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**EXPERIMENTAL CHARACTERIZATION OF
VELOCITY AND ACOUSTIC FIELDS OF SINGLE-
STREAM SUBSONIC JET**



UNIVERSIDADE FEDERAL DE UBERLÂNDIA
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ACOUSTIC FIELDS OF SINGLE-STREAM SUBSONIC JET**

Dissertação apresentada ao Programa de Pós-graduação em Engenharia Mecânica da Universidade Federal de Uberlândia, como parte dos requisitos para a obtenção do título de **MESTRE EM ENGENHARIA MECÂNICA**.

Área de Concentração: Transferência de Calor e Mecânica dos Fluidos.

Orientador: Prof. Dr. Odenir de Almeida

Coorientador: Dr. Rod Self

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Dedico este trabalho à minha esposa, Luísa e aos meus pais, Paulo e Iris.

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PROENÇA, A. R. **Caracterização experimental do campo de velocidade e campo acústico de um jato simples subsônico.** 2013 149 f. Dissertação de Mestrado, Universidade Federal de Uberlândia, Uberlândia.

Resumo

O objetivo deste trabalho é estudar e caracterizar aerodinamicamente um jato livre operando em regime subsônico e identificar a assinatura acústica do mesmo. Esse estudo busca analisar fundamentalmente as estruturas turbulentas e o ruído total produzido em diferentes números de Mach. Tal estudo é crucial para o entendimento desses mecanismos de geração e propagação, e encontra extrema importância para aplicações aeronáuticas, como, por exemplo, a exaustão de motores a reação (jato). A investigação é feita através da análise dos dados obtidos em experimentos utilizando tubo de pitot, anemômetro de fio-quente e ensaios acústicos. Neste trabalho também são descritos os procedimentos experimentais de cada etapa de análise, bem como as características dos laboratórios utilizados para o estudo do ruído de jato. Com os dados provenientes das medições com tubo de pitot são estudados os perfis de velocidade média. As propriedades médias também são analisadas com o sistema de anemometria, que ainda é utilizado para estudo da intensidade turbulenta em onze linhas axiais, variando da linha de centro até a borda do bocal (lipline). Estes resultados são comparados com a literatura e é constatada a acurácia dos anemômetros de fio-quente para intensidades turbulentas menores que 15%. Os dados aerodinâmicos mencionados são obtidos para números de Mach 0,25, 0,50 e 0,75, a partir da saída do bocal até treze diâmetros na direção do jato. O estudo acústico é feito através da análise do nível de pressão sonora obtido em seis posições no campo distante, com ângulos de observação variando de 40 a 110°. Diferentes velocidades também foram analisadas, desta vez, com números de Mach de 0.18 a 1.00 com passo de 0.05. Um banco de dados com o nível de pressão sonora em função da frequência é construído a partir destas informações.

Palavras Chave: Jato subsônico. Jato livre. Ruído de jato. Câmara anecóica. Rig de jato.

PROENÇA, A. R. **Experimental characterization of velocity and acoustic fields of single-stream subsonic jet.** 2013 149 p. M. Sc. Thesis, Universidade Federal de Uberlândia, Uberlândia.

Abstract

The purpose of this work is to study and characterize aerodynamically a free jet operating at subsonic regime and identify its acoustic signature. This study aims to analyze fundamentally the turbulent structures and the total noise produced at different Mach numbers. This kind of research is crucial to the understanding of these mechanisms of noise generation and propagation, and it is extremely important for aeronautical applications, for instance, the jet engine exhaust. The research is done by analysing the data obtained in experiments using pitot tube, hot-wire anemometer and acoustic measurements. This work also describes the experimental procedures for each step of analysis, as well as the characteristics of jet noise facilities. The data from measurements with a pitot tube was used to study the mean velocity profiles. The average properties are also analyzed with an anemometry system, likewise used to study the turbulent intensity at eleven axial lines, ranging from the centerline to the edge of the nozzle (lipline). These results are compared with literature and has verified the accuracy of hot-wire anemometers for turbulent intensities lower than 15%. The aerodynamic data are obtained for Mach numbers 0.25, 0.50 and 0.75, from the nozzle exit to thirteen diameters in the direction of the jet. The acoustic study is carried out by analyzing the sound pressure level obtained at six positions in the far field, with observer angles ranging from 40 to 110°. In this campaign more velocities are studied with Mach numbers from 0.18 to 1.00 with step of 0.05 are described. A database with the sound pressure level as a function of frequency is constructed from this information.

Keywords: Subsonic jet. Free jet. Jet noise. Anechoic chamber. Jet rig.

LIST OF SYMBOLS

Roman Symbols

a_0	Ambient sound speed, m/s
c_0	Sound speed in gas, m/s
c_p	Specific heat capacity (constant pressure), J/(kgK)
c_v	Specific heat capacity (constant volume), J/(kgK)
C_{ij}	Cross-stress tensor
D_j	Jet diameter, m
E	Turbulence energy spectrum
f	Frequency, Hz
I	Sound intensity, W/m
k	Turbulent kinetic energy, m ² /s ²
l	Length scale, m
L_{ij}	Leonard's stress tensor
M	Mach number
M_j	Jet Mach number
P_{amb}	Ambient pressure
P_D	Dynamic pressure
P_T	Total pressure
PR	Pressure ratio
p_{ij}	is the viscous stress tensor.
r	Radial coordinate
R	Gas constant, J/K
St	Strouhal number, $St = fD_j/U_j$
τ_{ij}	Reynolds' stress tensor

T_{ij}	Lighthill's stress tensor
T_j	Jet exit temperature, K
T_0	Ambient temperature, K
TR	Temperature ratio
U_j	Jet exit velocity, m/s
U_0	Mean velocity, m/s
u'	velocity fluctuation at a point
$W_{monopole}$	Radiated sound power by a monopole source
W_{dipole}	Radiated sound power by a dipole source
$W_{quadrupole}$	Radiated sound power by a quadrupole source
x	Axial coordinate

Greek Symbols

λ	Dissipation length scale (Taylor macroscale)
λ_L	Wavelength
δ_{ij}	Kronecker delta function
ε	Turbulent dissipation rate
η	Kolmogorov length scale
θ	Observer angle, °
ν	Kinematic viscosity, m ² /s
ρ	Fluid density, kg/m ³
ρ_0	Fluid density at rest, kg/m ³
γ	Thermal conductivity, W/(mK)
μ	Dynamic viscosity, Pa/s

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CHAPTER I

INTRODUCTION

The word “Aeroacoustics” refers to the study of sound produced by flows and this chapter gives one general vision about the principal issue around this subject: aircraft noise. It is explained why aircraft noise is a question related to the daily lives of many people, which requires much effort from companies and the scientific community. It discusses some programs that are used to deal with the aircraft noise and the sources of noise coming from different aircraft components and phases of flight. Some solutions are shown as well as brief words about the noise related to the jet engine, the main subject of this work. Finally, a summary about the thesis’ chapters contents concludes the introduction.

1.1 General context

The modes of transport or ways of travel were always guided among the topics of greatest interest of humanity. Traversing quickly over the centuries, there has been the development of ships, trains, cars and aircraft, beyond a diverse range of modifications and innovations. The concept of “long trips” modifies itself, where what was long becomes short even though the physical distance remains unchanged. Safety, comfort, speed and also leisure items are increasingly exploited in transportation.

There is no doubt about air transport being one of the safest modes of travel as well as the fastest growing. An impressive number of flights are going on daily and research related to development of this area has increased in many subjects. One of them, the aircraft noise, became an issue of substance after commercial air lines service adopted jet engines,

in the early 1960s (Smith, 1989). The aircraft noise is the noise pollution produced by any aircraft or its components during a flight.

In comparison with the older airplanes, those of today are much quieter than 20 years ago and will be replaced by even quieter aircraft in the future (Lee and Edmonds, 2011). The modern high bypass turbofan engines are quieter than the turbojets and low bypass used before. Nevertheless, from another point of view, the number of flights is increasing and the local noise limits are more restrictive. The aircraft became 75% less noisier over the last 30 years, however the air traffic is growing and citizens are still exposed to high noise levels. To guarantee airports working at permitted noise levels, noise monitoring systems have been installed. The Fig. 1.1 shows information about Heathrow Airport to illustrate the case. The graph is about the population and the total area within the 57 dBA from 1988 to 2011. Additionally, movements per annum in that airport are also explored. The data proof that the number of people affected had been decreasing, however last years the trend is more to be stabilized than decrease.

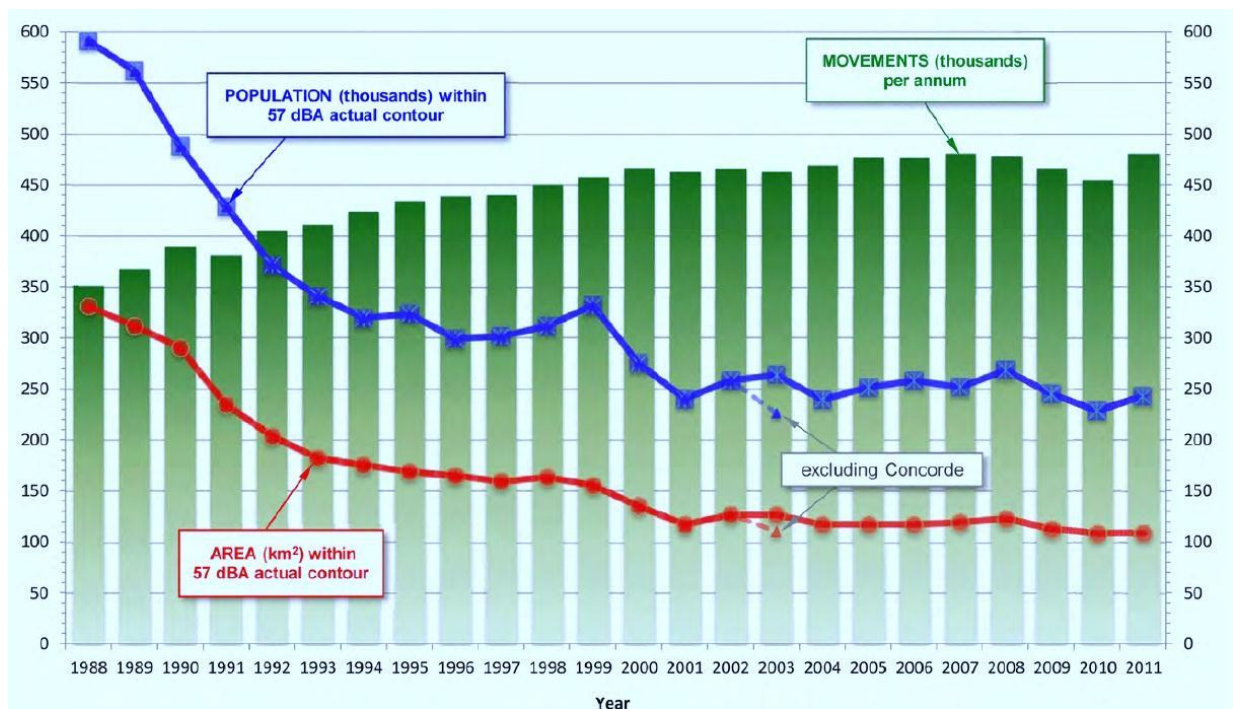


Figure 1.1 – Heathrow traffic and noise contour area/population trend (1988 – 2011) – Source: ERCD Report 1201 – Noise Exposure Contours for Heathrow Airport 2011

According to Smith (1989), researches show noise is the most undesirable feature of life in the urban community, where the traffic noise prevails as the main contributor. It has

long been one of the most significant challenges facing airport operators and their neighbours.

The generation of noise happens whenever the passage of air over the aircraft structure or through its power-plant causes fluctuating pressure disturbances. To have the flight conditions efficiently is extremely necessary maintain these air and gas flows controlled efficiently. Thus, there are many contributors for noise to be produced.

Figure 1.2 shows the trend of noise exposure to aircraft noise (global trend), which plots the population in millions exposed to the aircraft noise for 55, 60 and 65 dB along the years 2000 to 2025.

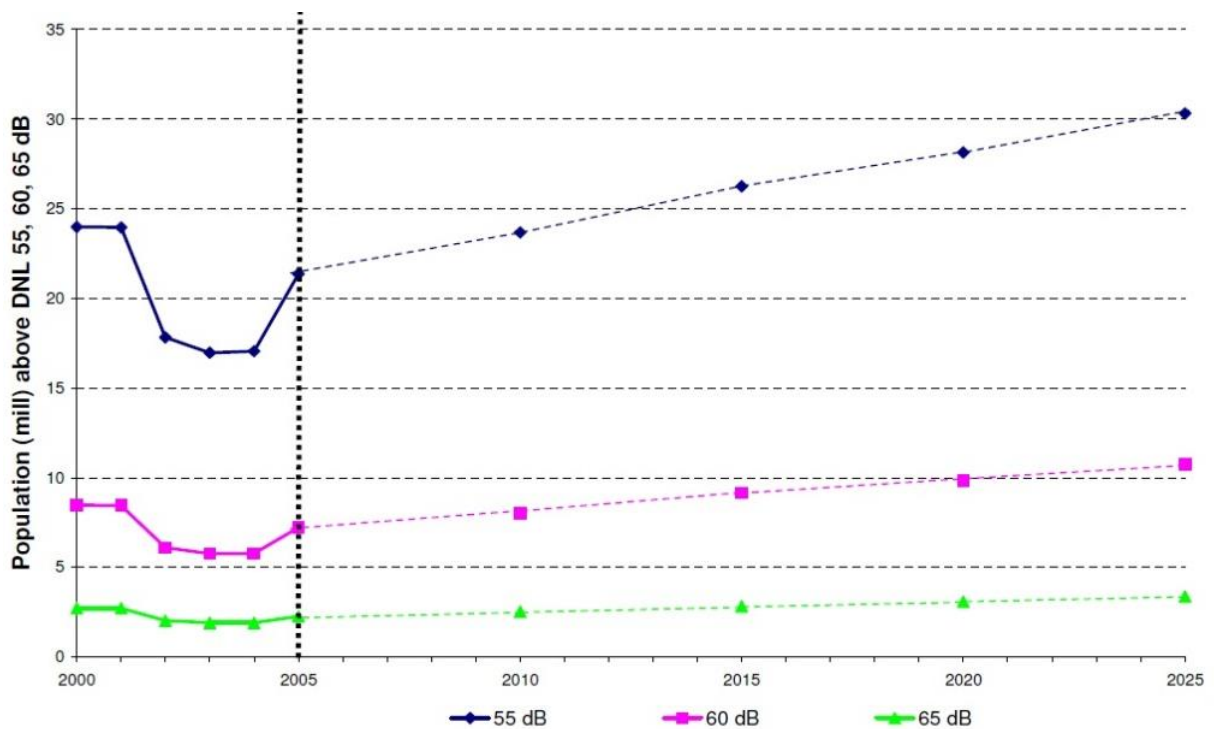


Figure 1.2 – Trend of noise exposure to aircraft noise. Source: 7th USA/Europe Air Traffic Management R&D Seminar, Barcelona 2007, “Trends in Global noise and emissions from commercial aviation for 2000 through 2025”.

Furthermore, a wide range of researchers are interested in aircraft noise and health effects. The human hearing system recognizes an extremely vast range of sound frequencies, from 20 Hz to 20 kHz. The problem is not too simple and the human hearing has different responses along the frequency range, beyond each one has a unique system. Increasing in age usually entails in the high limits of the audible frequencies. This response is best represented in terms of Effective Perceived Noise Level expressed in units of EPNdB.

This unit takes into account the sound energy received by a listener, the ear's response, the added annoyance of pure tones in the noise and the duration of the noise. The studies are often related to explain how and how much the body respond to aircraft noise in terms of health, sleep, welfare and performance.

1.2 Noise mitigation programs and noise certification

With the new rules about the noise limits which some airports adopted in the past, many aircraft could see their operation days counted. The development of better technologies in terms of aircraft noise was inevitable, but the old aircraft ones had to find alternative solutions in order to keep working. It was not rarity to those extremely noisy aircraft flight lightweight to increase their climb performance until reach one airport less sensitive to the noise limits and then take on the fuel needed to arrive at the final destination (Smith, 1989). Although it could solve the problem with some airports, it increased the fuel and time wasted during one travel.

After recognized as a real issue, the aircraft noise was responsible for the creation of both local and international authorities, as well as the modification of some aircraft organizations to include the subject "Noise" in their programmes. The "noise certification" is the process which the aircraft manufacturers have to demonstrate that their product meets basic noise and safety standards.

The Associação Brasileira de Normas Técnicas (ABNT) imposes the NBR 13368 norm (1995), prescribing the methodology to monitor aircraft noise. Some other regulations about that subject can be found in NBR 10268, showing how to measure the noise levels in airports and the NBR 11415, about the terminologies of aircraft noise. The Brazilian Enterprise of Airport Infrastructure (INFRAERO) has been faced by some challenges over last years. In 2008 the organization received a fine of R\$10,000,000.00 due to the absence of an environmental license to the Congonhas Airport. That airport is surrounded by many residences, commerce shops, schools, hospitals and so on. After that, a report was done in order to achieve the required license. However, some environmental organizations are complaining through studies that the airport has not been fulfilling the environmental regulations, showing the existence of too much noise during the permitted hours and some noise while prohibited hours.



Figure 1.3 – Congonhas Airport

The International Civil Aviation Organization – ICAO – introduced noise certifications which made the premature demise of many models. ICAO is a specialized agency of the United Nations, created in 1944 to promote the safe and methodical development of international civil aviation throughout the world. Both the EU and the UK have adopted ICAO's recommended "Balanced Approach to Airport Noise Management". This Balanced Approach consists of four main elements: noise at source, operating procedures, land use planning and operational restrictions. In the United States of America, since aviation is a public issue around late 1960s, there are legislations around the aircraft noise controls.

Another group is called European Aviation Safety Agency, a common initiative by the European Union to keep air transport safe and sustainable. It started in 2003 and is based in Cologne - Germany. On its website is possible to find out Type Certificates Datasheets of a wide range of aircrafts from Airbus, Boeing, Embraer and several manufacturers. Those datasheets contain information about maximum mass during take-off limits, the permitted noise levels for the class which the aircraft presents (noise certification is based in aircraft performance, in other words, airframe and engine) and the noise measured during the inspection for lateral, flyover and approach, as indicated in Fig. 1.4. The noise certification basis is the ICAO Annex 16, Volume I.

Trajectory and Certification Locations

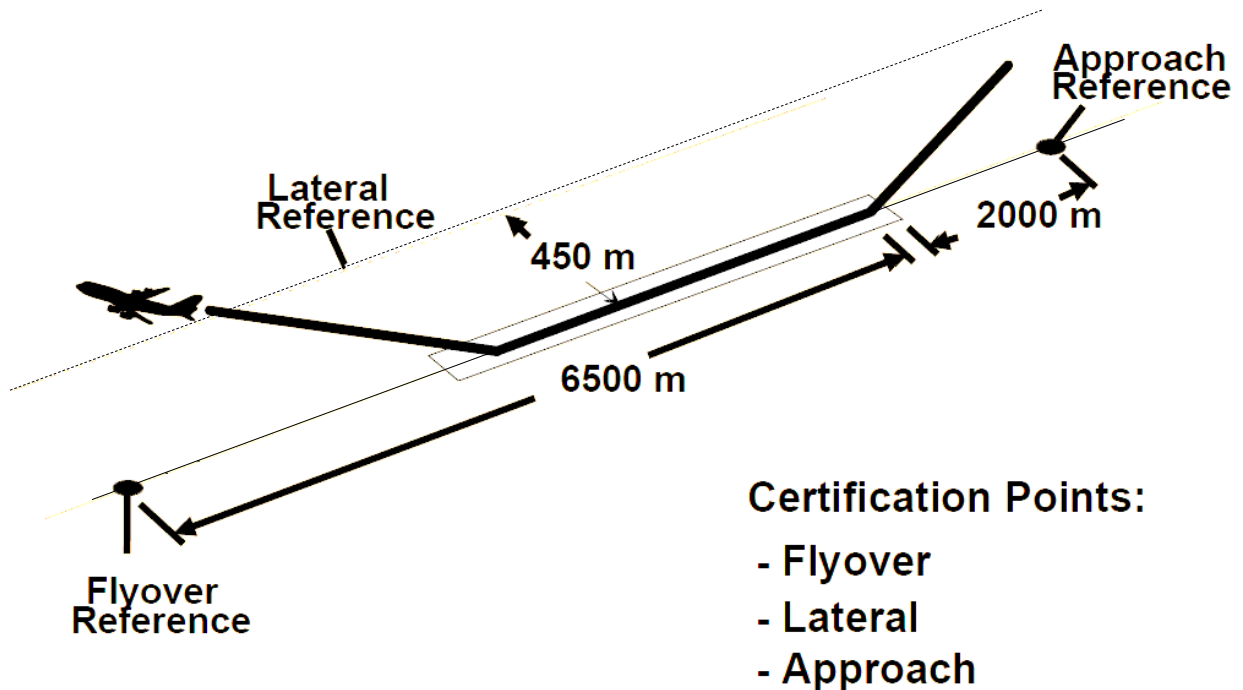


Figure 1.4 – Trajectory and certification locations (Hupe, 2008).

Other important organization is the Federal Aviation Administration, or FAA, created in the United States of America. Aircraft were divided into “Stages” according to weight, number of engines and passenger capacity. Aircraft noise levels are certified as Stages 2, 3 and 4. The Stage 1 aircraft are the ones which never had been tested and certified before and it is expected them to be the loudest. Stage 2 aircraft are the second noisiest, and so on. In 1990, during a congress in the USA, the Airport Noise and Capacity Act agreed to the phasing out Stage 1 and Stage 2 aircraft, but just to aircraft weighing more than 75000 pounds (or around 34 tonnes). A group of airport operators, mainly in Ohio, New York and New Jersey States are trying to change that, since the small aircraft at first Stages has caused an annoying noise. The group says the real action can only come from trying to reduce noise at its source. The Stage 4 was stated in 2005, when the FAA adopted a new noise standard for subsonic jet aircraft and subsonic transport category large aircrafts. Thus, the new aircraft design must incorporate the latest available noise reduction technology after 1st January, 2006. The USA Congress has also authorized the FAA to devise programs to insulate houses near airports.

For many years aircraft noise has been measured by averaging-out the noise levels at Heathrow Airport. Some specific measures have been used, like LAeq (most common

international measure, represents equivalent continuous noise level) and Lden (split the measures in Lday, Levening, Lnight, each one related to specific hours during the day). The UK Government says people start to become significantly annoyed by aircraft noise by 57 dB LAeq. Reports were developed and a study about the aircraft noise close to the airport and its distribution was carried out. A comparison along the years show that in 1980, 2 million people had been living in a region with 57 dB LAeq contour and it was reduced to around 252,000 in 2010, despite the fact the runway had increased almost twice. Fig. 1.5 shows one example of the LAeq contour comparison between the years 2010 and 2011. As well as the FAA provide in United States, the houses close to Heathrow airport has received noise insulation and vortex protection schemes (Lee and Edmonds, 2011).

