure 5.25: One-third octave-band A-weighted spectrum; directivity angle, 90 deg; motor operational setting, 21 Hz; frequency tone, 4 kHz.

Figure 5.26: One-third octave-band A-weighted spectrum; directivity angle, 120 deg; motor operational setting, 21 Hz; frequency tone, 4 kHz.
Figure 5.27: One-third octave-band A-weighted spectrum; directivity angle, 60 deg; motor operational setting, 21 Hz; frequency tone, 8 kHz.

Figure 5.28: One-third octave-band A-weighted spectrum; directivity angle, 90 deg; motor operational setting, 21 Hz; frequency tone, 8 kHz.

Figure 5.29: One-third octave-band A-weighted spectrum; directivity angle, 120 deg; motor operational setting, 21 Hz; frequency tone, 8 kHz.
Chapter 6

Conclusions and recommendations

Two major topics were investigated during this work. The first related to the propagation of sound through a jet shear layer and the effects jet turbulence might have on disparities between the sound emitted and the signal measured. Secondly, a passive jet noise reduction concept by means of a nozzle design was analysed on their noise reduction capacity. The present Chapter presents the final remarks on the development achieved throughout this thesis on both subjects.

6.1 Conclusions

One of the objectives of this work was to investigate the effects of a shear layer on sound propagation in the Aeroacoustic wind tunnel of Instituto Superior Técnico. Aerodynamic measurements were conducted to determine the velocity profile of the jet and the shear layer’s aerodynamic characteristics. The velocity profiles were obtained by means of a pitot tube. Furthermore, acoustic measurements were performed to determine the effect that the shear layer has on the transmission of sound with a special emphasis on tones spectral broadening. This phenomenon is caused by the interaction of sound waves with turbulent eddies on the jet’s shear layer. This implies that the energy of a single tone is distributed over a range of frequencies around the frequency of the emitted tone.

Referring to the experiments performed without nozzle installed, the aerodynamic results showed agreements with theory. A uniform velocity profile with a cross-sectional length similar to the diameter of the tunnel exit was obtained at the position closest to the tunnel exit. For further downstream positions, the profile tended to flatten and stretch. One particularly interesting detail related to the velocity profile was that for all the velocity profiles obtained, there was a slight reduction of the jet velocity in a region near the jet central axis, which became more evident for higher motor operational frequency settings. This had already been observed before in similar experiments performed in [85] and there is no evident explanation to justify it. The shear layer thickness estimated for both jet boundaries also agreed to what was expected, growing linearly along the stream-wise direction. Yet, there were some deviations between the thickness values obtained for the two boundaries of the jet at each stream-wise position. The boundary on the right side of the jet (downstream direction as reference), seems to be somehow affected by the proximity to the anechoic chamber wall.

In terms of the acoustic experiments performed without a nozzle, by varying parameters such as wind tunnel
speed, source frequency, and shear layer thickness, the acoustic effects of these variables on the spectral broadening phenomenon have been identified. In general, the results obtained were in accordance with the ones obtained by Candel [62] and Sijtsma *et al.* [64], detailed in Section 2.4.4. As expected, spectral broadening increased with increasing wind tunnel speed, source frequency, and the shear layer thickness. Moreover, the location of the shoulders from the peak on the frequency axis, increased with increasing wind tunnel velocity, seemed to decrease with increasing shear layer thickness, and it is independent of source frequency. In terms of different microphone positions, no conclusions could be drawn from the results obtained. In general, the results obtained for this first experiments were very satisfactory. The fact that the sound waves had to cross two jet boundaries, and so, two shear layers, must have some type of effect on the spectral broadening phenomenon that could not be predicted by the type of tests conducted. Besides, the angle under which the microphone is positioned with respect to the source causes an oblique path through the shear layer. This oblique transmission of the sound wave was studied by Erwert [69] and McAlpine [70] in which the authors concluded that resulted in an asymmetric spectral shape around the peak. The oblique orientation of almost all microphones used in the present tests relative to the jet cross-stream direction can be assumed to have had a negative impact on the quality of the results obtained.

The other objective of this work was to evaluate the jet noise reduction capacity of a nozzle with chevrons. This was achieved by comparing the noise levels of the wind tunnel jet with the nozzle with chevrons installed and a circular baseline nozzle installed. As before, a series of aerodynamic measurements were conducted to characterize the flow coming from each nozzle. Next, a series of acoustic experiments were conducted to evaluate how the different nozzle designs affected the free jet sound levels across the entire frequency spectrum and for different directivity angles. Results were obtained for the jet noise on its own, and the jet combined with several pure tones being played by a speaker.