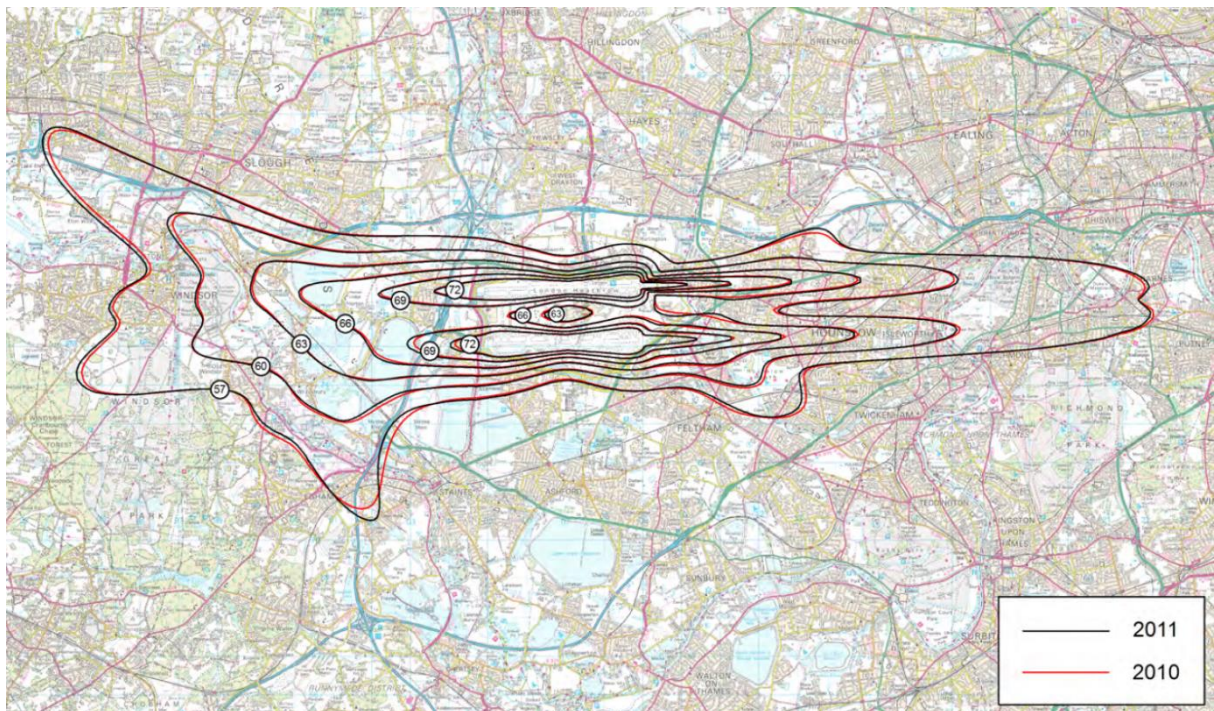


Figure 1.5 – Heathrow 2010 and 2011 LAeq contours (Lee and Edmonds, 2011).

Many airports also have a night flying restrictions like Congonhas Airport in Brazil and London's airports Heathrow, Gatwick and Stansted. The purpose is to reduce noise exposure at night, when the background noise is lower than during the day and the neighbours are sleeping, increasing the sensibility to noise. Thus, the noise events are perceived to be louder. The FAA adds a 10 dB penalty to aircraft operations conducted between 10:00 p.m. and 7 a.m.

Different kinds of surveys are been carried out to solve or at least minimize aircraft noise. ICAO, for example, has some reports which there are four solutions category: the

noise at its source, land-use planning management, operational measures and operational restrictions. They can be looked individually, however is common to work with them integrated. The development of each section depends on pace of technological improvements, or research programmes, and usually involves high costs/time (Hupe, 2008).

The European “Visions 2020” is proposing to reduce the noise impact by one half relative to 2000 technology and the USA Noise Reduction Goals, to reduce perceived noise impact by $\frac{3}{4}$ within 25 years (from 1997) (Dobrzynski, 2008). Recently, a new approach was inserted in this context, called Flightpath 2050 (European Commission, 2011). This program was produced by the aviation community focused on two main challenges: meeting the needs of the European citizens and the market, as well as maintaining global leadership. One of the environment goals is to reduce the perceived noise emission of flying aircraft by 65%, moreover reduction in CO₂ and NO_x emissions.

Also, there are many examples of projects between companies and universities. A huge integrated aircraft noise project, the SAX-40, a silent aircraft, is one of the most well-knowns. The goal is to develop a conceptual design for an aircraft whose noise would be almost imperceptible outside the perimeter of a daytime urban airport. The timeframe is about 2030 and many technical challenges have to be overcome until there. They desire to reduce noise but also fuel burn by eliminating level segments, keeping aircraft higher and at lower thrust levels for longer than traditional landing approaches. The project is developed by two universities, Cambridge University and Massachusetts Institute of Technology, as well as aerospace partners, as industry, airline and airport operators. That is just a brief sample to show how many companies and universities are working hard in order to develop new tools and solutions to this issue and research groups are usually divided into the subjects involved.

1.3 Sources of aircraft noise

The noise produced by an aircraft can be heard as a whole, however it is produced in different parts and by the interaction of these items. According to the aircraft performance during each phase of flight, one region or equipment may contribute more or less to the “total noise”. In other words, the aircraft on the ground, while taxiing, on run-up from the jet exhaust, during the take-off, underneath to departure and arrival paths, over-flying while in route and landing produces different noise not only in terms of amplitude but also in its composition.

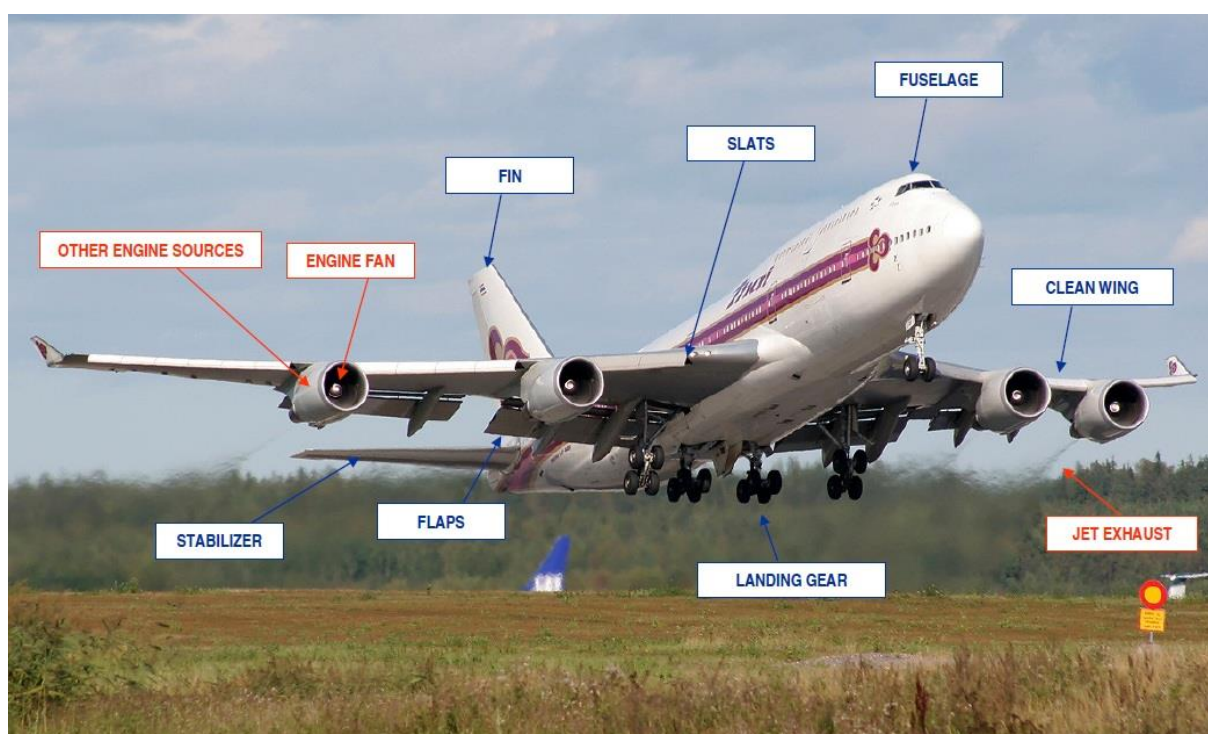


Figure 1.6 – Aircraft and noise sources

Many efforts have been made to understand the noise produced by engines and their sections separately. The turbines and other mechanical parts are the mainly responsible for the noise produced during the take-off and climb and in a general point of view the major sources of aircraft noise. During the approach, the engine noise is also considerable. However, due the advances in engine noise reduction, the airframe is noisier during this phase. The engine noise also can be divided into two general categories: internally generated noise or turbomachinery noise and externally generated noise or jet noise. The turbomachinery noise can also be divided from its components, comprised of fan noise, compressor noise, combustion or core noise and turbine noise. Although high bypass-ratio turbofans have considerable fan noise, the jet noise is responsible for the majority of engine noise (Almeida, 2009). This subject is extremely important and is the main motivation of this work.

The aerodynamic noise is also important and is caused by the airflow around the aircraft fuselage and control surfaces. Likewise the engine noise, the aerodynamic sources also increase with velocity. The density is an important factor, which within low altitudes the noise is bigger than high altitudes. Also as the engine noise, different aircraft components are different sources of noise. Thus main wings, tail plane, slats, trailing edge flaps, fuselage, landing gear and wheel bays are the most important individual items noise producers, in special the high-lift devices and the landing gear (Smith, 1989).

Figure 1.7 brings information about the noise during the take-off and approach according to the sources related to the airframe and engine.

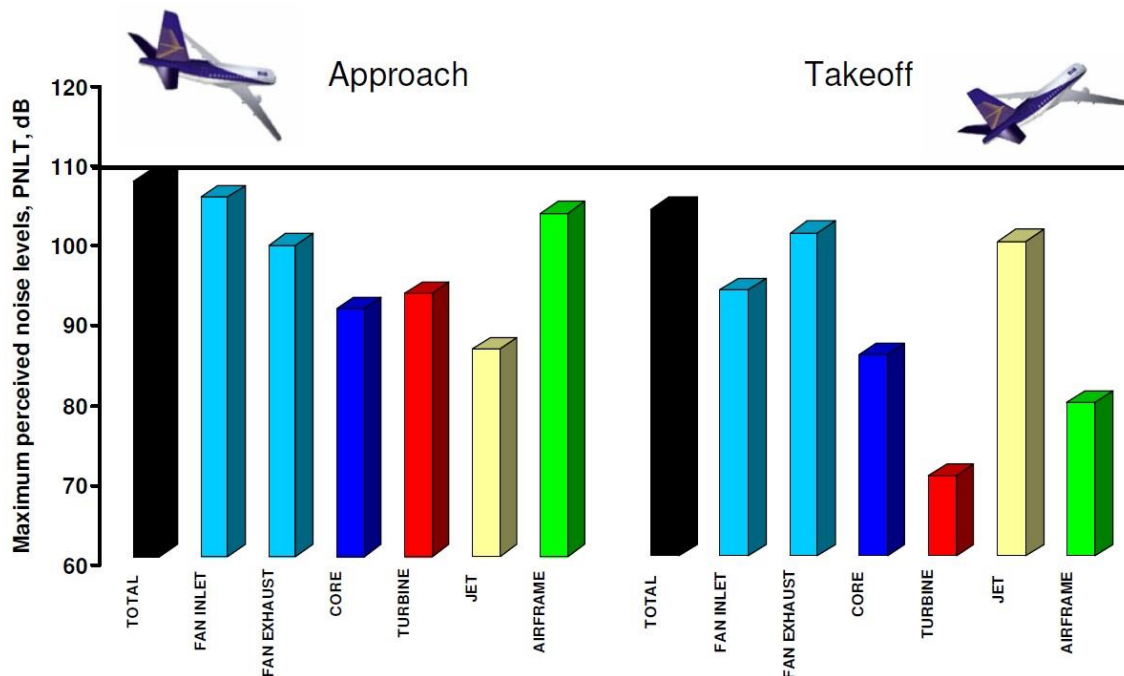


Figure 1.7 – Noise component breakdown at take-off and approach (Almeida, 2009)

The aircraft systems like the cockpit, cabin pressurization conditioning systems, Auxiliary Power Unit (APU) and others also increase the total noise, although their noise components are not too much expressive as the ones from the others parts of the aircraft such as stated before.

1.4 Jet engines

The aircraft engine is the component responsible for the propulsion system which generates mechanical power. Without delving in this context, piston engines (shaft engine, V-type engine, radial engine), turbine powered engines (turboprop), jets engines (turbojet, turbofan), pulse jets and rocket are examples of different sorts of engines and each one represents a massive effort in many years of study. This work is related to jet study and consequently applied to basic of jet engines or also called gas turbine engines. Next figures expose the evolution of the engine reduction noise technology from ending 1950s to beginning 2000 during the take-off phase. There are two clear different trends, a dramatic

reduction in the first 20 years and a new rate of reduction really small in the 30 years after. With larger aircraft and higher jet velocities required in this second range, to reduce the noise of the engines the challenge had been also increased.

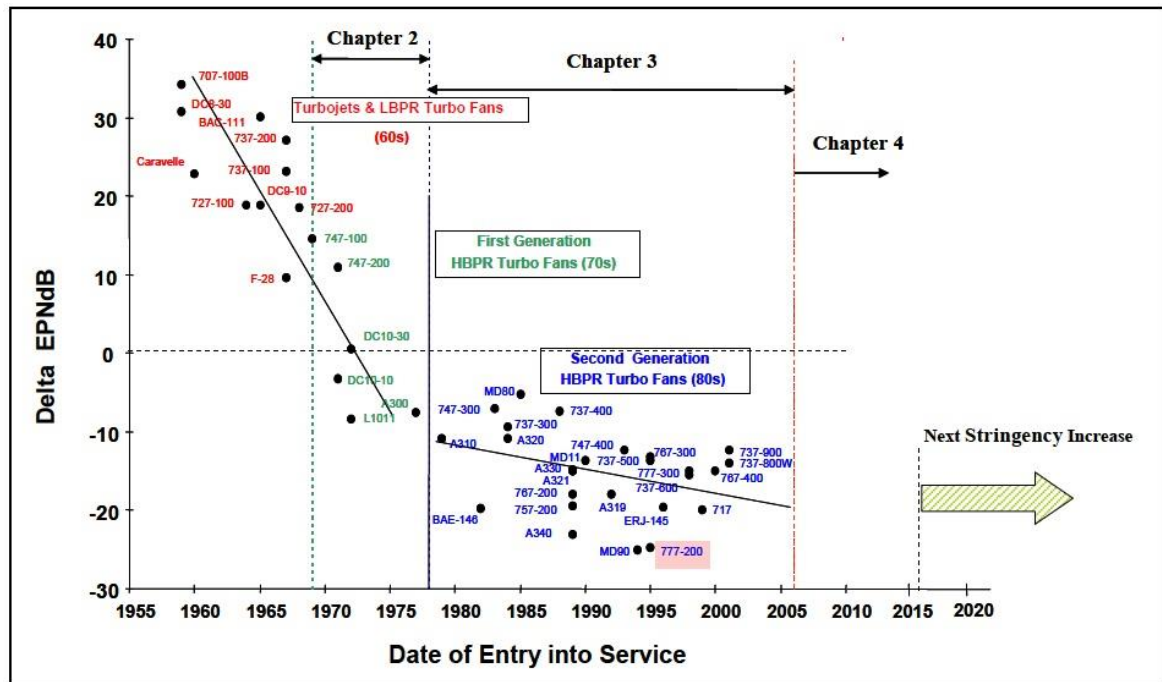


Figure 1.8 – Progress in aircraft noise reduction from 1955 to 2005 (Viswanathan, 2008).

The jet engines are present in most of passenger and military aircraft nowadays. They can be classified according to the type of compressor (centrifugal, axial and centrifugal-axial flow) and also the path the air takes through the engine and how power is produced.

Taking the second definition, the turbojet engine is the simplest of all jet engines. It is composed by a compressor which passes air at a high speed ratio, a combustion chamber which contains the fuel inlet and igniter, turbine section which accelerated exhaust gases providing thrust and the exhaust where the jet is discharged. All of the propulsive force derived from exhaust gas and the turbulent mixing of this exit jet within the ambient is considered the main mechanism for jet noise. Today these engines are mostly used in military aviation.

The turboprop engines drive a propeller through a reduction gear. It derives its propulsion by the conversion of the majority of gas stream energy into mechanical power to drive the compressor, accessories and the propeller load. In this case, almost 90% of the propulsive force comes from propeller and about 10% comes from the exhaust gas. They are

often used in small aircraft and agricultural applications, once they are suitable to perform well at slow airspeeds and fuel efficiency.

The turbofan engines were designed to merge the best features of the turbojet and turboprop and they are largely used today. There is an additional thrust to diverting a secondary airflow around the combustion chamber. The air in the first stage enters the compressor section as in the turbojet. The secondary stage bypass the engine core and exiting at increased pressure and velocity through the fan exhaust. It also can leave the nozzle separately or mixed from the primary or potential engine air. The jet noise benefits arise from the fact that the turbofan jet exhaust velocities are lower than those of a turbojet, since the jet temperature is lower due the mixing between hot flow (potential core) and cool flow (secondary core) and the additional energy added by the extra turbine stages. For example, the early turbojets exhaust velocities were of order 650 m/s and modern turbofans have velocities lower than 450 m/s in the potential core and less than 300 m/s in the cold stream. About 75% of the propulsion comes from the fan and 25% comes from exhaust gas. Today the most used engines are the high bypass ratio turbofan engines. It was primarily developed for fuel saving but it also brought significant reduction in jet noise (Almeida, 2009).

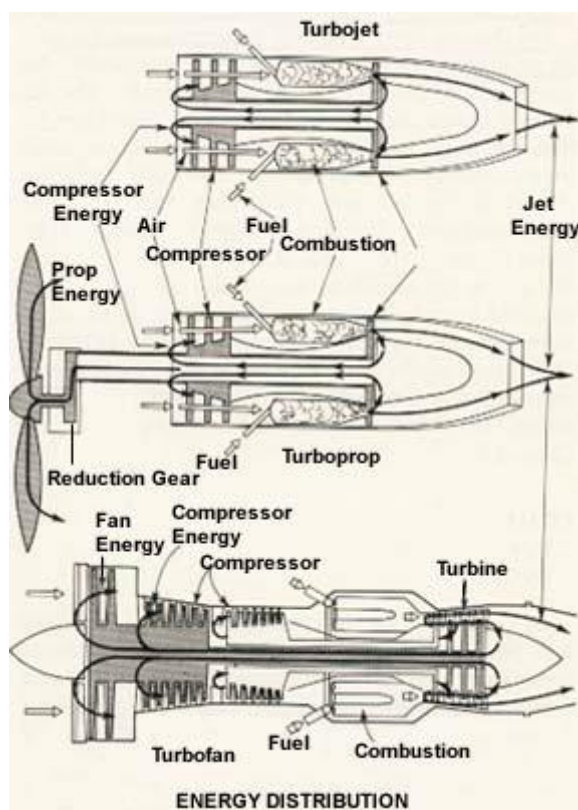


Figure 1.9 – Schemes to the energy distribution for a turbojet, a turboprop and a turbofan, respectively from up to down (http://www.thaitechnics.com/engine/engine_type.html).

The term “jet noise” is usually taken to mean the noise of jet-powered aircraft. However, strictly speaking, it is about only those sources associated with the mixing process between the exhaust flow of the engine and the atmosphere, as was said before during the division in jet and turbomachinery noise. This mixing noise is the only component generated during subsonic operations. In super critical jet there is also a secondary noise source which appears from shock-waves.

1.5 Ways to study the problem

Likewise many engineering problems, the aerodynamic and acoustics jet surveys can follow three paths: analytical, numerical and experimental investigations.

When the Reynolds number is high or, in other words, when the nonlinearities due to the inertial terms in the equation of motion are much larger than the viscous terms, to solve the governing equations become even more difficult. In fact a good mathematical model to depict the real physics or as close to real as possible solved analytically generally requires too much effort. Nevertheless, first principles methodologies such as Lighthill equations published in 1952 are well known. That paper is considered a birth of the research area “Aeroacoustics”. The motivation was to predict the sound produced by a free jet, and the new approach was called by himself an “analogy”, providing a formal definition of the acoustical field in the presence of a flow. The sound production represents a tiny fraction of the energy in the flow and the direct prediction of sound generation is very difficult, so this acoustical field is an extrapolation of an ideal reference flow, where the difference between both is identified as a source of sound. Another important point to highlight in this work is the proportion between the sound intensity produced by turbulence and the local volume over which the turbulent stresses are correlated. Thus, for any methodology it is clear that study the fluid dynamics related to the jet is extremely important to understanding jet noise (Schram, 2003; Tam, 1998; Rienstra and Hirschberg, 2011).

There are many techniques available considering different mathematical and numerical approaches. Semi-empirical methods and computational fluid dynamics (CFD) coupled with computational aeroacoustics (CAA) comprehend other possibilities. While Lighthill's analogy is very general for order of magnitude estimates, numerical simulations sometimes are more convenient using another methodology called Vortex Sound Theory (Rienstra and Hirschberg, 2013). This work will not enter in its merit, but this model uses an irrotational flow as reference flow, since vorticity is in general limited to a smaller region in

space than the corresponding velocity field (where is located the Lighthill's sound sources) this theory is more convenient for low Mach numbers and isothermal flows.

Many different numerical methods appear each year including new methodologies and modifications of the “old” ones. The physics of jet is always involved with the acoustic issue, thus a numerical model is composed by the transport phenomena equations, turbulence models, discretization methods and so on. Direct Numerical Simulations (DNS) are being made as well as Large Eddy Simulations (LES) and Reynolds Average Numerical Simulations (RANS), but when solving some real configuration in an “industrial time”, the Reynolds numbers used in reliable simulations are still below the range of the practical applications. The advent of new technologies in computer field has helped to improve these methodologies but it has yet to be improved in order to obtain accurate results with less computational costs.

Probably the most established way of investigating a subject that we turn our attention is to perform controlled experiments. In this case, real scale experiments often become prohibited since the costs involved are too high. In a world where things change so frequently and new products are expected, experiments with such costs are not interesting to manufacturers. Scale experiments or reduced models are very important in this context and the knowledge about the data and its extrapolations are really useful. By considering semi-empirical or empirical methods, it can be said that these methods are fast, reliable and have a long application in industry. However, one of the greatest problems in these methods is the restriction or applied considerations used to derivate them and also the envelope of operating conditions to be applied. As tailored tools for some specific jet noise predictions, many times they are restrictive to certain geometries, velocities, temperature and pressure ranges. Nevertheless, it is also observed that companies and organizations are interested in predicting the noise from jets using methods related to particular cases, and, sometimes, for just only one family of aeronautical engines. A deeper approach will be made in later chapters about the test facilities, equipment, sensors and the ways to acquire data from jet experiments.

1.6 Projects involved

Part of the present work was developed along with Embraer S. A., a Brazilian aircraft manufacturer, by means of two projects: “Silent Aircraft: An Aeroacoustics Survey” and “Developing of enhanced solutions through aeroacoustics assay to the problem of external noise aircraft - DSA”, the first and second phases of the Embraer's project, respectively. The

first one was also funded by the São Paulo Research Foundation (FAPESP), while the second phase was sponsored by Funding of Studies and Projects (FINEP). Those projects are divided in subgroups according to the subject, which this work is into the Jet Noise group. The integrated project is compound by some Brazilian's universities, among them the Federal University of Uberlândia.

This work is also part of a cooperation project between the University of Uberlandia and the University of Southampton, specifically the Institute of Sound and Vibration Research. The jet aerodynamic and acoustic results were provided in the ISVR's laboratory called DOAK Lab. The test matrix was built up in beginning of August, 2011, and the measurements were made with the supervision of the Fluid Dynamic and Acoustics Group – FDAG, especially Dr. Rod Self. The laboratory in question is an anechoic chamber built for subsonic and supersonic acoustic measurements. This work also was done to extend the applications of the DOAK Lab to aerodynamic measurements, what will be shown in another chapter.

1.7 Objectives and author's contribution

The general purpose of this work is to study and characterize aerodynamically a free jet operating at subsonic regime and identify its acoustic signature. The survey is divided in two sections: aerodynamic results for a free, single, subsonic and cold jet at Mach numbers of 0.25, 0.5 and 0.75 and acoustic results to the same kind of flow at Mach numbers 0.15 to 1.00, through a step of 0.05. In the aerodynamic study, mapping the jet using pitot tube and comparing the results with the hot-wire anemometer were done in order to plot the mean and fluctuating profile velocities and test the hot-wire resistance at high flows. There is a lack in results of hot-wire anemometry of high frequency response at high velocities (e.g., Mach 0.75), and the present work bring considerable information for different jet velocities and a wide domain around the jet. The acoustics results take place in the database context as well as a basic theory directed for a wide velocity range.

The current moment of the Aeroacoustics Research Group at Federal University of Uberlandia, under coordination of Prof. Odenir de Almeida has to be taken into account. The Group started its works recently (2010) and has been consolidated over time in terms of knowledge, main issues developed, procedure in both academic and industrial sectors, cooperation programs and mainly student formation. Thus the first works produced by the Group have a special "internal importance", since they report the developing of the team to new students that should join the team hereafter. Furthermore, the course Aerospace

Engineering was started at the University in 2010 and has recently arrived to the application courses, including the subject of Aeroacoustics. Therefore, one of the goals is to perform a fundamental analysis over the subsonic jet looking at a complete mapping of the jets region at different velocities. This review is done through literature comparisons and correlations among the aerodynamics and acoustics data shown.

The results presented herein are not restricted only to the experimental front, but also to the surveys with semi-empirical methods and even numerical methods which need some input parameters or validation. While the Group has been developing numerical methods at the Fluid Mechanics Laboratory (MFLab), an expansion to build an anechoic chamber is desired for a near future, where the experience acquired in this work will be applied. The present work dedicated one sub-section to discuss the mainly parameters of an anechoic chamber.

As stated before, some aims coming from involved projects. Currently, an anechoic chamber has been built at Federal University of Santa Catarina as part of EMBRAER's Project. The familiarity about basic equipment, tools, sensor, air supply and data acquisition achieved in this work is also a support to that Project. The cooperation with the ISVR during the experiments aims the acquisition of knowledge about jets and enlarges the laboratory to reliable aerodynamic measurements.

The points described can be summarized as:

- This work is an “initial guide” in terms of basic knowledge about the topic to students who are starting in this subject and aim to join the Aeroacoustics Research Group at the Federal University of Uberlandia working within the experimental area.
- Mapping of the mean velocity along axial and radial lines from the jet using pitot tube and hot-wire anemometer. Turbulence intensities or fluctuating velocities along axial and radial lines from the jet using hot-wire anemometer are also studied.
- Noise of a free jet in comparison with the aerodynamic results, since the understanding of jet noise is tied to the understanding of turbulence in jet flows. Also, a review of the most important terms in jet aeroacoustic, including the basic theory involved, instruments used during the measurements, far-field results for different observer angles and velocities.
- The data acquired form a database which could be used in semi-empirical and numerical methods. This contains relations between the aerodynamic properties and the acoustic signature of the jet.

- Some modifications were made in the DOAK Laboratory to enable aerodynamic measurements, what revealed some issues to improve the system and the results shown that it was achieved.
- Understanding about measurements, equipment, sensors and test facilities of jet aerodynamic and jet noise measurements.

1.8 Thesis outline

This work was developed at the Federal University of Uberlandia (UFU) in cooperation with the Institute of Sound and Vibration Research (ISVR) located at University of Southampton. It was supported by the Rolls Royce UTC in Gas Turbine Noise, the Brazilian technological development project called “Aeronave Silenciosa”, and the UNIEMP Institute during the first experiments (2011) and CAPES during the properly MSc period (2012 – 2013). The experimental activities were conducted at ISVR in the period from August to December in 2011 and March to May in 2013. From January in 2012 until here the activities were conducted at UFU.

The thesis is composed of six chapters.

Chapter 1 gives an introduction about the main subject of this work. A general context is presented going from the most general observation until the subject of this work. It is also exposed about some programs to reduce aircraft noise and noise certifications. The sources of aircraft noise are soon mentioned and a general vision to the jet engines and jet noise is given. Lastly, the ways to explore the problem and the main objectives were shown.

The basic theory related to aerodynamic and acoustics of free single jets is given in Chapter 2. This chapter composes an important item for those who during the regular graduation course did not have the opportunity to further study the jets physics.

The bibliography review is presented in Chapter 3. The focus of this chapter is on the modern experimental works around jets using pitot tube, hot-wire anemometry and far-field and near-field acoustics. Also, some jet rigs around the world are brief discussed.

Chapter 4 shows the methodologies taken in this work. The rig is described as well as equipment, sensors, data acquisition systems and post-processing scripts. The experimental procedure is also evidenced. The tests matrix used during the experiments and some sketches for the principal contents and configurations are presented.

Chapter 5 presents the results and is divided into two sections: one containing the aerodynamic results and the other with the acoustics results. The aerodynamic section includes the results for average and fluctuating quantities from pitot tube and anemometry

measurements. Some velocities profiles are also showed. For the acoustical results, the spectrum of sound pressure level graphs for the condition studied taken place.

The conclusion of this work is presented in Chapter 6, general observations and comments are made, which is a summary along the main results, principal issues which had to be solved along the whole work, and the suggestions to future works.

The Appendices are used mainly in order to clear the possible questions along the experimental procedures and the results. Thus, Appendix I is used to exhibit the secondary and additional results or split some plots to improve the visualization and make the main text easier to read. Appendix II demonstrates the procedure to data correction to the aerodynamic measurements, since there is a flow mass variation during long measurements. The Appendix III contains some issues found during the measurements and is placed in the end of this dissertation. It is useful since most part of the problems faced in this work should be common in this kind of measurements.

CHAPTER II

AERODYNAMICS AND ACOUSTICS THEORY OF SUBSONIC JETS

“Fluid mechanics is the study of fluids either in motion (fluid dynamics) or at rest (fluid statics) and the subsequent effects of the fluid upon the boundaries, which may be either solid surfaces or interfaces with other fluids” (White, 1991). That is important to contextualise the sections presented in this work: although the main aim is to predict and hereafter control the noise produced by flows, it is indispensable to study the jet’s physics theory, once the structures formed along this flows are closely associated with noise production. Therefore, the jet noise topic is a multidisciplinary subject, where the understanding of fluid mechanics is imperative to aeroacoustics.

This chapter is a brief summary of the aerodynamic and acoustic theory related to jet flows. First of all, a general overview of the jet’s physics of single flows is given. This section is divided mainly in aerodynamic and turbulence parameters in free jets. The aim is to present the most important aspects and variables. Secondly, some remarks about the basic principles of acoustics and the Acoustic Analogy of Lighthill are presented.

2.1 Jet aerodynamics

A free jet flow occurs when a fluid is pressurized in a duct and moves out through a nozzle discharging in a quiescent medium. This particular flow can be classified according to many parameters, which the important ones are explained below.

The nozzle geometry sets jets with particular aerodynamic and acoustics properties: plane jets (in an idealization), rectangular jets and circular jets are some examples. The

results shown in this and most studies in the literature are conducted on circular nozzle. That is totally understandable since most of the current jet engines have a round nozzle.



Figure 2.1 – (a) Rolls Royce Trent 900 engine which generates a coaxial circular jet. (b) Indy Transponder with rectangular nozzle.

The quantity of jets studied is another parameter. A single jet discharging in a quiescent surrounding is the simplest configuration. It was used in this work and, although the simplest, many jet engines used nowadays have a single jet as a result of its discharge. Furthermore, more complex jets can be studied from simpler ones. For example, the modern turbofan engines, highly applied in aircraft industry, produce the so-called coaxial jets, shown in Fig. 2.2. Researchers have developed models which this kind of jet is divided in different regions and each region is evaluated separately, approximated by results from single jets in the same conditions as the region analysed. One example is the semi-empirical model called Four-Source, which was developed at the Institute of Sound and Vibration Research by Fisher et al (1998) and was based on works of Ko and Kwan (1975, 1976). As the name suggests, the coaxial jet is divided in four regions in this model, and each one is associated to a single jet to noise producing calculation, also according to the nature of the structures generated in each area.

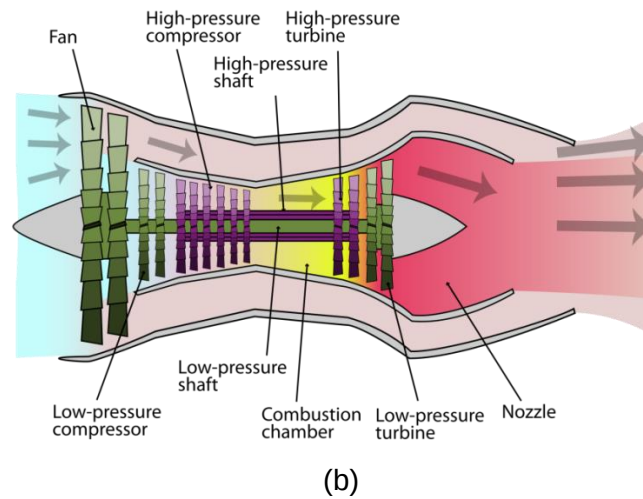
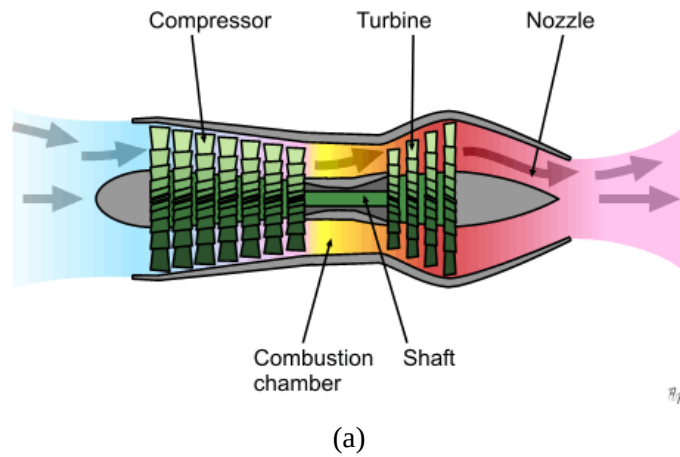


Figure 2.2 – Examples of: (a) a turbojet (single jet); and (b) a turbofan (coaxial jet).

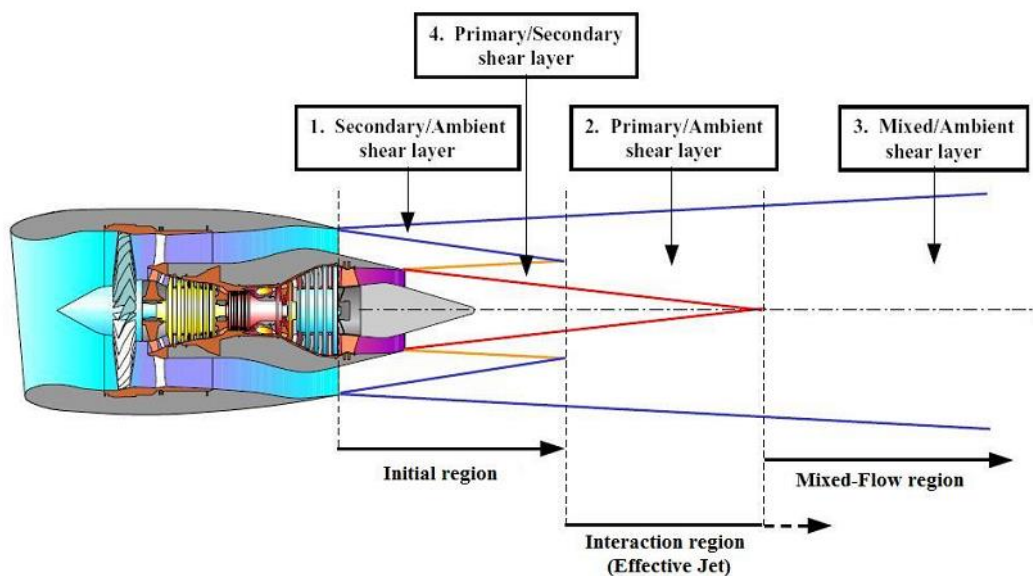


Figure 2.3 – The Four-Source scheme (Almeida, 2009).

There are also cases where two or more jets are discharged not on the same axis, but in a crossflow geometry, the called cross-jets. Beyond the shock between jets, there are many examples of jet interactions. Actually, along practical applications in aircraft, the jet is frequently interacting with other parts, such as wing and fuselage. In a more general point of view, many studies are interested in the interaction between a jet and a surface, forming the class of installed jets. Whilst the study of free jets has had an important role in the development of engines and other machines along the years, the research associated with installed jet has been the interest of aerodynamic and acoustic measurements.

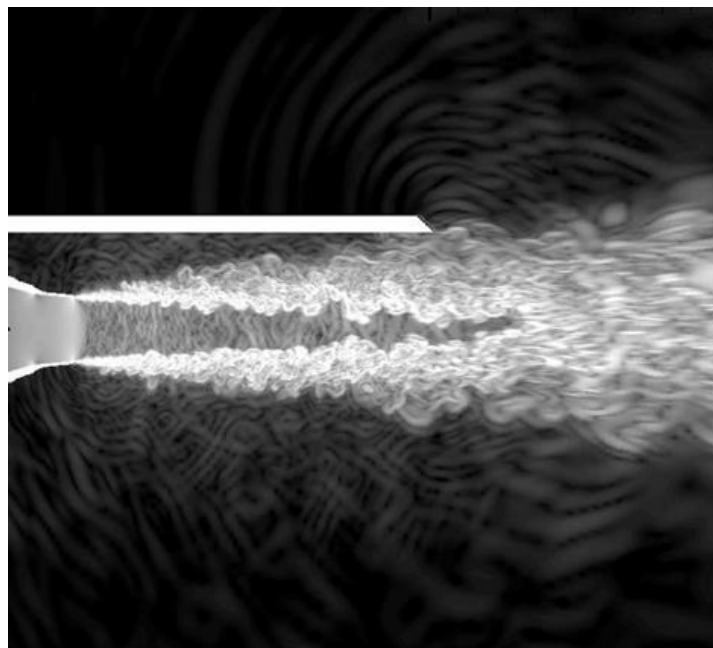
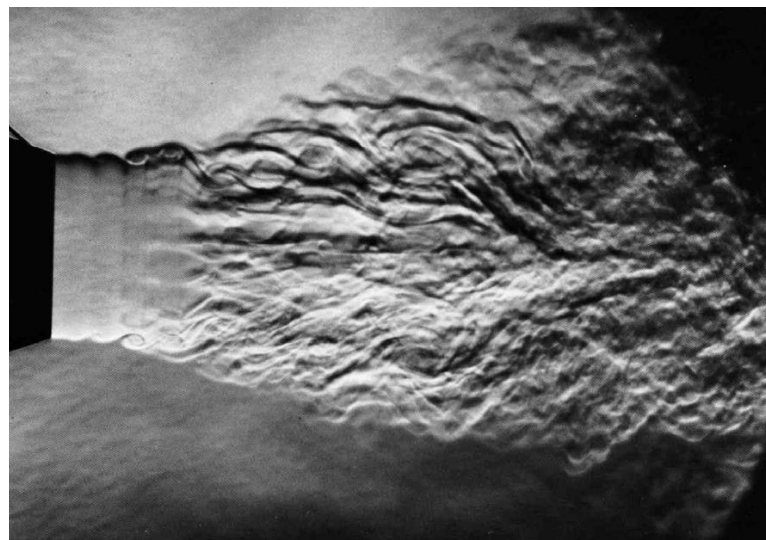


Figure 2.4 – Simulation of exhaust nozzle under installed configuration (Argonne National Laboratory).

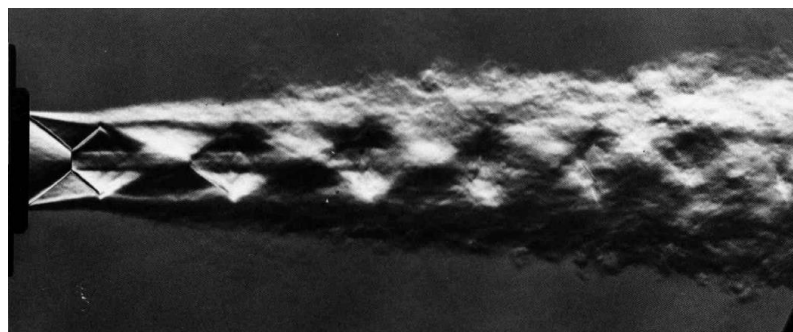
Temperature involved in the process is another parameter which can change the problem. An isothermal jet is represented where there is no difference (or it is negligible) between the temperature of the jet and the temperature of the ambient. When the jet is heated in relation to the medium, some particularities are found. In the case of more than one jet, coaxial or cross-flow jets, for example, there is a temperature ratio between the jets from different sources, which also changes the properties of the jets in comparison with the isothermal ones.

The range of velocity also divides the study of jets. Firstly, an important dimensionless parameter, the Mach number, which is the ratio of the velocity of observed object to the speed of sound in the medium in which the object is immersed, generates two distinct categories of aerodynamic groups: the subsonic and supersonic flows. In simple

terms, subsonic flows are the ones which the mean velocity is under the speed of sound in that ambient, whilst supersonic flows the velocity is higher than the speed of sound (higher than Mach 1). The physics related to subsonic and supersonic flows are substantially different, since the latter has the formation of shock waves which in turn directly the profile of the aerodynamic properties as well as the noise sources. Other classifications are given, such as transonic (around Mach 1) and hypersonic (Mach number higher than 5). In fluid mechanics, the Mach number is also used for other classifications: the incompressible and compressible flows. The compressibility effects are typically considered significant for Mach number higher than 0.3 or very large pressure changes in the flow. It means that for low velocities the density can be considered constant, which simplifies the governing equations, as shown in the next section. However, the jet flow applications in aeronautical devices usually exceed this Mach condition.



(a)



(b)

Figure 2.5 – Subsonic jet (a) and supersonic jet (b) becoming turbulent. (Van Dyke, 1982)

Situating the present work, the jet studied here is classified as a free, rounded, single, cold, subsonic, compressible jet.

2.1.1 Basic physics of single jets

According to Abramovich, “jet” is a special fluid motion where tangential separation surfaces are evidenced. Velocity, temperature and specie concentration are some flow parameters that describes the tangential separation. Other important point related to the physical properties is the static pressure distribution along the different layers: it remains continuous (Abramovich, 1938).

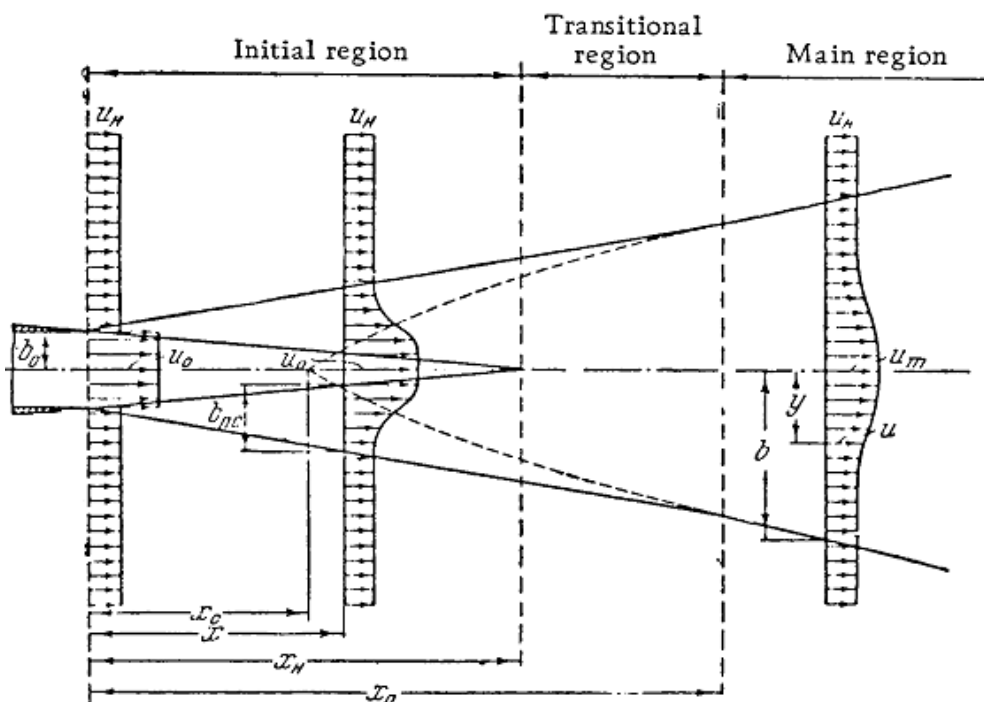


Figure 2.6 – Diagram of a single jet (Abramovich, 1938).

After several observations, the free single jet is well defined in three different regions. It is assumed that the jet has a uniform velocity profile U . There is an initial region that contains the potential core. Inside this core, the flow is laminar and velocity remains constant. An annular mixing layer forms between the moving fluid and the medium, and experimental evidences show that the flow in this region becomes turbulent within about one-half diameter downstream of the nozzle exit. It is known that in this turbulent mixing region the flow structure is self-preserving in the sense that the average properties of the turbulence and the mean flow are similar at any section. The mixing layer thickness is very small in the initial part of the jet, and then spreads out (Abramovich, 1938).

With the end of the potential core, after four or five diameters downstream the exit jet, a transitional region arises. In this region, the uniform growth of mixing layer ceases. Its length is again four diameters and in the end of this region a self-preserving flow takes place, originating the final region called the fully developed. Therefore, the first two regions comprise the developing portion of the jet, and the mean velocity profile becomes self-similar after that. This region seems to grow from an apparent origin, as can be seen in the Fig. 2.6. Whilst the velocity profile has the same momentum, the mass rate does not remain constant. The fluid is fed back by the ambient in a process known as “entrainment”. Entrainment is the movement of one fluid by another, which is responsible for increase the mass flow along the jet axis (Souza, 2005).



Figure 2.7 – Entrainment by an axisymmetric turbulent water jet (Van Dyke, 1982)

Besides the three regions of a single rounded jet are well established, different nomenclatures are used, for example, the near field, the intermediate field and the far field, corresponding to the initial, transitional and fully developed regions (Fellouaha and Pollard, 2009). There is no consensus about the length of each region as well, although usually it is not a substantially discrepancy.

In few words, increasing the axial distance, the jet decays and spreads. The laminar interface becomes unstable and the entire jet becomes turbulent downstream of the nozzle.

The turbulent jet boundary layer is a region of finite thickness with a continuous distribution of velocity, temperature and concentration on the boundary between the flow and the medium. This shear layer presence regions extremely different: one influenced by the jet parameters and the other with the medium properties. The instabilities in the separation

surfaces generate eddies both along and across the flow (Abramovich, 1938). More details about these structures are given in the next section.

The flow is statistically stationary and axisymmetric, which means the statistics depends on the axial and radial coordinates, but not circumferential coordinate θ . The longitudinal velocity is some orders of magnitude higher than the transverse velocity components. For this reason, commonly velocity profile graphs and other properties are mainly governed by the jet axis component. Moreover, a fully turbulent jet discharging into ambient fluid has a mean axial velocity distribution almost independent of Reynolds number.

In order to describe the mean velocity profiles of a steady jet, a well-established method makes use of three graphs, illustrating the mean velocity profile, U/U_0 , as a function of radius $r/r(\frac{1}{2}, U)$, the mean centreline velocity, U_0/U_j , as a function of axial location x/d and the jet half radius $2r(\frac{1}{2}, U)/d$ as a function of axial location, where U_0 is the jet mean centreline velocity, $r(\frac{1}{2}, U)$ is the radius at which the velocity is half the centreline velocity and d is the jet exit diameter (Harch and Bremhorst, 1977). Some examples are shown in the Fig. 2.8.