Due to lack of time, the velocity profile was only measured at a single position, corresponding to the exact stream-wise point where the speaker would be placed for the acoustic tests. The profiles obtained with each nozzle were slightly different from each other and from the one obtained without a nozzle at the same position. Firstly, the jet showed higher velocities for both nozzles then without nozzle, which was expected due to the nozzle’s convergent characteristics. Between the two nozzles, the circular one displayed higher velocities. For the 21 Hz motor operational setting, the jet coming from the circular nozzle registered velocities around 33 m/s while the chevron nozzle did 30 m/s. In terms of the velocity profile length, the ones obtained with nozzles installed were smaller than the ones obtained without a nozzle, which makes sense as the exit diameter is smaller for the nozzles. Yet, the chevron nozzle showed a lengthier velocity profile than the circular one, this is related to the fact that chevrons promote a faster mixing between the jet and the quiescent air and so, more ‘outside’ air is accelerated. The increased mixing between air flows also had consequences on the size of the shear layer thickness, which was indeed estimated larger when the chevron nozzle was installed (21 Hz MOS).

The acoustic results obtained with the speaker turned off, and so, a simple comparison of the free jet noise, showed that there is no significant benefit in using the chevron nozzle. Only at a directivity angle of 60 deg were the chevrons an overall advantage. For the remaining angles, there were large frequency bands, that seemed to get larger for more aft angles, where the chevrons increased the jet noise. In general, the reduction of SPL obtained at some frequencies never appeared to balance those frequency regions where there was a significant SPL increase.

The speaker was then used to alternatively play different frequency tones that would ease the evaluation of
the effect each nozzle design had on noise reduction. The results obtained were very similar to the ones obtained without the tone. The chevrons increased/reduced the noise levels at the exact same frequencies as for the case without the speaker. No direction conclusion could be drawn on the relation between the level of attenuation of the pure tone peak and its frequency.

With the results obtained it is difficult to qualify the effect that the chevron nozzle has on jet noise reduction. Even though it seems that, for the grand majority of the frequency spectrum, the chevrons reduce the noise levels, there is a ‘dark’ frequency range where the chevrons highly aggravate the jet noise levels. Previous experimental studies performed on chevron nozzles, covered in Chapter 2, concluded that chevron nozzles were in general most effective at lower frequencies and at aft angles. Even though there was a slight benefit of using chevron nozzles at various directivity angles and frequencies, those specific trends were not experimentally verified.

It is important to mention that for this thesis, the highest jet velocity tested was around 0.09 Ma. Normally, studies on chevrons use wind tunnel jets with a minimum velocity of 0.5 Ma, this significant difference makes it impossible to compare results with other works. Additionally, the fact that the velocity is so low makes it impossible to understand how much of the noise levels registered are coming from the jet itself, rather than other electronic equipment associated with the wind tunnel. These indistinguishable sources can induce into error on the chevrons jet noise reduction capacity.

6.2 Future work

Regardless of the positive results obtained for the experimental verification of spectral broadening, there are a few improvements that could be interesting to implement for future works on the subject. In terms of data treatment, it could be relevant to remove the background noise from the narrow band frequency spectrum presented, something that was initially thought but not fulfilled. For a more detailed aerodynamic analysis it would also be relevant to measure the turbulence intensity associated with the jet. It is also interesting to analyse the effect that the oblique microphone position has on the results and if possible use a different support for the microphones closer to the jet. At last, theoretical predictions could be made based on the model derived by Mcalpine [70] and compared with the experimental data.

In terms of the work related to chevrons, the results obtained can be considered satisfactory, yet there is a lot to think and to improve. The main problem concerning future experiments with the nozzles is the low velocities reached by the jet in this facility. It should be considered whether or not it is worth it to proceed to experiments with other nozzles at such low jet velocities, as the results obtained were not very conclusive. Secondly, to proceed to such tests, it is highly recommended to first improve the microphone support and its fixation method. It would be important to reach higher directivity angles, although it seems impossible due to the anechoic chamber dimensions. If the objective is to continue testing other nozzles, it would be interesting to do a comparison study between nozzles with different chevron characteristics and qualify its effect on jet noise reduction.