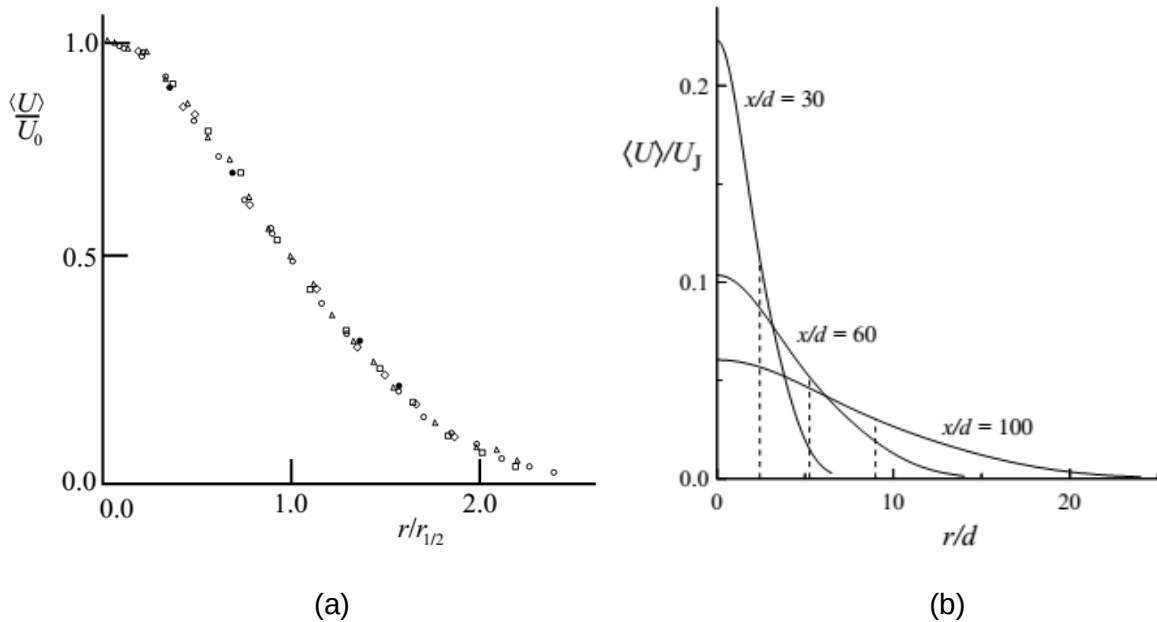


Figure 2.8 – (a) Mean axial velocity against radial distance in a turbulent round jet (Wignanski and Fiedler, 1969). (b) Radial profiles of mean axial velocity in a turbulent round jet (Hussein, 1994); reproduced from Pope, 2010.

The spreading of the mixing layer is another important characteristic of the jet flow. According to Lilley (1958), this linear spreading of the jet is consistent with the existence of large eddies, randomly distributed, which are in a form of energy equilibrium. These eddies are centered on average at the position of maximum shear.

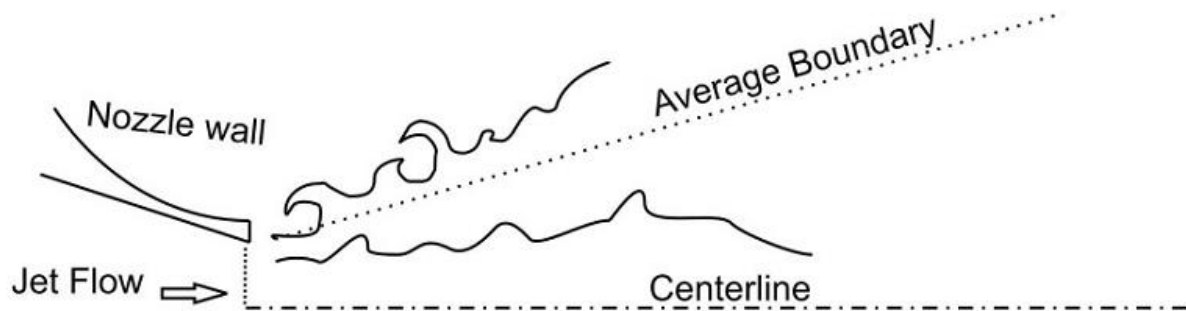


Figure 2.9 – Mixing layer region by Almeida (2009)

The variation of the mean velocity profile and the mean square turbulence velocity across the mixing layer are shown in the next figure. It can be seen that most of the turbulent energy is confined to a fairly narrow region at the centre of the mixing layer. What has been identified by measurements is that the peak turbulence intensity u'_{max} occurs on the centreline of the mixing layer (Goldstein, 1976).

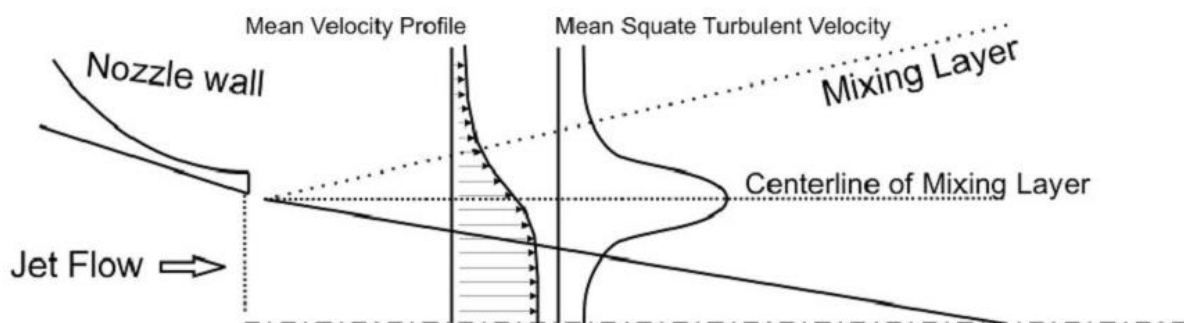


Figure 2.10 – Mixing layer velocity distribution (Almeida, 2009).

Lastly, laboratory observations reveal that all turbulent round jets possess the same opening angle, regardless of fluid (if the jetting fluid has no buoyancy with respect to the ambient fluid), orifice diameter and injection speed. The universal value is 11.8° , yielding a ratio radius to distance of 1-to-5.

2.2 Jet turbulence

One of the most challenging problems of engineering and physics nowadays is a phenomenon very present in our daily routine: the turbulence in the fluids. Despite getting along with the observation of turbulence from many centuries through simple qualitative representations, the physics of this type of flow is intriguing and there is still much to learn, but the complexity is such that it has been named some researchers as the 'last of the classic problems' in open. Current studies of turbulent jet flows have been stimulated by the aircraft noise problem.

Although the laminar flow has their physics well-known and modeled mathematically, the transitional condition and fully developed turbulence is still an open field. The phenomenon of transition occurs when the laminar fluid becomes unstable with the existence of inertial forces and / or gradient of potential energy large enough to overcome the flow resistance to keep it laminar. Some factors that influence this process are known: existing level of disturbance, surface roughness before the exit nozzle, pressure gradient, compressibility effects, heat transfer and density stratification, among others. As previously mentioned, jets are transitioning flows already in the region close to the nozzle and from low velocities, becoming turbulent fully developed some diameters after the exit.

The jet in its most basic form is a type of free shear flow, i.e., it does not have submerged bodies within their domain nor some kind of solid limit on its borders. In free shear flows, the source of instabilities is connected to an inflectional velocity field. Before move along in jet turbulence, next item describes some characteristics of turbulent flows with emphasis in jet flows.

2.2.1 General concepts of turbulent flows

Turbulent flows have fluctuation of pressure and of velocity superimposed on the main flow. Generally, turbulence is a dynamic system in which the number of degrees of freedom is "high enough" and its general concept helps in understanding the nature of the flow jet type. Lesieur (1997) cites three fundamental characteristics for the flow to be turbulent: the flow needs to be unpredictable in the sense that small uncertainties will amplify nonlinearly, it must necessarily increase the rate of mixing of properties and it must have an extensive range of spatial wavelengths. A jet has no trouble filling these three points. Other features necessary for the onset of turbulence and its relation to the flow here studied are mentioned below (Silveira Neto, 2002).

Irregularity and instability: In the sense that a purely deterministic analysis is impossible to perform. First, there were only accepted statistical efforts and the phenomenon

was considered to be purely random. Nowadays a plausible solution presented is considered part of the scales that comprise the turbulence as deterministic (large structures) and other random (small structures). If the structure has a longer life than their time of rotation characteristic, for example, it may be considered statistically consistent. The fluctuations are time and space-dependent.

High diffusivity: Although considerations taken as inviscid fluid, the small scales are transformed into heat by viscosity. Fluctuations generating high gradients in the flow are responsible for this event. This feature has an important practical application, since the properties mixing process is greatly accelerated, which is attractive for most jet applications.

The Reynolds number characteristic must exceed unity. Thus, the inertial forces overcome diffusive or viscous forces. The nonlinearities that amplify the disturbances, causing instabilities, are not contained in the term inertial. Jets where the working fluid has low kinematic viscosity such as air, typically always have high Reynolds numbers.

Dimensionality and rotatability: The development of vortices and three-dimensional structures in turbulent flows is uncontrollable. Even if a region would be irrotational, next to it there must be structures in rotation. The interaction between the vortices formed produces the effects of stretching and tilting them. Associating these movements to the velocity field, there is the appearance of components in the three orthogonal directions. The behavior of large and small structures that appear in this process occurs differently: the first line up preferentially to the main flow while the latter are well distributed, not by adopting a preferred alignment.

Process dissipative: Viscosity generates shear deformations which increase the internal energy of the fluid. Thus, the turbulence needs a continuous supply of energy to overcome this viscous loss. Without the energy increment, turbulence decays. If the medium is non-dissipative, such as atmospheric gravitational waves and random sound waves, there is no turbulence. In the case of a jet it is important to understand the process of formation and energy transfer between the structures.

Continuous medium: Relating the smallest scales of turbulence with molecular scale, it is clear that the smallest structures are large enough to apply the continuum hypothesis. The Navier-Stokes equations can be used to govern the fluid motion (with a limit of Mach number equal to 15, which scales no longer satisfy the molecular mean free path).

Multiplicity of scales: Necessarily, the spectrum involved in this kind of phenomenon is continuous and wide.

The velocity field irregularly varies significantly with position and time. In the figure below, it can be seen the fluctuations of velocity component 'u' in the centerline of the output

of a jet relative to its mean time. Note also that the phenomenon is far from being regular and the existence of various scales.

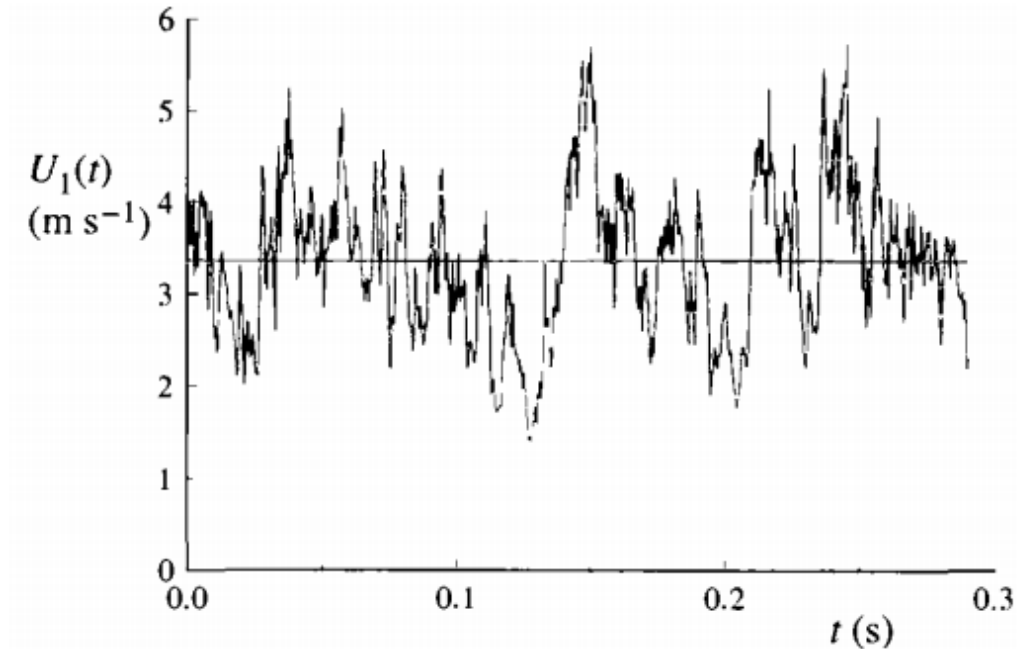


Figure 2.11 – Mean velocity and velocity fluctuation measured during 0.3 seconds in a centreline of a low velocity jet.

2.2.2 The turbulence spectrum

As previously mentioned, a characteristic of turbulence is the existence of various length scales ranging from the domain size to the dimensions of the smallest structures, known as the Kolmogorov scale.

Following the idea of Richardson and the cascade energy transfer from larger to smaller structures (which the largest receive the highest kinetic energy of the main flow and feeds the lower scales until the viscous stress dissipate the whole energy), it is necessary for a continuous injection of energy in order to maintain the flow.

The scales of turbulence are distributed by a continuous range that extends from the lowest to the highest scale. Each of these ranges contributes an amount of turbulent kinetic energy 'k', which is associated with the wave number characteristics of this scale. Therefore, the turbulent kinetic energy is the integral of energy contributions by all scales that make up the spectrum.

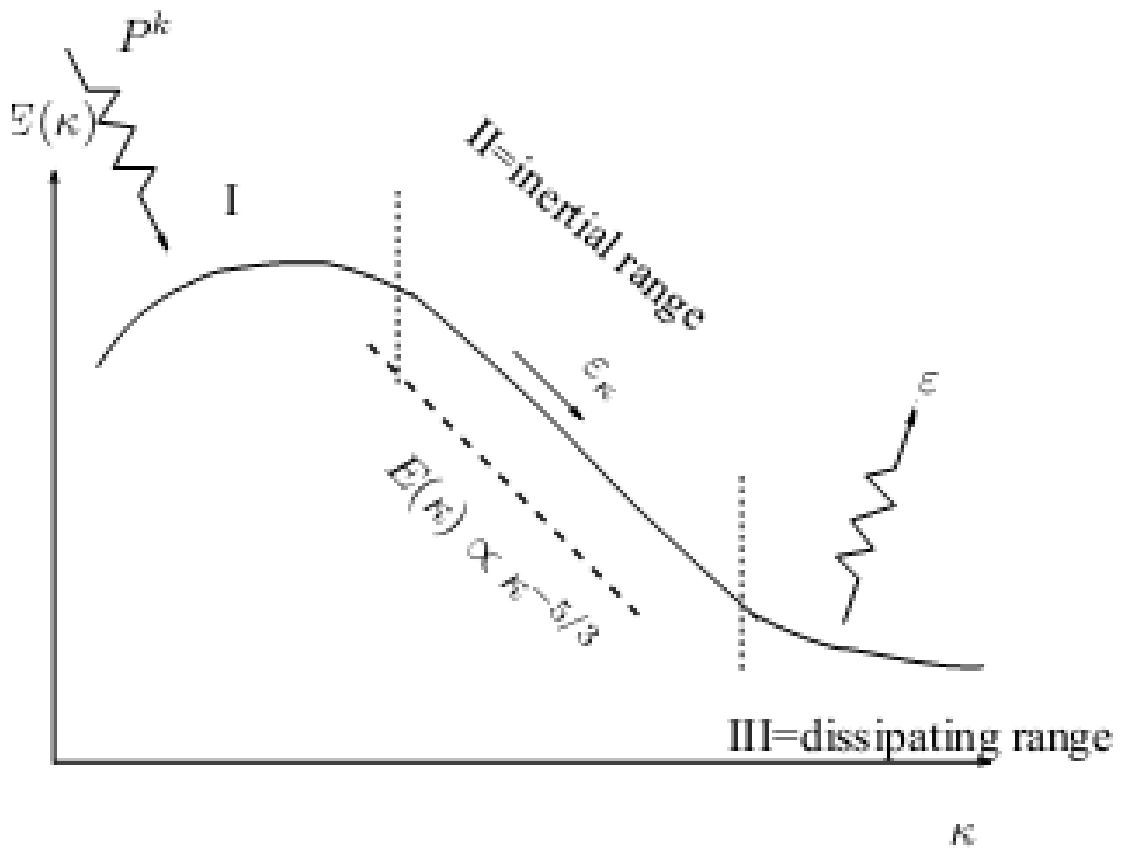


Figure 2.12 – Three regions of the energy spectrum of turbulence.

It is observed in the spectrum three distinct regions: Region I, with smaller wave numbers (large structures) and contributing the largest portion of the total energy. This is the region of energy injection. The region II, or sub-inertial range, where energy is transferred from higher to lower scales and where there is Kolmogorov's spectrum law, with the decay of $-5/3$ and fully turbulent flow. Finally, region III, corresponding to the smaller scales, where there is dissipation of energy.

The overall turbulent kinetic energy is obtained by integrating over the space wave number:

$$k = \int_0^{\infty} E(k) dk \quad (2.1)$$

In that way, the kinetic energy is the sum of the three components of velocity fluctuation:

$$k = \frac{1}{2} (\overline{u^2} + \overline{v^2} + \overline{w^2}) = \frac{1}{2} \overline{u_i u_j} \quad (2.2)$$

Beyond a qualitative description of the range of different scales structure in a jet flow, the turbulence theory defines three different length scales often related to the regions

showed in the last figure, which are: the integral length scale (l), the Taylor microscale (λ) and the Kolmogorov microscale (η). This scenario enables comparison between the energy transfer and the dissipation rate, ε . The correlation among the scales, turbulence and fluid properties are not showed in this current work, but further information on this field can be found in (Lesieur, 1997).

2.2.3 The circular jet structures

The Fig. 2.13 illustrates a turbulent circular jet and its structures. Initially, it is possible to check the appearance of the Kelvin-Helmholtz instability, which induces the formation of secondary instabilities. The interaction of primary structures with longitudinal counter-rotating filaments creates transverse oscillations, which with its amplification degenerate into turbulence. The flow conditions are very important to define the transition of flow, which normally occurs close to the nozzle exit.

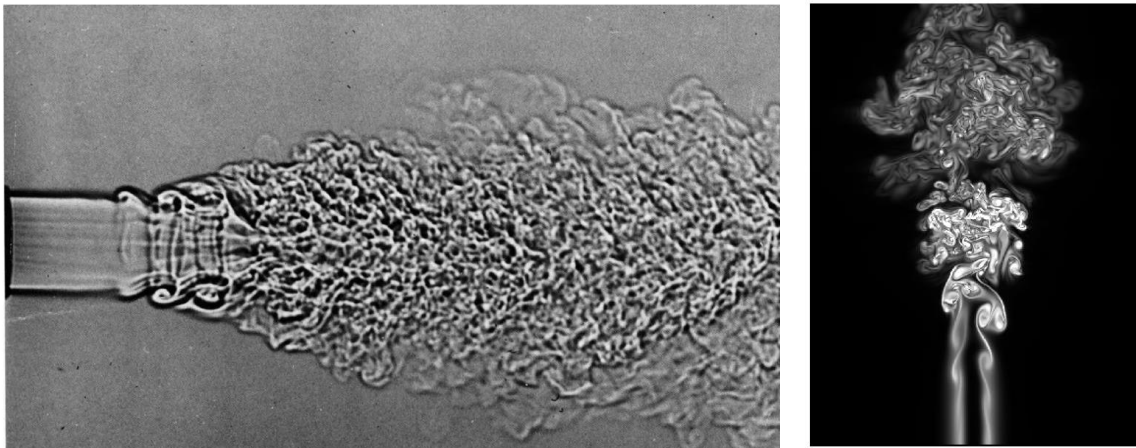


Figure 2.13 – Structures in a circular subsonic jet (Van Dyke, 1982).

As stated before, jets and all free shear layer flow transitioning to turbulence at low Reynolds number. The phases of this transition can be seen in the diagram shown in Fig. 2.14: (1) convergent nozzle; (2) the potential core flow; (3) toroid of high vorticity concentration; (4) generating of bidimensional toroidal vortices; (5) pairing of annular vortices; (6) tridimensional fluctuations on the toroidal vortices; (7) degeneration in tridimensional turbulence, (8) reorganization of turbulence on large scales, which are composed of other multiple scales.

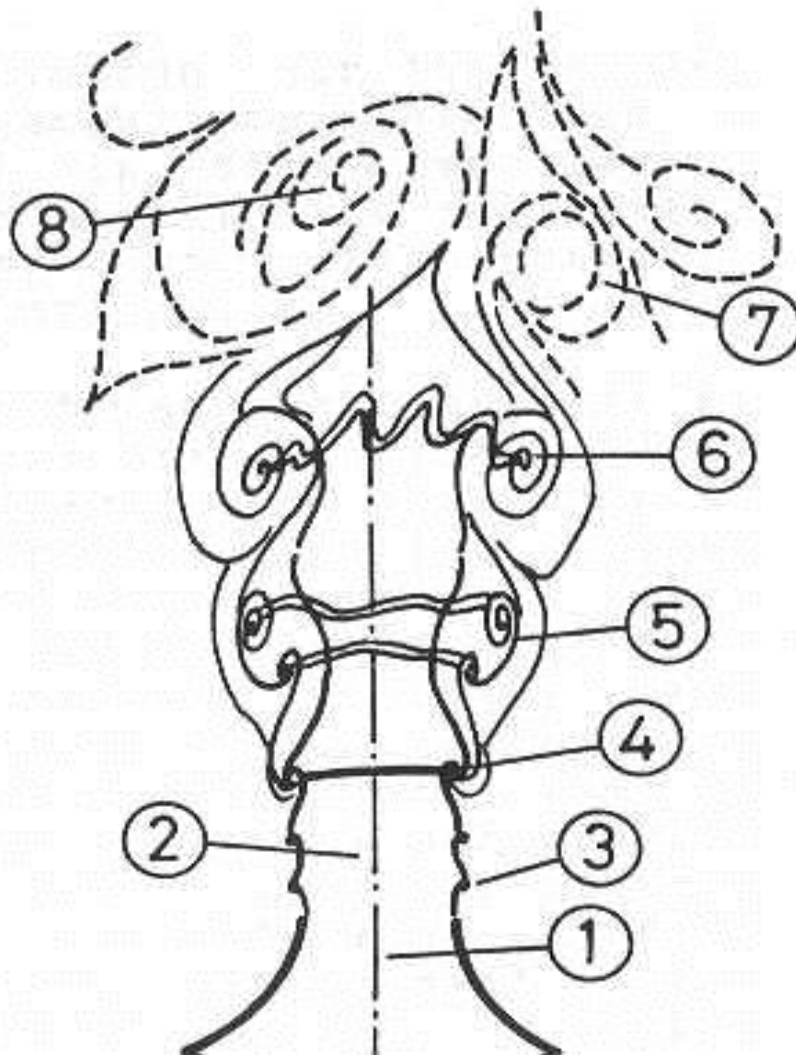


Figure 2.14 – Distinct regions of a fully developed turbulent circular jet.

The axial length of the transitional-flow region where toroidal vortices are found depends on the Reynolds number. This region shortens as Reynolds number increases. Thus, for high Reynolds number jets (and applications which have importance in aeroacoustics), vortex pairing is, in fact, an infrequent event, and it is not very significant.

Experimental evidence suggests that the vortex structures existing in the final stages of transition persist in the region where flow is fully turbulent and large vortex structures arise naturally in the turbulent flow (Lilley, 1958). It is also known that the main turbulent motion includes all the small eddies responsible for the dissipation.

Another important aspect, as stated before, the longitudinal velocity is higher than the transversal velocity, therefore it is expected that eddies inside the flow will be generally more elongated in the streamwise direction. As presented by Harper-Bourne (1998), the longitudinal correlation length L_1 in the direction of the flow is about twice the longitudinal

correlation length L_2 in the radial direction. Additionally, these quantities vary linearly with distance from the nozzle exit plane, as:

$$L_1 \approx 0.1x \quad L_2 \approx 0.05y \quad (2.3)$$

with x and y being the longitudinal and transversal coordinates inside the flow. In the fully developed region the correlation length is relatively independent of x over 20 jet diameters. This flow dynamic structure is well characteristic of compressible subsonic jets. For supersonic jets, the appearance of shock patterns inside the flow alters the nature of the jet flow.

2.2.4 Basic governing equations

The mathematical models used to represent transport phenomena problems usually are complex non-linear equations, which are simplified in most cases in order to be solved analytically or numerically with the aid of a computer or even a computer cluster. Even though the equations of viscous flow have been known for more than 100 years, it is very difficult to solve these equations in their complete form and at high Reynolds numbers the equations are impossible to solve with present mathematical techniques (White, 1991). Thus, this section presents the most general accepted and widespread equations of classical mechanics, the conservation laws, since they were the base to the development of aeroacoustics and the Acoustic Analogy formulation.

2.2.4.1 General equations

The three more important basic equations to turbulent flows are: conservation of mass (continuity), momentum (Newton's second law) and conservation of energy (first law of thermodynamics). These equations for an incompressible, newtonian fluid are:

$$\text{Conservation of mass: } \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (2.4)$$

$$\text{Momentum: } \frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] \quad (2.5)$$

$$\text{Conservation of energy: } \frac{\partial \rho T}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j T) = \frac{\partial}{\partial x_j} \left[\frac{k}{c_p} \left(\frac{\partial T}{\partial x_j} \right) \right] \quad (2.6)$$

Velocity in general is a vector function of position and time having three components usually named u , v and w . The equations above were showed using the tensorial notation.

Although in liquids it is difficult to obtain compressible flows, in gases a pressure ratio of only 2 / 1 is enough to cause sonic flows. For jets is extremely important take into account the equations to compressible flow, especially for experimental works. For flows with Mach number greater than about 0.3 the errors associated with incompressible assumptions cannot be neglected and the equations 2.1 to 2.3 also have to include the density changes in the differential terms. Furthermore, there are four variables to solve now: velocity, pressure temperature and density. It is necessary the use of an equation of state.

The theory associated with compressible flow is quite complicated, thus, some simplifications are necessary.

First of all, to calculate the Mach number is usual to consider the flow composed of a perfect gas. The calculation also depends upon a second dimensionless parameter, the specific-heat ratio of the gas, ' γ '.

$$\gamma = c_p / c_v \quad (2.7)$$

Assuming perfect gas, three equations can be stated:

$$p = \rho RT \quad (2.8)$$

$$R = c_p - c_v = \text{constant} \quad (2.9)$$

$$\gamma = c_p / c_v = \text{constant} \quad (2.10)$$

Therefore, the relations between pressure, temperature and density ratios for an isentropic, perfect gas are found as follows:

$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1} \right)^{\gamma/(\gamma-1)} = \left(\frac{\rho_2}{\rho_1} \right)^{\gamma} \quad (2.11)$$

where, for a jet, the index '1' refers to the jet and '2' is related to the ambient properties. The constant ' γ ' is equal to 1.4 for air.

For a perfect gas the speed of sound is defined as:

$$a = \left(\frac{\gamma p}{\rho} \right)^{1/2} = (\gamma RT)^{1/2} \quad (2.12)$$

Rearranging the equations, for a perfect gas there is the follow temperature to Mach number relation:

$$\frac{a_0}{a} = \left(\frac{T_0}{T}\right)^{1/2} = \left[1 + \frac{1}{2}(\gamma - 1)Ma^2\right]^{1/2} \quad (2.13)$$

The isentropic assumption gives the other two relations:

$$\frac{p_0}{p} = \left(\frac{T_0}{T}\right)^{\frac{\gamma}{\gamma-1}} = \left[1 + \frac{1}{2}(\gamma - 1)Ma^2\right]^{\frac{\gamma}{\gamma-1}} \quad (2.14)$$

$$\frac{\rho_0}{\rho} = \left(\frac{T_0}{T}\right)^{\frac{1}{\gamma-1}} = \left[1 + \frac{1}{2}(\gamma - 1)Ma^2\right]^{\frac{1}{\gamma-1}} \quad (2.15)$$

2.3 Jet aeroacoustics

The turbulence theory presented before is fundamental to jet noise research. As stated in the first chapter, the noise caused by jets is about only those sources associated with the mixing process between the exhaust flow and the atmosphere. This sub-section summarizes the correlation of the flow dynamics with the noise production and propagation mechanisms.

In subsonic jets, it is largely accepted that shearing action of the fine-scale fluctuations and the large scale coherent structures are dominant in the noise produced. Thus, due the fine-scale fluctuations, the jet noise spectrum has a broadband shape, as shown in the Fig. 2.15. Although the large coherent structures are always present in subsonic jets, it seems to be more effective in terms of noise contribution at moderate and low Reynolds number flows. For supersonic jets the noise is also related to screech tones and broadband shock-noise, where these mechanisms are dominants.

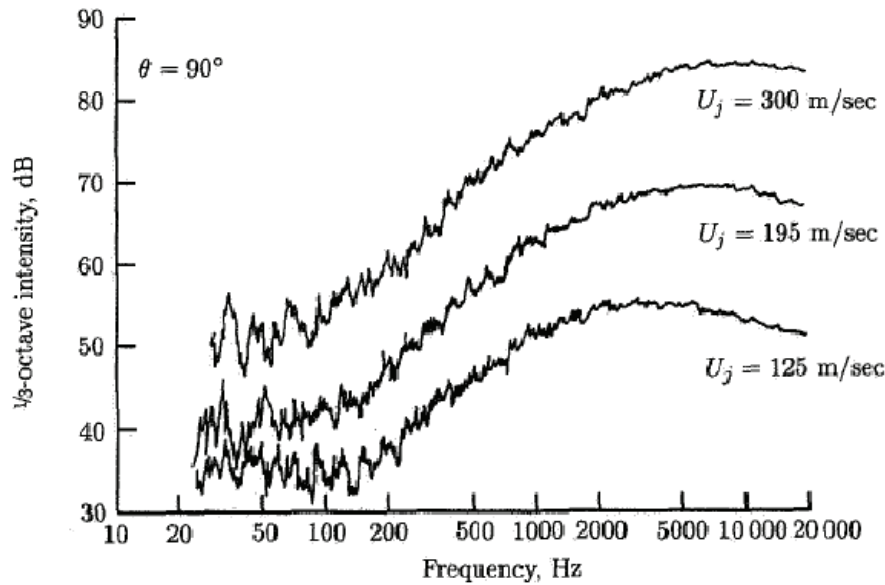


Figure 2.15 – Jet noise spectra at 90° observer angle for three different velocities. (Hubbard, 1991)

The eddies are physically small near the origin of the shear layer and then grow in size downstream of the jet. At some axial location in the jet wake, both small and large scale eddies coexist. The size of these structures can be correlated with the frequency of the noise generation: fine-scale eddies are responsible for high frequency, whilst large scale eddies are of lower frequency.

Since the large eddies contain the bulk of the energy in the turbulent motion, it is expected that they control the overall amount of acoustic power. The number and size of these large eddies is dependent upon the manner in which the turbulence is produced. Therefore, the total acoustic power produced by a jet will depend upon the manner in which the turbulence intensity is generated.

While the low-frequency sound end of the power spectrum will depend upon the driving mechanism of the turbulence (since it is produced by the large-scale eddies), the high-frequency sound end of the same spectrum may be independent of the driving forces. The small-scale eddies are associated with rapid fluctuations in the turbulent fluid and they can be thought of as being transported by the large-scale eddies. Thus, the large-scale eddies have some influence on the high-frequency sound, however it is, primarily a Doppler effect which may be neglected for low Mach number turbulence.

2.3.1 Radiation of sound

The acoustic source distribution can be expanded as a Taylor series and the ‘multipole’ of increasing order is defined according to the terms of the series.

A point source is called monopole if it is compact and radiates sound equally well in all directions. This radiation is equivalent to that produced by a pulsating sphere, whose radius alternately expands and contracts in a sinusoidal mode. Thus, the monopole source creates a sound wave by introducing and removing fluid alternately into the surrounding area.

The relation between the radiated sound power and the flow parameters when monopole sound is generated by unsteady flow velocities is given by:

$$W_{monopole} \propto \frac{\rho L^2 U^4}{c} \quad (2.16)$$

where ρ is the specific mass of the gas, c the speed of sound, L is the length of the flow in the source region and U the flow velocity in the source region.

A point source is called dipole if it is created by superposing two monopoles sources of equal strength, opposite phase, separately by a distance which is much smaller than the wavelength of the sound and equal magnitude. The sound field of a harmonic dipole can be represented as a sphere which oscillates back and forward. It does not radiate sound in all directions equally, where the pressure reaches maxima for angles 0 and 180°, whilst it is dissipated for 90 and 270°.

The dimensional dependence of the dipole sound power in a fluid with a uniform mean density is given by:

$$W_{dipole} \propto \frac{\rho L^2 U^6}{c^3} \quad (2.17)$$

A point source is called quadrupole if it is created by superposing two dipoles sources. In this case, there are two principal possibilities: lateral quadrupole and linear quadrupole. In a lateral quadrupole the two dipoles do not lie along the same line. The sound is radiated in front of each monopole source, however, it is cancelled at points equidistant from adjacent opposite monopoles. In a linear quadrupole source, two opposite phase dipoles lie along the same line. In this radiation, there is an evident transition from near to far field.

The dimensional dependence of the radiated quadrupole sound power is given by:

$$W_{quadrupole} \propto \frac{\rho L^2 U^8}{c^5} \quad (2.18)$$

From the equations 2.13, 2.14 and 2.15, it can be seen that the dimensional dependence of the dipole differs by a factor M^2 from the power output of the monopole, and the quadrupole differs M^2 from the dipole source.

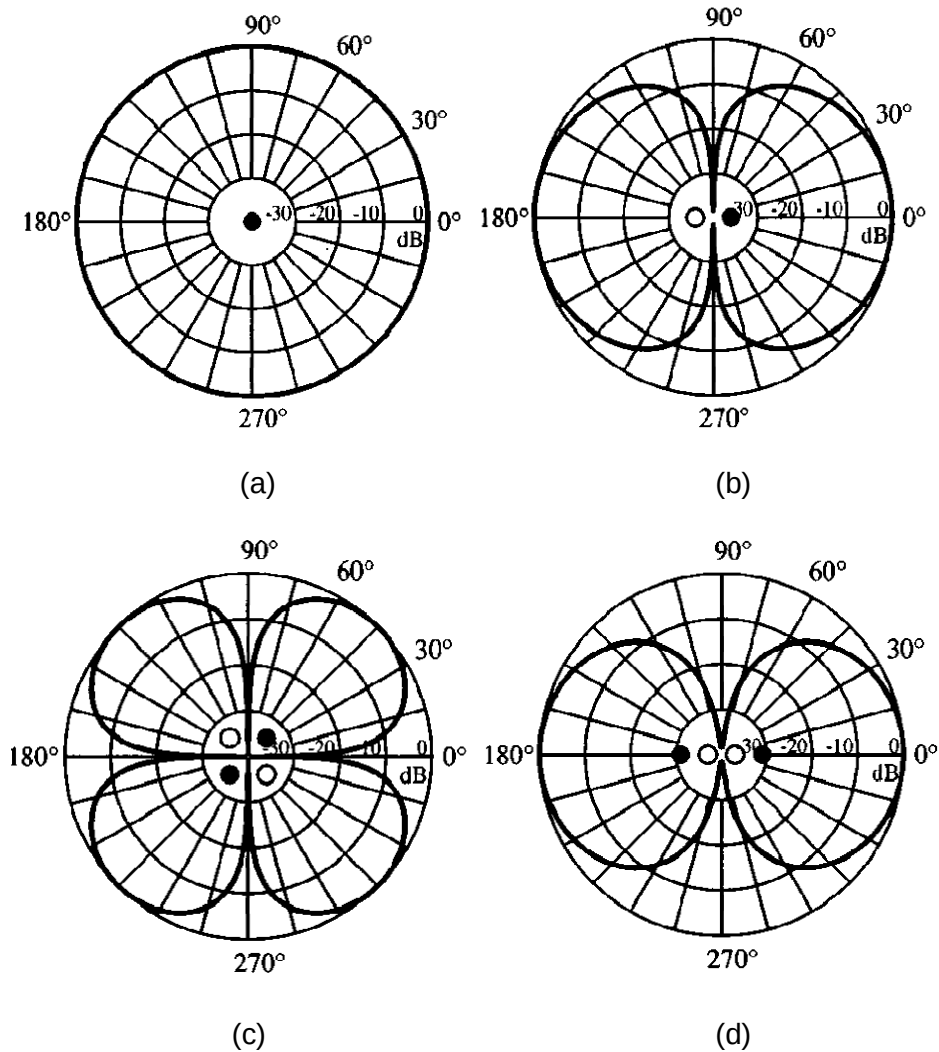


Figure 2.16 – Directivity patterns for (a) Monopole, (b) Dipole, (c) Quadrupole (lateral quadrupole) and (d) Quadrupole (linear quadrupole).

2.3.2 Directional sound pattern in jets

Aerodynamic quadrupoles and entropy dipoles are the dominant source types in high speed, subsonic, turbulent air jets. The quadrupole radiation is the dominant sound source for subsonic isothermal jets. Its strength is larger when the turbulence and mean velocity gradients are high, such as in the turbulent mixing layer of a jet. The dipole sources arise when an unsteady flow interacts with surfaces or when there are substantial variations of mean fluid density, as seen in hot jets.

The sound sources are convected downstream by the mean flow. The moving sources tend to radiate more noise in the direction of motion, and this effect is more pronounced at higher speed. This directiveness makes the maximum noise be radiated in directions inclined at observers angles between 30° up to 50° .

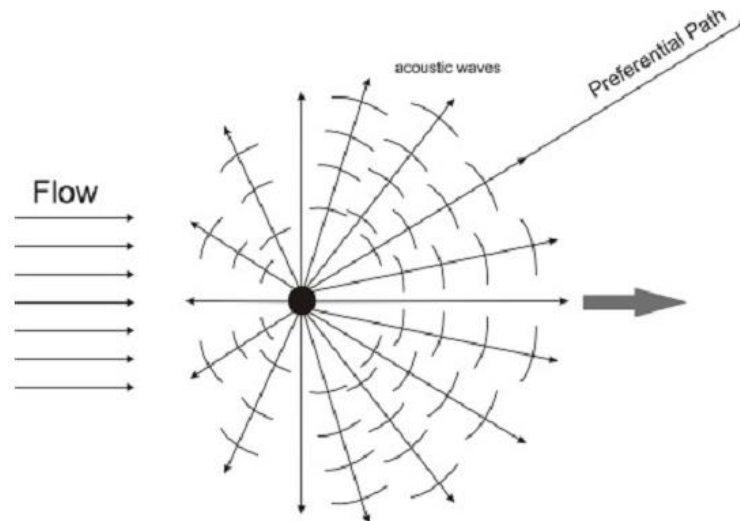


Figure 2.17 – Convection effect (Almeida, 2009).

Additionally to the convection effect, the sound generated is affected by refraction. When the wave front propagates to the far-field regions, its path tends to bend away from the jet axis. This effect creates a cone of relative silence downstream of the noise-generating region. (Tam, 1998). Experimentally, the presence of a cone of silence in which the noise intensity drops by more than 20 dB has been demonstrated by Atvars et al (1965).

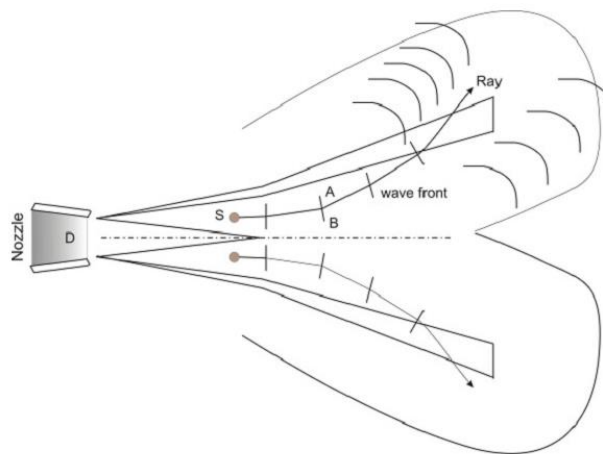


Figure 2.18– Refraction effect (Almeida, 2009).

The sound generated by a turbulent jet also can be divided into two parts: the contributions from interaction of turbulence fluctuations with the mean flow and the turbulence fluctuations interacting with themselves. These components are often referred as shear-noise and self-noise, respectively. Considering isotropic turbulence under no convection effects, the self-noise is radiated equally in all direction, while the shear-noise gives a dipole-like contribution. These two contributions give an ellipsoid-shaped sound radiation pattern when superimposed, with most radiated along the jet axis. Combining these effects with the convection and refraction described above, the directional sound patterns is shown in the Fig. 2.19.

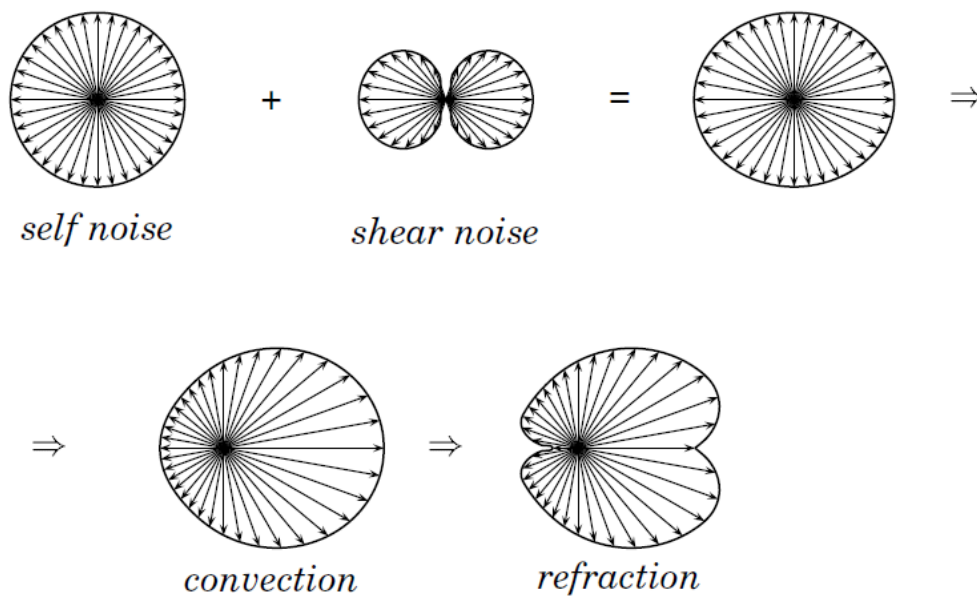


Figure 2.19 – Superimposition of the effects resulting in the directional sound pattern.

2.3.3 Lighthill's acoustic analogy

The prediction of the sound produced by a free jet was the motivation for James Lighthill to propose in 1952 a new approach that he called an “analogy”. It was shown that the acoustical pressure which is generated in the far field by an unsteady flow was the same as that for an analogous problem where a specific volume contribution of quadrupole sources was present in the absence of flow. Lighthill's Acoustic Analogy is considered one of the first theoretical models applied to jet noise prediction. This is often referred as the start of aeroacoustics.

The starting point is the conservation equations, shown in their tensor form in the equation 2.4 to 2.5. Lighthill's mathematical model is called the Acoustic Analogy because it

is based on a rearrangement of the exact Navier-Stokes equations into the form of an inhomogeneous wave equation for the fluctuating fluid density.

The famous Lighthill's equation is given by:

$$\frac{\partial^2 \rho}{\partial t^2} - a_0^2 \frac{\partial^2 \rho}{\partial x_i \partial x_j} = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} \quad (2.19)$$

where the Lighthill's stress tensor is:

$$T_{ij} = \rho u_i u_j + p_{ij} - \rho a_0^2 \delta_{ij} \quad (2.20)$$

p_{ij} is the viscous stress tensor.

The left side of the Eq.(2.30) can be interpreted as a wave operator responsible for the propagation of density fluctuations while the right hand side is interpreted as an acoustic source distribution. The latter must be known throughout the flow field and consider all interactions between the flow and the acoustic wave motion generated by the flow. In Eq.(2.20), $\rho u_i u_j$, a non-linear interactions term, is considered to be a quadrupole, whilst $(p_{ij} - \rho a_0^2 \delta_{ij})$ a dipole source.

Although the whole procedure was not shown here, the equations 2.19 and 2.20 are derived without approximation from the full Navier-Stokes equations.

The jets represent a distribution of incoherent sources. The sub-section about directivity of jets noise showed that the far field noise is directional. It is best expressed in terms of intensity, which is function of the distance and the observer angle.

Other famous results from Lighthill is about a dimensional analysis of intensity field in terms of typical velocities and lengths in the flow, which achieves the "eighth power law": the intensity is proportional to velocity to the power of eight, $i \propto U^8$. The mean square value of the radiated sound field from cold subsonic jets increases in this proportion with velocity. As the integral of similarity variables is the same for all jets, the intensity of sound is given by:

$$I(R) \approx \frac{\rho_s^2 U_j^8 D^2}{\rho_0 c_0^5 R^2} \quad (2.21)$$

In order to allow for convection of quadrupoles, the Eq.(2.21) is rewritten:

$$I(R) \approx \frac{\rho_s^2 U_j^8 D^2}{\rho_0 c_0^5 R^2} (1 - M_0 \cos \theta)^{-5} \quad (2.22)$$

The eighth power law is also well confirmed experimentally, although it is based on low Mach number flow. For supersonic flows the noise dependence changes in proportion to the cube of the jet velocity.

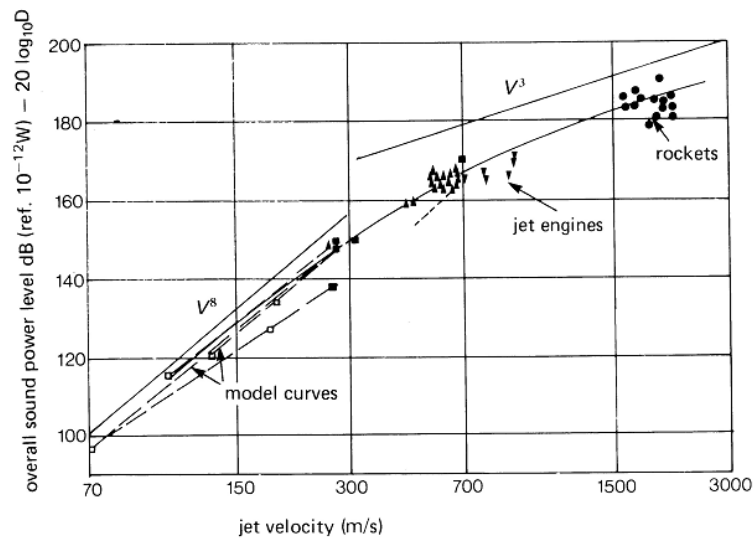


Figure 2.20 – Variation of acoustic power levels as function of jet velocity. (Dowling and Ffowcs Williams, 1983)

CHAPTER III

LITERATURE REVIEW

This chapter presents a review of some experimental researches related to single jet properties, as well as information about jet noise facilities. It was mentioned that research in this area is extremely necessary to achieve the noise certification scheme, but it is not due to lack of research in the past. There have been many years since the scientific community started to study jet flows. Thus, this chapter contains only a small part of the experimental work in jet survey.