Throughout this work, a certain number of difficulties and limitations emerged that had direct consequences on the experimental procedure used. As a result, follows a few recommendations for future experimental aerodynamic and acoustic experiments. To begin with, it is necessary to put some type of illumination inside the anechoic chamber and improve the chamber’s door fixing mechanism. Further, if the plan is to continue doing experiments
with the nozzles, the way those nozzles are installed in the wind tunnel exit should also be reviewed. The most relevant of all situations is a slight problem that concerns the Labview acquisition program. In an initial stage, the objective was to connect more sensors (including the pitot tube and a temperature sensor) to the DAQ board, yet it turned out to be impossible due to a series of overwriting errors during the acquisition process. The overwrite errors are commonly encountered for circular buffered acquisitions. The error indicates that information is lost and occurs when LabVIEW does not read data from the PC buffer quickly enough. Samples that are written to the circular PC buffer are overwritten before they are read into Application Development Environment memory. If the only data being acquired is from the microphones, then the program is enough. If not, one should consider implementing a Producer/Consumer Design Pattern architecture for the program.

Just to conclude, it is important to mention a few interesting observations concerning the aerodynamic experiments conducted that can possibly be evaluated at a near future. The first is the fact that all velocity profiles obtained showed a slight decrease of velocity for the central region of the jet for no apparent reason. Also, the right boundary of the jet seems to be somehow affected by the proximity to the anechoic chamber wall, resulting in an asymmetric profile.
Bibliography


Appendix A

Additional results from the aerodynamic/acoustic experiments

A.1 Wind Tunnel velocity profile results: without nozzle

The next Figures shown in more detail the results obtained for the jet velocity profiles in the test section of the wind tunnel.
Figure A.1: Jet velocity profile obtained for Position 1 ($x_s = 0.75m$).
Figure A.2: Jet velocity profile obtained for Position 2 ($x_s = 1.90m$).

Position 2: frequency setting = 7 Hz

$T = 20^\circ C$, $P_{\text{atm}} = 1016.8\ hPa$

Position 2: frequency setting = 14 Hz

$T = 21^\circ C$, $P_{\text{atm}} = 1016.9\ hPa$

Position 2: frequency setting = 21 Hz

$T = 20^\circ C$, $P_{\text{atm}} = 1016.7\ hPa$
Figure A.3: Jet velocity profile obtained for Position 3 ($x_s = 2.70m$).
A.2 Additional results: acoustic experiments without nozzle

A.2.1 Varying wind tunnel velocity

Figure A.4: Spectra for different tunnel velocities ($x_{\text{speaker}} = 0.75\,m$, $f_{\text{speaker}} = 2.5\,kHz$, Mic 1).

Figure A.5: Spectra for different tunnel velocities ($x_{\text{speaker}} = 1.90\,m$, $f_{\text{speaker}} = 2.5\,kHz$, Mic 2).
A.2.2 Varying source frequency

Figure A.6: Spectra for different source frequencies ($x_{\text{speaker}} = 1.90 m, U_0 = 9.5 m/s, \text{Mic 2}$).

Figure A.7: Spectra for different source frequencies ($x_{\text{speaker}} = 0.75 m, U_0 = 28.5 m/s, \text{Mic 1}$).
A.2.3 Varying source axial position

Figure A.8: Spectra for different axial positions \( f_{\text{speaker}} = 2.5 kHz, U_0 = 19 m/s \).

Figure A.9: Spectra for different axial positions \( f_{\text{speaker}} = 0.5 kHz, U_0 = 9.5 m/s \).
A.3 Jet noise only: circular and chevron nozzles

Figure A.10: Spectral comparison for a motor operational setting of 14 Hz for both nozzles, jet noise only

A.4 Jet noise plus pure tone: circular and chevron nozzles

A.4.1 EMOF: 21 Hz

Figure A.11: Spectral comparison at different directivity angles for a motor operational setting of 21 Hz and a pure tone of 0.5 kHz being played by the speaker.
Figure A.12: Spectral comparison at different directivity angles for a motor operational setting of 21 Hz and a pure tone of 2.5 kHz being played by the speaker.

Figure A.13: Spectral comparison at different directivity for a motor operational setting of 21 Hz and a pure tone of 4 kHz being played by the speaker.
A.4.2 EMOF: 14 Hz

![Figure A.14: Spectral comparison at different directivity angles for a motor operational setting of 14 Hz and a pure tone of 0.5 kHz being played by the speaker.](image)

![Figure A.15: Spectral comparison at different directivity angles for a motor operational setting of 14 Hz and a pure tone of 1 kHz being played by the speaker.](image)
Figure A.16: Spectral comparison at different directivity angles for a motor operational setting of 14 Hz and a pure tone of 2.5 kHz being played by the speaker.

Figure A.17: Spectral comparison at different directivity angles for a motor operational setting of 14 Hz and a pure tone of 4 kHz being played by the speaker.
Figure A.18: Spectral comparison at different directivity angles for a motor operational setting of 14 Hz and a pure tone of 8 kHz being played by the speaker.