The sub-section about experimental research in single jets is a review of selected works, in both aerodynamic and acoustic measurements, bringing a description of some experiments which has helped researchers to form the basic theoretical knowledge about the jet noise. Obviously, since aerodynamics and acoustics are indispensable to study jet noise, it is no rarely works which deal with both. The papers are reviewed following a chronological order.

The section “Jet noise facilities” is the result of a study produced in order to understand the general parameters of this kind of laboratory, aiming the project and construction of two jet rigs: one at UFSC, and other at UFU, posteriorly. This section also brings information about refurbishment and modification to optimize some of the facilities presented.

3.1 Experimental research in single jets

Experimental work on the mean velocity profiles of free jets has been reported for at least one century. Just some examples before moving to jet noise research, Trüpel published

his work in 1914 showing curves for the velocity components along the x-axis at different cross sections of a round air jet discharged into stationary air (Trüpel, 1914). Using an initial section with 0.45 m radius, the initial velocity of the jet was $u_0 = 87 \text{ m/s}$. Some results can be seen in Fig. 3.1, where the velocity profiles were determined at dimensionless distances of 0.67, 0.89, 1.11, 1.33, and 1.78 (x/D_j).

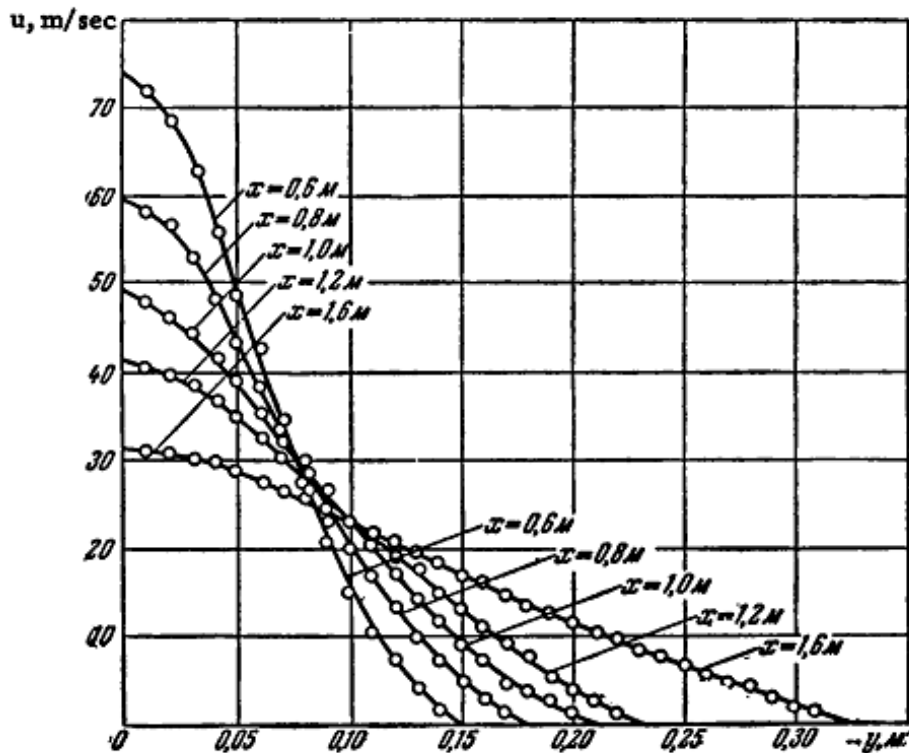


Figure 3.1 – Velocity profiles in different sections of a submerged jet (Trüpel, 1914)

As in studies made by other investigators, Trüpel's results show a continuous extends of the mean velocity profile of the jet, which the mean velocity becomes lower and wider with increasing distance from the beginning of the jet.

Some years later Förthmann's work showed results from a rectangular nozzle 0.03 m high and 0.65 m wide (Förthmann, 1936). He also studied the velocity profiles of an air discharge at 35 m/s. The data were acquired at axial distances 0, 0.2, 0.35, 0.625 and 0.75 m. The velocity profiles were shown as in the Trüpel's work, but interesting results are obtained when the same profiles are plotted in dimensionless coordinates: the velocity profiles of the initial area are similar, and this characteristic was observed for both, plane and round jet. Figure 3.2 shows one of the dimensionless velocity profile obtained by Förthmann.

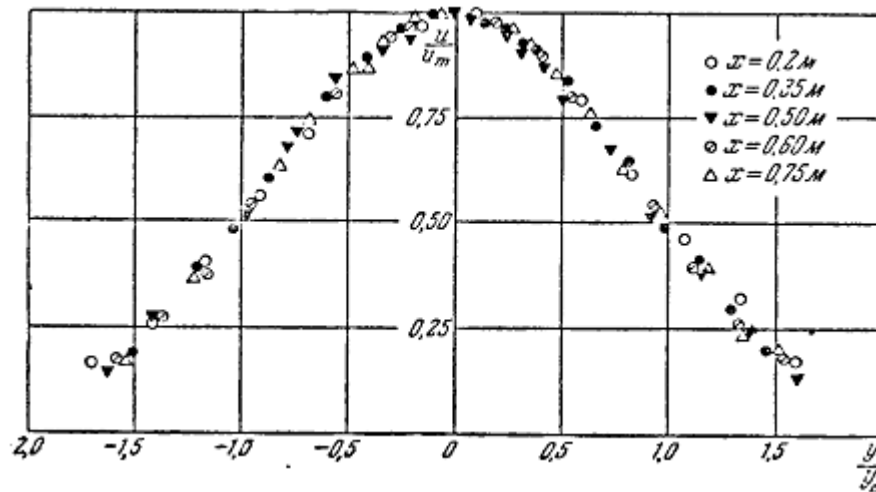


Figure 3.2 – Dimensionless velocity profile in plane jet (Förthmann, 1936)

The turbulent jet also was investigated in detail by Abramovich (1938), Corrsin (1943), Corrsin & Uberoi (1949,1951), Hinze (1959), and many others. At that time the main instrument was the pitot tube, and it was largely used to mean velocity measurements. Those works showed mean velocity profiles as well as some of the turbulent quantities in the free jet flow. Most of the statistical characteristics and similarity relationships showed in Chapter 2 where investigated that time.

Beyond the mean properties, the turbulent intensities and velocity fluctuations are extremely important to investigate. Point-wise measurements of turbulent fluctuations in velocity are traditionally obtained using hot wire anemometry. The use of this method in jet survey measurements also date from many years ago. Townsend (1956) presented a method of triple correlation of the two traverse velocity fluctuations data acquired with an x-arrangement. Laurence (1956) reported mean velocity profiles, intensity, spectrum and correlation of the turbulent field of a 3.5" round jet at different exit Mach numbers from 0.2 to 0.7, being considered as the first complete investigation in the mixing region of the jet. Lilley (1958) used Laurence's turbulence measurements to estimate the noise produced by a jet, with a good agreement with the main experimental results being obtained.

Although many consider the birth of the research in "Aeroacoustics" after the Lighthill's paper, as seen in Chapter 1, this issue was already being discussed and idealized in the late 1940s (Lilley, 1991). After Lighthill's Analogy, authors such as Davies, Fisher and Barratt (1962), Chu, (1966), Fuchs (1972), Lau and Tester (1979), and Bridges and Podboy (1998), have predicted the noise from a jet through associations between acoustic analogy and space-time correlations obtained from two-points. This rich type of turbulence data is required in many jet noise prediction theories, such as the Mani-Gliebe-Balsa (MGB)

theory. Although the measurements were somewhat primitive by today's standards, much important information remains valid to this day.

Single hot-wire anemometers can be used to measure the turbulence intensity, and the frequency spectra, whilst pairs of these sensors can be used to define the size and shape of the regions in which the turbulent velocities are correlated. In addition measurements of space correlations at retarded times can be used to define a convection velocity. It is then possible to obtain spectra and time scales in the frame moving with the turbulence (Davies, Fisher and Barratt, 1962).

Currently, the hot-wire and hot-film anemometers keep having an important role in turbulent jet measurements, including the case of jet noise. Measurements made in a low speed air jet ($Mach = 0.18$) with associated cross-spectra and spectral length scales of the axial and lateral velocity components were performed by Harper-Bourne (2003). This work describes a semi-empirical scheme for jet mixing noise that combines Lighthill's acoustic analogy (Lighthill, 1952) with second and fourth order two-point space-time turbulence measurements obtained by hot-wire anemometers. Two important differences were introduced from the other authors mentioned previously: firstly, the measurement of the two-point coherence properties is function of the Strouhal number; secondly, the adoption of a fixed frame of reference in which to evaluate the Strouhal number dependent turbulence measurements in Lighthill's equation. Thereby, the configuration used avoids the customary assumption of separation of space and time variables, allowing a more deterministic link between jet turbulence measurements and noise output.

This new scheme proposed by Harper-Bourne has been used by other authors, such as Morris and Zaman, (2010). This work provides a more complete picture of the relevant turbulent statistics, including a wider range of reference points in the jet, the presentation of both cross spectra as well as cross correlations, second and fourth order statistics, and comparisons with a RANS prediction method. In addition, the validation of the quasi-normal hypothesis is examined. The measurements are done for $Mach\ 0.25$, highlighting the hot-wire sensor restriction to low velocities.

Non-intrusive techniques have been developed whereas in high speed and heated flows the environment is too severe for intrusive instruments like pitot tube and hot-wire anemometer, which disturb the flow and can only be applied to low temperature subsonic flows. The work of Mielke et al (2004) shown a combined Rayleigh and Mie scattering technique developed to measure velocity, density, temperature, and turbulence velocity fluctuations in sparsely seeded, high-speed gas flows, used to make measurements in a 25.4 mm diameter free jet facility at subsonic and supersonic flow conditions. Bridges et al. (2003) used particle image velocimetry (PIV) to calculate turbulence quantities in nozzle flows from

instantaneous 2D velocity maps. Garg and Settles (1998) developed a technique based on focusing schlieren deflectometry to make turbulence measurements in compressible flows. Usually, these techniques are more complex to operate and the costs involved are relatively higher than the hot-wire anemometer system. Furthermore, the high temporal and spatial resolution obtained with hot-wires (fluctuations up to several hundred kHz and eddies down to 1 mm or less) give a special worth to these remarkable instruments.

Nowadays, a massive amount of published works are related to comparison between experimental and numerical results of free turbulent jets. To validate a numerical model, accurate experimental data with as much information about the input and control parameters as possible must be provided. These methods (numerical and experimental) are not exclusive, but complementary to each other (Silveira Neto, 2002).

Ghahremanian and Moshfegh (2011) presented numerical results of three-dimensional modeling of an isothermal, free jet with four different RANS turbulence models (two Low Reynolds turbulence models and two transition models), validated with hot-wire anemometry data to the three major regions of free turbulent round jet stated at Chapter 2. The comparison showed an excellent agreement between experimental and numerical results for Low Reynolds turbulence models but the two transition models could not completely predict the decay of the centerline velocity in all regions. It is well known that due to the complexity of turbulent flows, the turbulence models are usually representative to a specific class of problem, requiring a careful validation before the application of a numerical method in a particular category of flow.

Evidently, jet noise can be acquired directly using a set of microphones. According to Tam (1998), precision instrumentation and facilities for jet noise measurements became available in the second half of 1980s, permitting a large bank of high-quality narrow band jet noise data to be gathered thereafter. One important consequence is the incontestable evidence that jet noise is composed by two basic components: one from the large turbulence structures and other from the fine-scale turbulence. Tam et al (1996) found that each contribution can be described by a similarity spectrum with a specific shape.

One of the mainly applications of acoustic measurements of free jets is the composition of database in order to predict jet noise by interpolation and extrapolation data, usually through a semi-empirical model. For example, ESDU 98019 and SAE ARP 876D are databases for single jets obtained in different experiments, each one has its specific data for the Strouhal number, temperature ratio, and observer angles.

The SAE ARP 876D database was provided in 1965 and the prediction method was revised in 1978 and 1994. The measured values of temperatures ratio are 1.0, 2.0, 2.5, 3.0 and 3.5. The Strouhal number ranges from -1.6 to 1.6. The ratio V_j/a_0 is integrated into the

Strouhal number by the coefficient ξ , and the maximum velocity achieved was 300 m/s. These data are measured to angle from 0 to 160° (formed by the line of the observer with the engine exhaust axis) in a 10 basis (SAE, 1994).

The ESDU database is more recent (data acquired in 1998, method revised in 2001). The temperature ratios are 1.0, 1.5, 2.0 and 2.5. The Strouhal number is bounded between -1.5 and 1.5, but in many cases the database limits are reduced because the calculation of sound pressure levels in this method extrapolate the data. The ratio between the fully expanded jet velocity and the ambient speed of sound is also used differently: in this case is an independent variable, fixed at 0.50, 0.75, 1.00, 1.25 and 1.50. The angles used are multiples of 10, ranging from 30 to 120.

Few years ago, the lack of data available was a considered problem in research groups. As the jet noise is a profit factor in the aeronautical industry, there was not much database in an open literature. Other point is the lack of information of the input parameters and the restrictions in some parameters as velocities and observer angles in the available database. The recent cooperation projects between universities and companies have supplied or at least soften this issue.

Even currently, jet noise experiments are very difficult to perform and best practices for accurate measurements are discussed by Viswanathan (2010). The next section shows four jet noise facilities, their equipment and procedures in order to run clean measurements.

3.2 Jet noise facilities

This section is divided in two sections. Firstly, general features of an anechoic chamber used to jet noise measurements and two works to illustrate an academic and an industrial scale are presented. Secondly, a brief description of some facilities is given.

3.2.1 General features

Essentially, a jet rig for noise evaluation is composed by a system of compressors (or a single compressor), pressure regulator valves, pipes, silencer, combustion chamber (when heating the flow becomes important) and the nozzle application. The high pressure air is passed through the pipes and it is regulated by controlling valves. For hot jets, this air stream is passed through the combustion chamber where it is heated by the combustion process. This process is to simulate the hot gases exhausting at the same temperature expected in a real aircraft engine. The silencers are installed in the pipe system in order to remove internal noise such as that coming from bends and valves along the line. The silencer is a very

important element to have a “clean” flow through the nozzle application without additional noise. For hot jet cases, there is an extra concern about the dilatation of the metallic pipes which could influence the final nozzle application. Extra care must be taken in this case in order to compensate this dilatation. At the end of this system there is the nozzle application simulating the exhaust system of modern aeronautical engines. Such nozzle is encompassed generally in a large square room with walls covered with absorbent material in order to make it anechoic. Microphones are placed in line close to the nozzle or making an arc centered at the nozzle exit plane. Common configurations have at least 10 microphones with an arc radius varying from 30 up to 60 jet nozzle diameters. The noise is collected by the microphones and digitally processed through a system of modern equipment such as amplifiers, digital filters, FFT-algorithms, in order to reach the required metric for sound analysis. Finally, the jet discharge inside the room is handled by an exhaust system, in order to remove the amount of fluid continuously inject. This system consists of an exhaust and another silencer.

Despite the fact that the system is relatively simple, many physical limitations are applied through it. Many of them related to the control of the flow (flow dynamics) and a lot of them related to the noise itself. It is important to notice that the final objective is to have a physical flow dynamics of the jet and pure noise from it. All equipment must be correctly designed and built in order to reach such task.

The jet noise problem is being envisaged by many researches around the world comprising small and large experimental facilities. Even in small test facilities is possible to have successful results. This is the case of Papamoschou et al (2009) who, in one of their experiments, used 8 microphones of 3.2 mm (Bruel & Kjaer, Model 4138) placed in a manner to create an arc of 1 m radius. The center of this arc was placed in the exit plane of the tested nozzle. For each group of 4 microphones there was the connection with signal amplifiers (Bruel & Kjaer, Nexus 2690-A-OS4) and connected to frequency filters of 300 Hz up to 100 kHz. In this experiment, it was used another instrument for frequency analysis – the optical deflector. With this instrument it is possible to identify regions inside the flow that emits such a specific frequency. All acquired data has been computed and processed through a National Instrument PCI-6070E) installed in a simple computer Pentium 4. All the results are expressed in terms of plots and metrics for the noise emission. The tests have been conducted in a small anechoic room as depicted below.

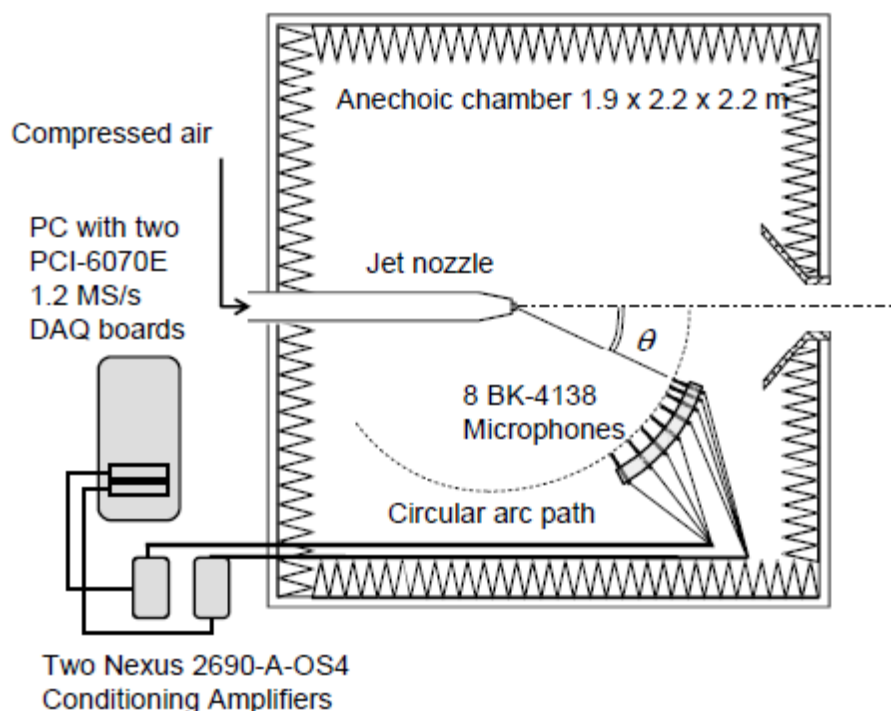


Figure 3.3 – Schematic of an anechoic chamber with a jet rig

Another important work in this area is that presented by Nance and Ahuja (2009), developed at Georgia Institute of Technology, Atlanta, GA. In this work the main objective was to separate the turbulence noise characteristics. The experiments were carried out in the *Georgia Tech Research Institute/Cobb County Research Facility (CCRF)*, as illustrated in Fig. 3.4. The chamber of 6,7 x 6,1 x 8,5 meters was completely covered with wedges of polyurethane with 38 centimeters. This configuration brought the chamber anechoic down to 1% for frequencies above 200 Hz. Two ducts, one for heating and one for control give the desired flow characteristics. The heating could impose flow temperatures of order 815 °C. A compressor feeds the installation with air at approximately 20 atmospheres. In the main line, silencers are installed in order to remove undesired additional noise. For the noise signature, microphones could be installed in any place in the chamber. In the case of study, the microphones were placed in an arc of 3 meters away from the nozzle exit plane. Fig. 3.5 illustrates the configuration of the room.

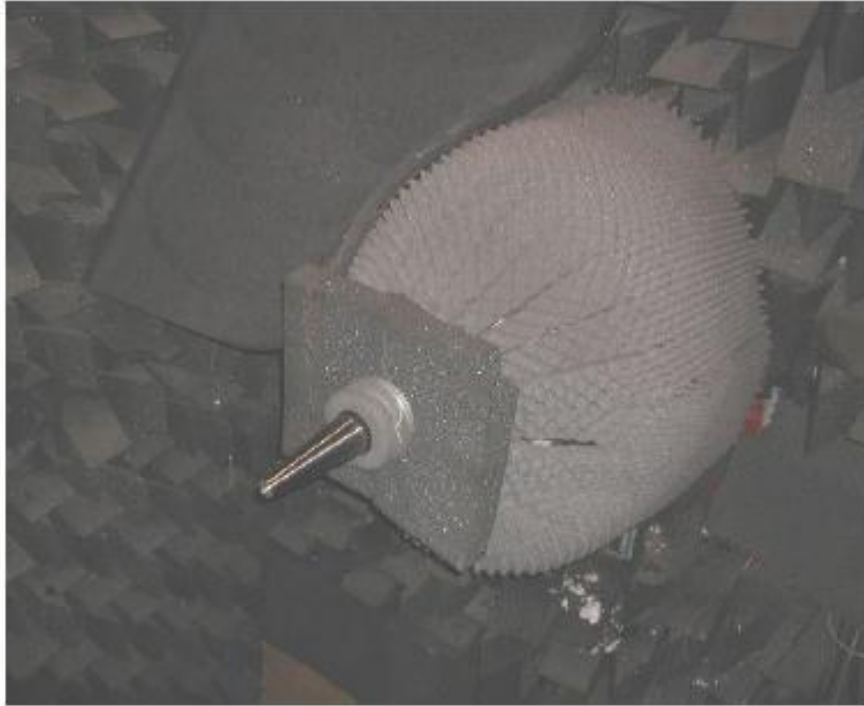


Figure 3.4. Details of the anechoic chamber and nozzle configuration (CCRF).

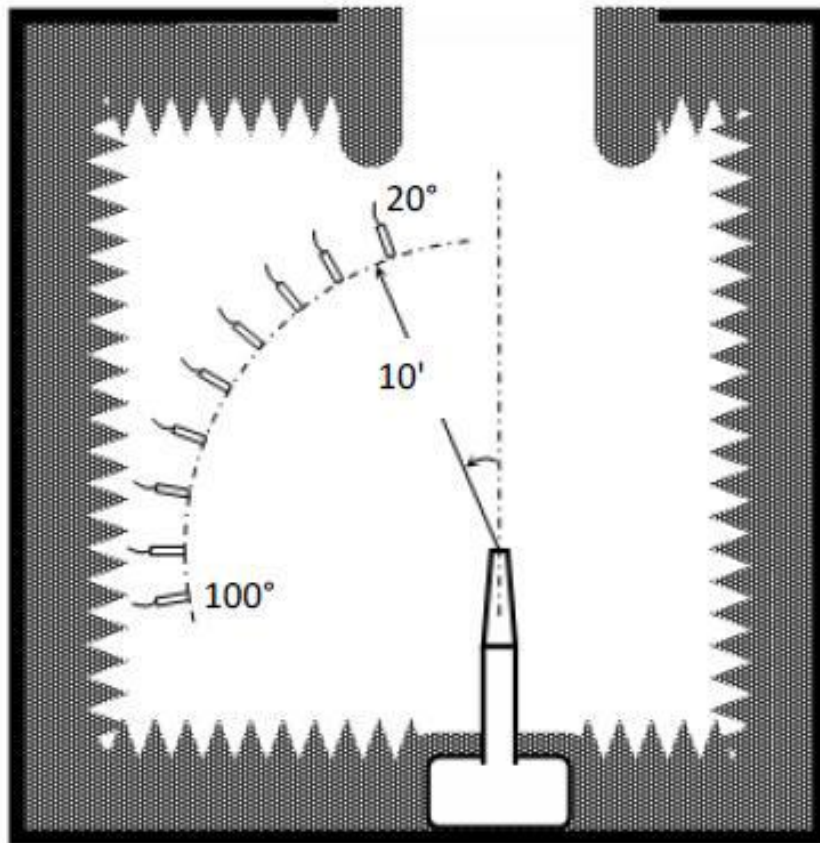


Figure 3.5. Schematic view of the experiment room.

The work of Ahuja (2003) presented a general overview about designing clean jet noise facilities and making accurate jet noise measurements. Such paper is very detailed and contains important information for those considering the design and assembly of an installation for measuring jet noise.

3.2.2 Test facilities by description

All jet noise theories and methodologies based on the Lighthill principles contain some level of empiricism, derived from measured data. As more noise reduction concepts have been proposed, the need to produce more accurate data increases. This sub-section aims to present different rigs configurations for jet noise measurement and the improvements of the anechoic chambers related in the literature. A large range of different parameters are presented.

3.2.2.1 NTL3800 rig - Boeing Low Speed Aeroacoustic Facility (LSAF)

Information about this Anechoic Chamber was found in Viswanathan (2002; 2003; 2006). The NFL3800 rig was built by The Boeing Company, early 1990 and an extensive refurbishment was carried out in 1998. The jet rig consists of high-temperature supply piping, burners, instrumentation and aerodynamic fairings designed for a high flow capability of 20 lb/s (single-flow mode) and 30 lb/s (dual-flow mode). The streams may be heated up to 1083 K. A six-component force balance referred E3-balance is integrated to the rig. The support structure for the balance and a service module are mounted on air bearings and may be placed anywhere in the anechoic chamber. An aerodynamic strut contains all air lines, fuel lines and instrumentation in a manner that avoids interference with force measurements.

The mass flow rates are provided by the critical flow Venturi tube installed in the primary and the secondary supply ducts. When tests using a single-stream configuration the second supply line is used to remove the boundary-layer bleed through the aerodynamic strut. To dual-stream nozzle an additional evacuation line was added to still permit the use of the bleed system.

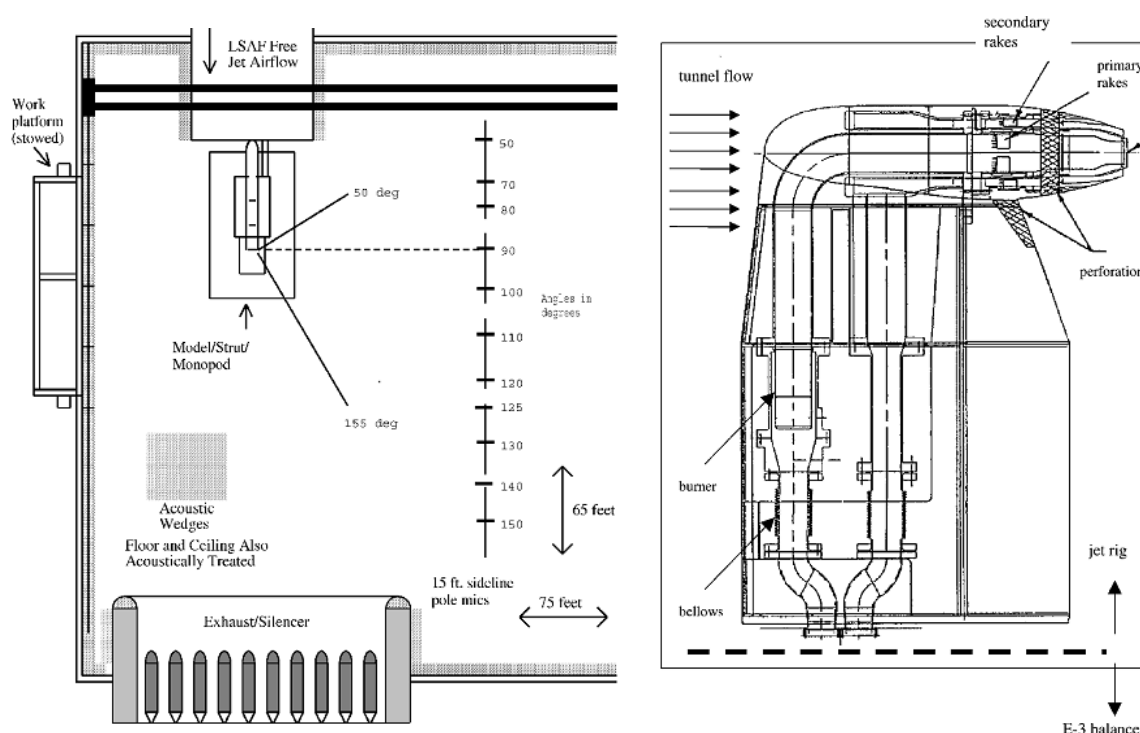


Figure 3.6 – Plan view of LSAF test cell (not to scale) and Schematic of NTL3800 jet simulator (Viswanathan, 2003).

The jet simulator has a close-coupled propane burner, which consists of a fuel injector and a swirl plate upstream to enhance mixing of the fuel with air. The flow at the nozzle entrance is measured by pressure and temperature rakes. There are three rakes of pressure (transducers) and three rakes of temperature (thermocouples) in which flow, primary and secondary. It possibilities a characterization of the flow before the exit nozzle and improvements may be done in sense of better pressure and temperature distribution. Installing flow conditioners and blockage devices could improve the aeroacoustic quality, but not flow quality.

Acceptable results were obtained after many design improvements and modifications to the entire flow system and fuel system.

For a nozzle test, the primary force component of interest is the axial force or thrust, checked periodically. Data obtained with the E3-balance were compared to data from Boeing Nozzle Test Facility (NTF) that is a dedicated test facility for measuring nozzle performance.

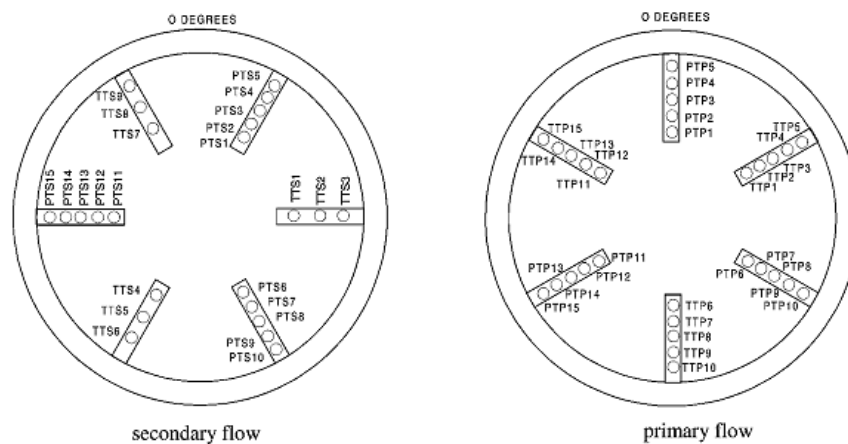


Figure 3.7 – Flow measurement system: pressure and temperature rakes (Viswanathan, 2003).

The microphones used for free field measurements in Viswanathan's works are Bruel and Kjaer Type 4939, laid out at a constant sideline distance of 4.6 m from the jet axis with a polar angular range of 50 – 155 deg, set at normal incidence without protective grid (frequency response up to 100 kHz). Linear or polar microphone arrays are usually adequate for simple axisymmetric nozzle. For nonaxisymmetric nozzles there is a strong azimuthal variation in the radiated noise field. The number of microphones to accomplish this objective is prohibitive, Boeing built an alternative approach: an azimuthal array that could be traversed in the axial direction. A stepping motor allows precise positioning at any desired axial location (polar angle).

It is important to avoid reflections from the microphone array and microphone holders, improper choice of gain setting, actual noise level running into the high levels of the electronic noise floor, and others. Viswanathan shows the considerations to use the microphones set at grazing incidence. In that configuration the dynamic range of the measurement system has to be much higher and the spectrum exhibited the turn-up at the higher frequencies (indicating that at these frequencies the measured signal was running into the electronic noise floor). Thus, the normal incidence is preferable for the acquisition of good data at higher frequencies because it is more sensitive. It is important to permit the extrapolation of data to engine scale. With this arrangement the magnitude of the corrections applied to the raw spectral measurements is small. The great benefit of setting the microphones at grazing incidence is due to the fact that the acoustic rays from a line of distributed sources are always at grazing incidence, no matter where the source is located, thus, no a priori knowledge of the distribution of the jet sources is required.

However, the study shown that regardless microphone orientation, the measured spectrum, with appropriate free-field corrections, is similar even for distributed sources, provided the microphone is located in the far field.

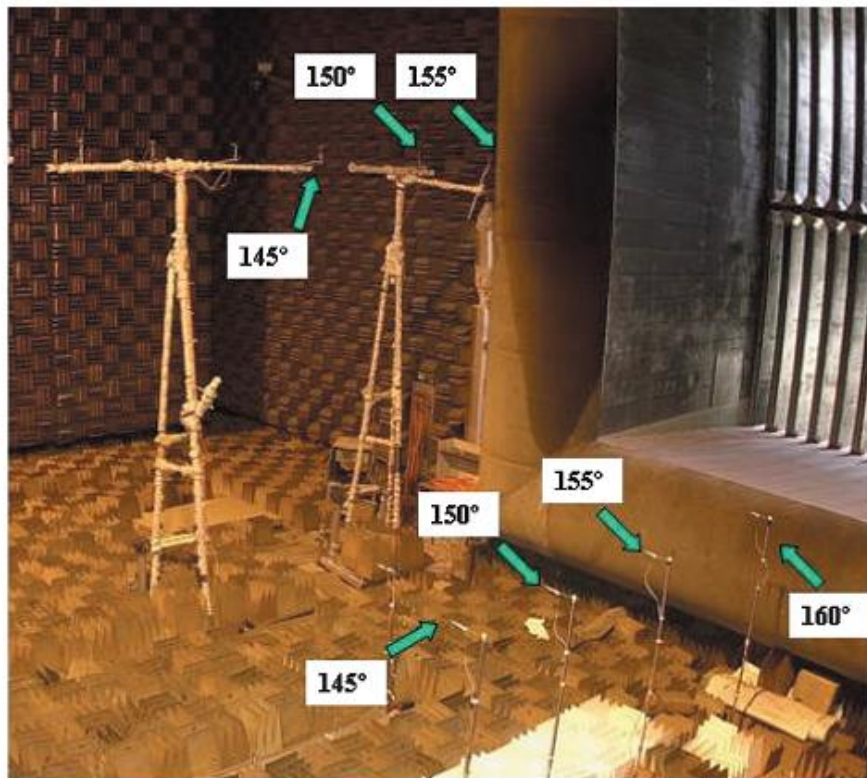


Figure 3.8 – Closeup of microphones at large aft angles and exhaust collector (Viswanathan, 2006).

The distance from the microphones to the noise sources has an important impact on the results. It has to be fairly to guarantee that microphones are in the far-field. However, the value of the atmosphere attenuation could be very high for exacerbated distance. To know where the far field is some methods are adopted.

One of them, the microphone is moved away or toward from the source and the radial decay (or growth) of the OASPL and the spectral level at individual frequencies are examined for spherical divergence (6 dB decrease for a doubling of the distance).

The measured reduction in spectral level with distance is compared with the theoretical decay rate, with some subjectivity. The author adopted another one, measuring the spectrum from nozzle of increasing diameters with the same linear array microphones, and comparing the normalized spectrum at the same jet conditions to detect near-field effects.

About the measurement system, Viswanathan points out several recommendations to better noise measurements: 1) choosing the microphones and the instrumentation system properly; 2) orientating the microphones at normal incidence and without the grid caps; 3) minimize reflections with good design of microphone mounting; 4) adequate dynamic response; 5) ensuring that the microphones are at the geometric and acoustic far field of the sources but not too much farther; 6) avoiding microphones too close to reflecting surfaces; 7) understanding clearly the limitations of the measurement system;

The size of the rig was dictated by considerations of the size of the wind-tunnel, wind-tunnel blockage effects and others, had to be compact and provided certain flow requirements. For airplane certification the frequency range of interest for the engine is from 50 to 10000 Hz. To measure 80 KHz give an eight scale model, and it is desire to avoid smaller nozzles with extrapolated or created data (mainly the nozzle has a complex geometry). The quality of noise data is linked to the nozzle size and the jet reservoir conditions. The requirement for a compact rig indeed imposes restrictions that must be comprehended and heeded. It is important to understand the test requirements, the cycle points, rig constraints, etc., in choosing the proper size of the nozzle to avoid measuring contaminated data.

Other point is the reflections from surfaces. It is clearly view that the microphone sting mounting system, exposed poles, exhaust collector, supports, and so on could produce reflections and these frequencies are geometry dependent. It is recognized that the microphone string, for example, would be impossible to eliminate completely any reflection. The goal is to minimize this effect through proper techniques.

About the refurbishment, to improve the rig and avoid some problems, modifications were performed. A new and upgraded data acquisition system with Hewlett-Packard E1433B analyzers was installed. Redesign and elimination of a few 90-deg bends in the supply pipe, installation of a screen upstream of the burner, installation of choke plates downstream of the burner, redesign of the fuel pump and the fuel nozzle, and many others. It is important to realize that the data quality from jet noise measurements require a continuous improvement work.

This rig was used by HSR program and test results or the capabilities were not published in the open literature (Viswanathan, 2003). A little more recent work can show the capabilities of this rig. Mengle et al. (2006) studied the interaction of propulsion and aeroacoustic with chevron nozzle and the particular parts of an airplane, like a wing, flap, flaperon and fuselage.



Figure 3.9 – View of the installed nozzle set-up at LSAF (Mengle et al, 2006).

Viswanathan confirms that issues of data quality cannot be consider isolated, once the flow quality and the aerodynamic performance of the nozzle also has to be kept in mind. It is important to take into account to justify the measure of both the noise and performance simultaneously, eliminating the variability and uncertainties between different tests. Other point is that the sources of noise are myriad, so strategies to reducing rig noise are not very obvious, once noise comes from valves, pumps, combustors, interaction between flow and steps, gaps, screw heads, flow noise due to high flow velocities, etc.

3.2.2.2 *Small Hot Jet Acoustic Rig (SHJAR)*

The SHJAR is located at the AeroAcoustic Propulsion Laboratory (AAPL), at NASA's John H. Glenn Research Center, was commissioned in 2001 to test jet noise reduction concepts and develop advanced measurement techniques. The AAPL is a 65 foot radius geodesic dome with its interior covered by sound absorbent wedges which remove sound reflections at all frequencies above 200Hz. Several rigs are located within and SHJAR's floor and surfaces are covered with fiberglass wedges.

This rig is a single-stream hot jet rig that can cover the range up to Mach number 2 and static temperatures ratios up to 2.8 (Bridges, 2005; 2006). A group of compressors are located in another building and provides 150-psi air and the maximum mass flow rate is 6 lbm/s. The combustor used is hydrogen and the maximum temperature is 1000 K. Two valves control the rate of airflow, providing fine control over the entire range conditions. The nozzle most testing has 51mm, but the compressor system supports larger nozzles with some limitation on cold setpoints at high Mach numbers. Before the nozzle exit, a screen

was added to ensure that the flow is smooth before the nozzle. This procedure created a drop pressure and this error was determined.



Figure 3.10 – Experimental configuration of SHJAR with microphone array (Brown and Bridges, 2006).

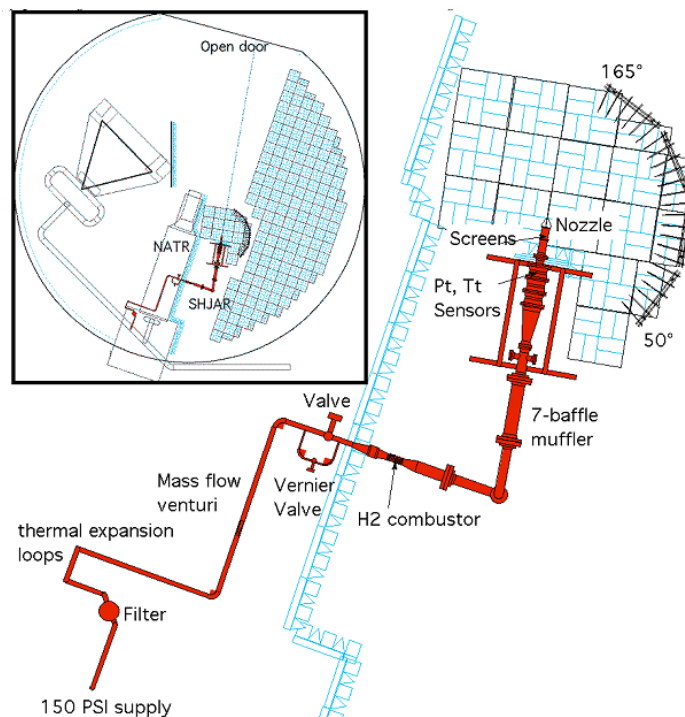


Figure 3.11 – Location of SHJAR in AAPL and demoting important rig equipments (Brown and Bridges, 2006).

Usually, measurements were performed using an array of 24 microphones on an arc at 5 degree intervals from 50 to 165 degrees. For 25 mm and 50 mm diameter nozzles the microphone array arc was made with a radius of 2.5 m, sufficiently in the geometric far field. For the 76 mm nozzle, the array was constituted on an arc 3.80 m. Bruel & Kjaer ¼" 3949 microphones were used. For the signal conditioning it has a Bruel & Kjaer Nexus amplifiers and, to record data, a DataMAX Instrumentation Recorder from RC Electronics Inc. is used for all microphones using a 90 kHz lowpass filter to limit the bandwidth at 200 kHz sample rate.

The rig has a PIV system to aerodynamic jet survey, and a hot-wire anemometer system is used for comparisons. Tests with two independent PIV systems were synchronized to provide time-delayed measurements of velocity fields with could be processed to produce the space-time correlations of interest to aeroacousticians. Each PIV consisted of a dual head Nd:YAG laser with a PCI frame digitizer.

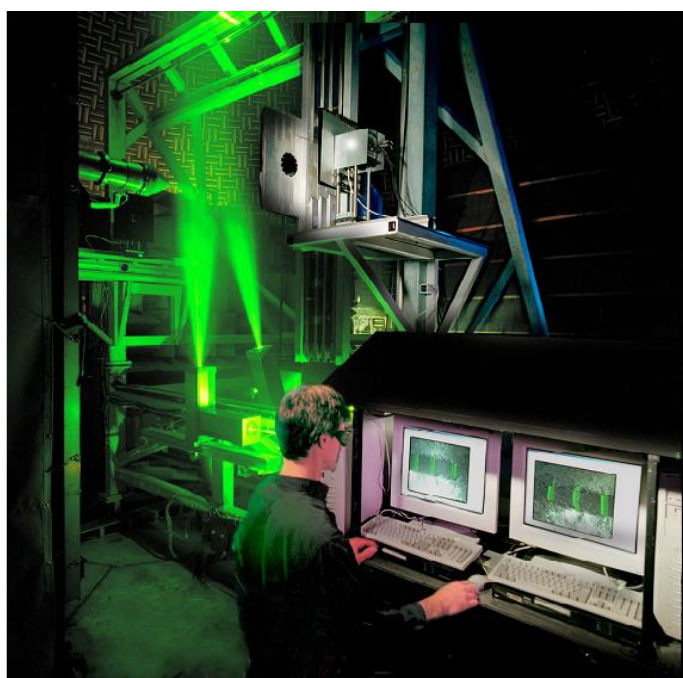


Figure 3.12 – Two-point space-time PIV system in operation (Bridges, 2006).

In comparisons with data from LSAF measurements previously mentioned and Tanna's work, the conclusion was that difference obtained is due to the details of the nozzle design.

3.2.2.3 Penn State Jet Noise Facility

Differently from the other two rigs mentioned, this Jet Noise Facility is located in a University and a representation is shown in the next figures.

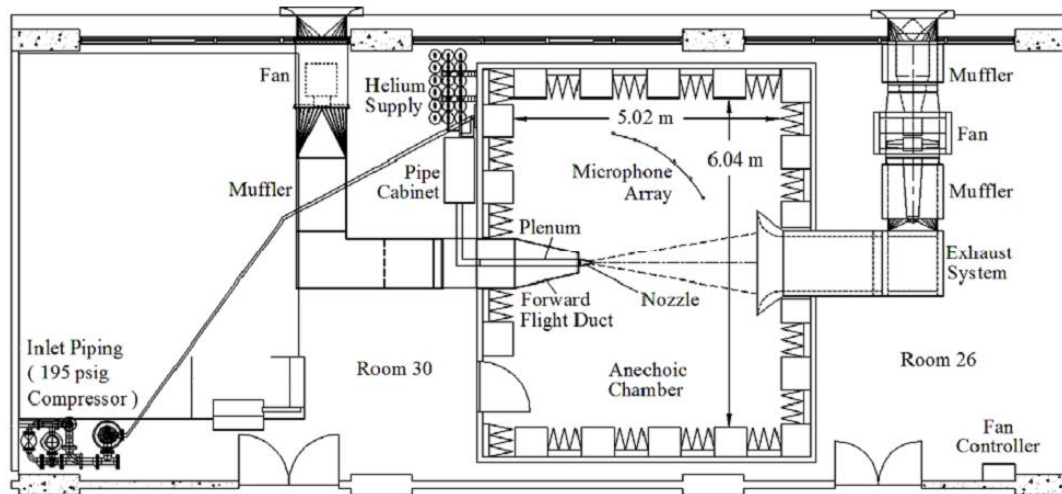


Figure 3.13 – The sketch of Penn State University jet noise facility (Kuo et al, 2009).

High pressure air is drawn from a tank by a CS-121 compressor combined with a KAD-370 air dryer both manufactured by Kaeser Compressors. It may produce 195 psi, regulated via pressure regulator and control valves. The pressure upstream of the nozzle is measured with a pitot tube connected to the transducer. In order to heat the air, a mixing with helium is provided. Hot air jets possess lower density and increased velocity, and it may be achieved by addition of helium. It needs a validation to compare heat simulated jets and heated jets.

The anechoic chamber is a 5.02 x 6.04 x 2.8 m room covered with fiberglass wedges and frequencies above 250 Hz are absorbed. The jet exhaust is collected by an exhaust fan installed downstream of the jet and prevents helium accumulation or pressure build up in the anechoic chamber.



Figure 3.14 – The Penn State University High Speed Jet Noise Facility, jet upstream and downstream direction, respectively (Kuo et al, 2009).

Kuo et al, 2009, shown a measurement performed using six microphones, from 30 to 80° equally spaced by 10°, hanging from a boom that extends from the plenum stand. The microphone array can freely rotate around a point located along the jet axis. The physical distance from each microphone to the nozzle exit is around 1.8 m.

The models used are Bruel & Kjaer 4138, 1/8" pressure-field microphones and GRAP 40DP. The microphone calibration is performed with a B & K acoustic calibrator model 4231. The analog time-domain signals from the microphones are routed through a Nexus, Bruel and Kjaer signal conditioner or a GRAS 12AN power module and then amplified and filtered. The time-domain is acquired by a PCI-6123 National Instruments DAQ board and stored in binary files. The sample rate is 300 kHz.

3.2.2.4 Anechoic Chamber at Delft University of Technology

The air flow supplied by a pressure vessel at 580-psi and the air supply system reduces the pressure by means of valve to 15–30-psi. Maximum safely attainable Mach number is about 0.33. The anechoic chamber's construction followed the Ahuja's procedure (Ahuja, 2003).

Briefly, it shows that the chamber should have some characteristics related to acoustical properties, far-field properties, aerodynamic properties, accessibility and adequate lighting in a way to allow quality and control data, besides an easy handling.

The space to build the chamber was limited. One of the consequences was the absence of wedges, leading to the choice of using only a layer of 71 mm-thick Soundac AC foam for acoustic insulation. The available interior size resulted is a 2.32 x 1.86 x 1.86 m room. The microphone arc radius is limited to 1 m. There is an exhaust opposite the nozzle with a diameter of 0.25 m rarely used due the background noise penalty resulting from an opening to the outside. Between the floor and the anechoic chamber there is a height of 0.5 m to avoid wall interference.

Lighting conditions is provided by a detachable PROmax 150 W small halogen construction light suspended to the ceiling, and during the measurements the light is removed to avoid acoustic radiation.



Figure 3.15 – Outside view of the anechoic chamber and inside view with nozzle and microphone (de Boer, 2011).

To air transport, pressure regulators and an acoustically treated muzzle tube was built. The pressure drop (580-psi to 30-psi) constitutes an additional noise source. A silencing construction was built to decrease this noise. The muzzle tube has an internal diameter of 120 mm, which has a 20 mm thick foam layer covering the walls, a permeable piece of sound-absorbing foam in the middle of the tube and a brass air diffuser where the flows enter. A honeycomb structure is located in the end of the tube to prevent swirl and three grids decrease the turbulence level.

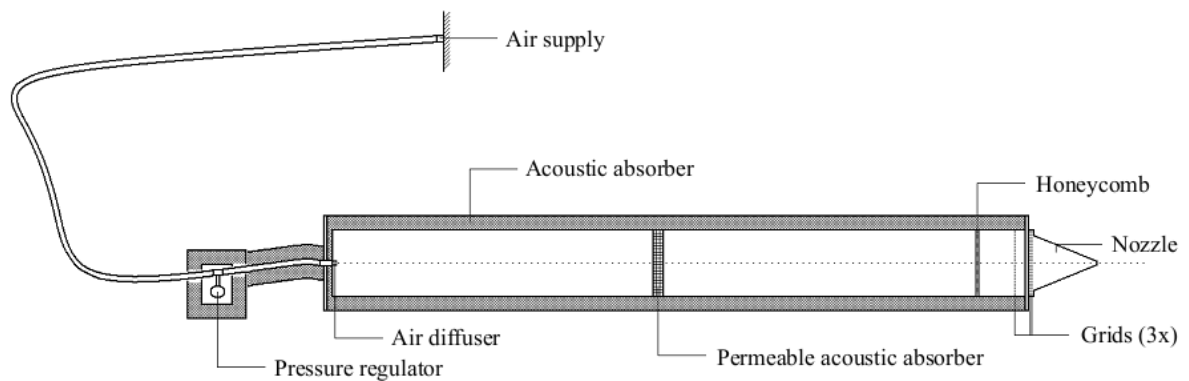


Figure 3.16 – Sketch of the air supply system (de Boer, 2011)

Interesting tests are carried out in this rig about the investigation on the acoustics of different nozzle types, including round nozzle, chevron nozzle and a two-tabbed nozzle. According to previous experiments the chevron and tabbed appendix decreases the noise (low frequencies) by increasing the mixing and disrupting the growth of large structures in the flow. The tabbed appendix also shift the noise spectrum to a higher frequencies.

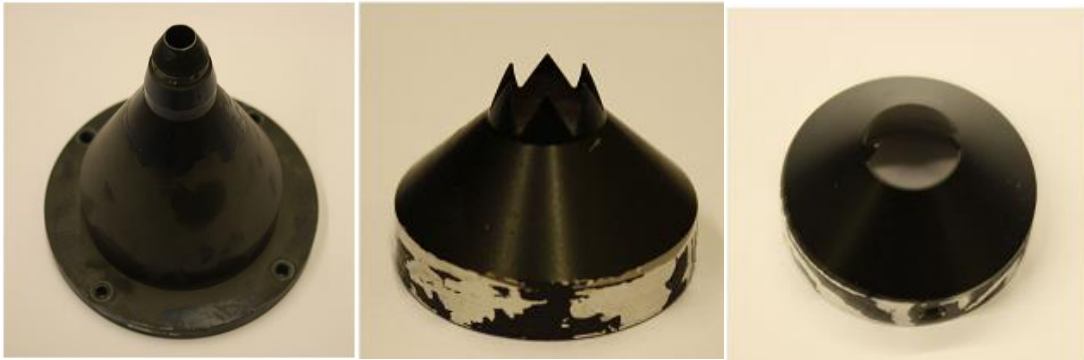


Figure 3.17: Round nozzle, chevron appendix and Tabbed appendix, respectively (de Boer, 2011).

The microphones used are the model CESVA MX-005 and Linearx M51. Both are condenser microphones and show a linear sensitivity relation between output voltage and pressure fluctuation. During the tests, the microphones were attached to a slide rail at both a 0.30 and 1 m radius at angles from 20° to 90° spacing by 10° . Other related equipment utilized are the filter Krohn-Hite Model 3940-11 and the data acquisition card by National Instruments PCI-6250.



Figure 3.18: Microphone measurements inside the anechoic chamber with $r = 1$ m and $\theta = 90^\circ$ (de Boer, 2011).

Two tests were performed aiming to determine the acoustical properties of anechoic chamber: an external noise absorption test and a measurement of the reverberation time, determining the transmission of environmental noise and the resonance / reflectivity of the anechoic chamber, respectively. Some results were compared with the semi-anechoic chamber built at the von Karman Institute built in a similar range.

CHAPTER IV

METHODOLOGY

The present work proposes a comprehensive study about the physics of a subsonic jet by aerodynamic and acoustic surveys aiming to better understand the mechanisms of production and propagation of noise in aircraft engines. In this chapter it is presented the methodology used to perform the aerodynamics and acoustic surveys. The present work is inserted in a cooperation program involving the Universidade Federal de Uberlândia, Brazil and the Institute of Sound and Vibration Research, located at University of Southampton, UK. While the previous sections were developed at the Fluid Mechanics Laboratory, UFU, the experiments were performed together with the Rolls Royce University Technology Centre in Gas Turbine Noise, part of the Fluid Dynamics and Acoustics Group at ISVR.

First of all, it is given a brief description of the Doak Laboratory, the Rolls Royce UTC facility located at ISVR, University of Southampton. Information about the flow control and the data acquisition system is presented in this section, as it is fundamental to explain some results. Secondly, the subsequent sections are related to both aerodynamic and acoustic equipment, where the measuring instruments are reported. It shows the pitot tube, anemometers and microphones configurations used in this work as well as the equipment necessary to calibrate, hold and move the sensors. Subsequently, it is given the experimental procedure applied. Lastly, the data post-processing is briefly described.

4.1 Doak Lab

The ISVR's Doak laboratory is a 15m x 7 x 5m anechoic chamber fully anechoic down to 400 Hz. The four walls, ceiling and the floor are covered with wedge type absorbent

material. A non-forced exhaust system is composed by a rectangular collector section allowing air to pass through into a small secondary acoustic chamber. It contains two silent cold jet rigs of 2" and 4" pipe diameter. The latter is located on the centerline of the chamber and it is used primarily for the investigation of full-scale bleed valves, having a in-line silencer. The 2" rig uses a labyrinth pot silencer and can be moved along the chamber. They are fed from two high pressure compressed air (20 bar) from two storage tanks and the range of velocity available for testing is Mach 0.2 to 1. Therefore, single jets measurements can be performed on flow regimes characteristic of civil aircraft. Both polar and a transversable azimuthal array of microphones can be used to give a complete three-dimensional sound field. The Fig. 4.1 shows a picture of the anechoic chamber when the 4" rig was being used to bleed valve investigation.



Figure 4.1 – Anechoic chamber at DOAK Laboratory during an transversable azimuthal array of microphones experiment.

There are some nozzle options and the one used in this work was a 38.1mm exit-diameter, convergent, conical nozzle used for most of the tests done at the Doak Laboratory. This nozzle was chosen because its aerodynamic and acoustic characteristics were well-documented in the Noise Test Facility (NTF) at QinetiQ, Farnborough, UK.

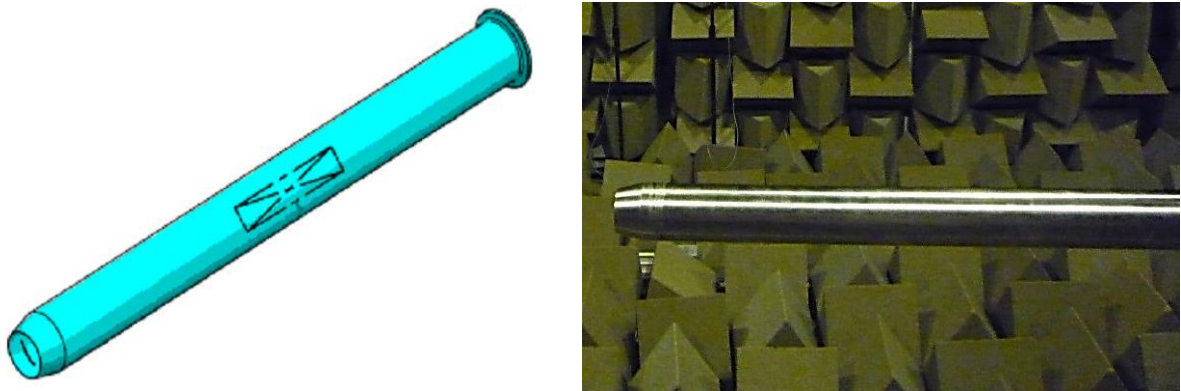


Figure 4.2 – Sketch and picture of 38 mm reference nozzle.

The present work was carried out with the 2" rig. The labyrinth silencer was placed in the middle of the chamber, just after the larger rig. The cold, subsonic jet was operated from the nozzle shown above. In order to run aerodynamics measurements a traverse system was placed inside the anechoic room. Details of these changes can be found in the next figure and compared to the Fig. 4.1.



Figure 4.3 – General view of Doak Laboratory with traverse system to hot-wire anemometer and pitot tube measurements.

4.1.1 Flow control and ambient condition measurements

In order to control the flow and to monitor the ambient conditions there is a room upstairs from the chamber equipped with the interface sensors, the data acquisition system, manual and electronic valve controls.

Although the air supply system can provide air at 20 bar pressure, it is held in relatively low pressure aiming safety and mainly energy saving. Thus, there is a manometer in the control room which provides instantly the pressure from the tank storages. This equipment was important to realize the flow behavior while running the jet for a long time. An acoustic measurement usually takes no more than 30 seconds of continuous measurement, whilst one aerodynamic mapping can last some hours running uninterruptedly. Therefore, the use of high pressure was indispensable during the mean velocity and turbulent intensities acquisition aiming a smaller flow variation. More information about the influence of the pressure upstream the rig is given in the Appendix III.

Before it enters in the anechoic chamber, the flow is controlled by some global valves. Firstly, there is a manual main valve which allows the air to both 2 and 4 inches rigs. The only functionality of this valve is to allow and block the air flux. Pictures of the main valve, the room control and the manometer described before are shown below.

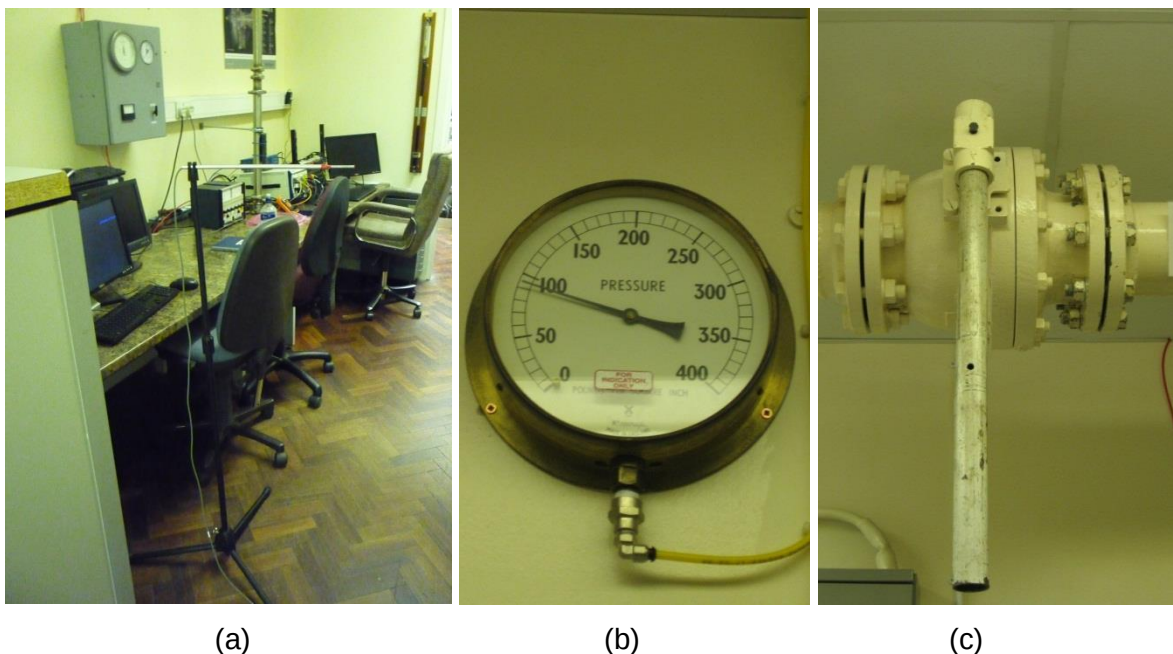


Figure 4.4 – (a) Overview of control room. (b) Manometer showing the pressure in the storage tanks. (c) The main supply valve.

After the main valve, there are specific control valves to each one of the 2" and 4" rigs. These devices have both coarse and fine adjustment. About the rig used, the flow is

regulated by two Emerson Whisper control valves that are controlled manually by a voltage and current analog system. In order to allow the exact mass flow rate cross the valve, a pressure transducer on the silencer gives the pressure just upstream the exit nozzle in terms of voltage. This voltage is read instantly by a multimeter and it is compared to the voltage obtained by the transducer calibration curve and compressible flow equations (quickly calculated using the control flow Matlab scripts). The operator has to open or close the control valve using the fine control until reach the desire pressure (or Mach number) to that measure. In addition, this rig can also be turned off at any time by a button from a manual safety valve.



(a)



(b)



(c)

Figure 4.5 - (a) One of the control valves to the 2" rig. (b) Valves precision power supply. (c) Box containing the safety bottom.

Beyond the pressure upstream the nozzle, other properties are also monitored, as the temperature and the mass flow rate. For this, a thermometer is placed into the pipe inside the control room, as well as a Venturi meter. The temperature is read by an interface showed in the next figure. The Venturi tube was not ready to be used during the first measurements, however, this had no negative impact on this work.

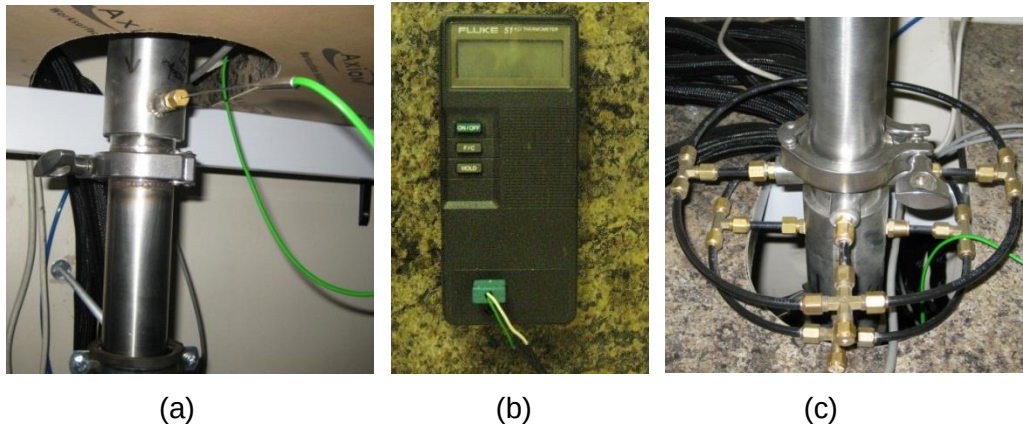


Figure 4.6 - (a) Thermometer used to estimate the jet temperature. (b) The thermometer interface. (c) Venture tube.

Lastly, it is extremely important to know the ambient conditions to calculate the exact flow regime during the measurements. The ambient pressure is recorded by a sensor inside the anechoic room. Chamber temperature and relative humidity are recorded using the standard data acquisition system (which will be described in the next sub-section) through the sensor showed below.

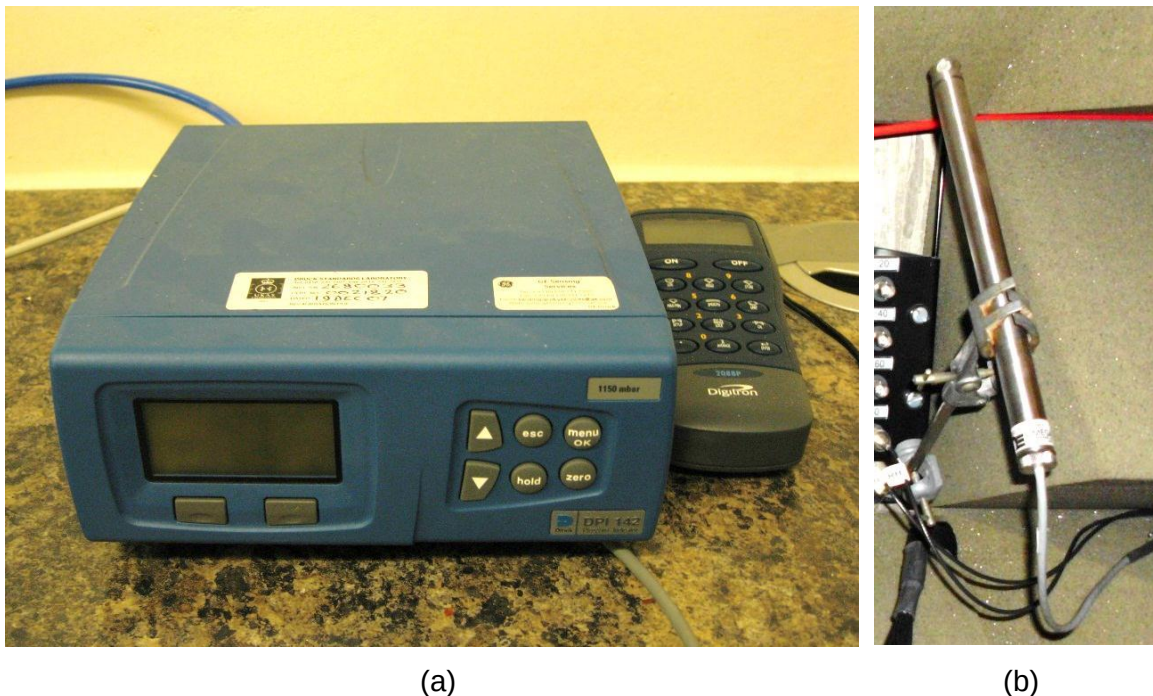


Figure 4.7 - (a) Interface showing the ambient pressure (DRUCK DPI 142/150 Pressure Indicator). (b) Sensor for the temperature and the relative humidity inside the chamber.

4.1.2 Data acquisition system

The main data acquisition system to control the flow and aerodynamic measurements with transducer sensors is a National Instruments board, series NI-PXIe-1042, which can acquire 32 channels of data simultaneously at a maximum rate of 100,000 samples/s/channel. This data acquisition system was used to control the mean flow properties, acquire data to the study of the mean flow variation over time, and the pitot tube measurements. The mean properties do not require a high sample frequency, thus, to these measurements, a frequency of 1 kHz per point measured was chosen.

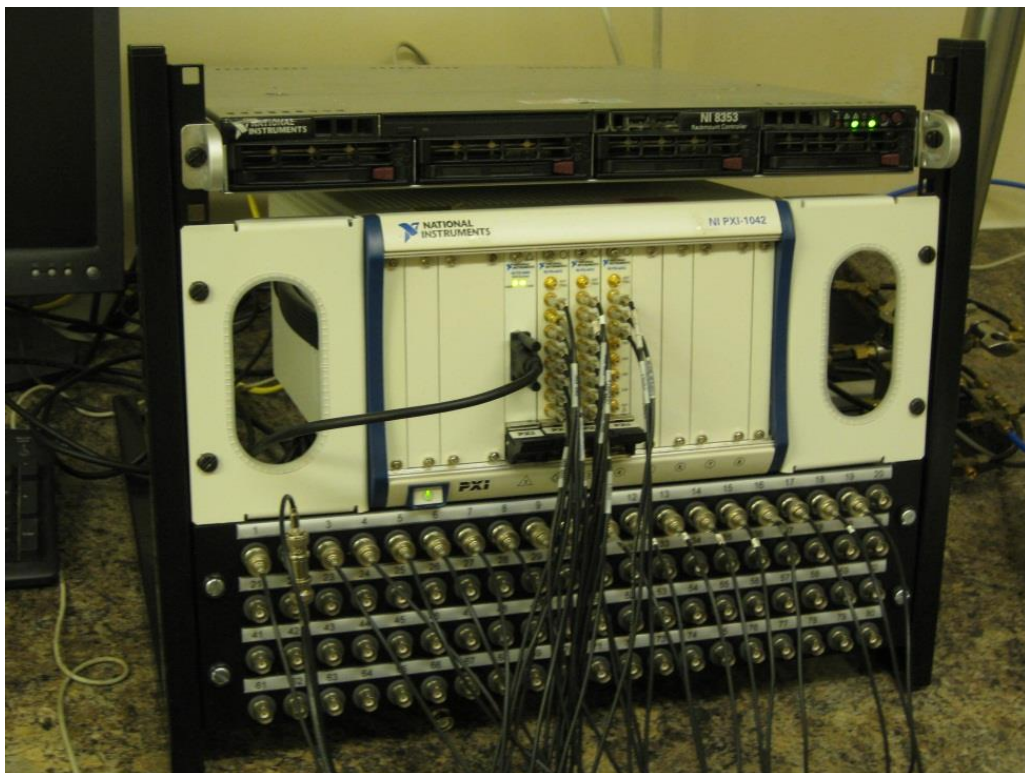


Figure 4.8 - National Instruments data acquisition board, series NI-PXIe-1042

The NI-PXIe-1042 was replaced by the NI-PXIe-1062q before the acoustic measurements. One of the greatest improvements is about the noise produced, significantly lower in the new system (about 43dBA). This chassis has 8-slot PXI Express backplane and up to 1 GB/s per slot. In the acoustic measurements data were acquired using one slot with 16 channels where only 6 were used with sample frequency of 200 kHz/s.

For both chassis, a hub is used to connect the instruments and equipment that are inside the chamber to the data acquisition system in the control room.

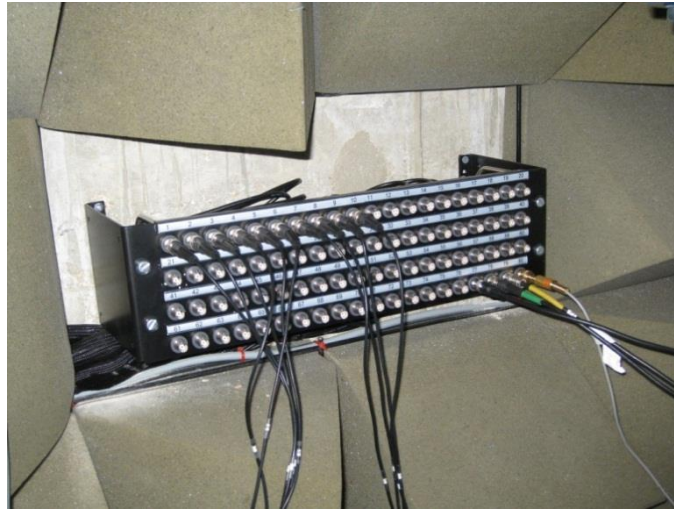


Figure 4.9 – The hub inside the chamber used to connect equipment and sensors to the data acquisition board in the control room

Lastly, the anemometer measurements use the Constant Temperature Anemometer System IFA 300. It has 3 channels for simultaneously data acquisition, although some issues happened and it is reported in the Appendix III. Each channel of anemometry contains a single bridge circuit and signal conditioner. The Constant Temperature Anemometer System IFA 300 is connected with computer via a serial interface to interactions with Thermal Pro software and sends data using an A/D board which convert the analogic into digital signal. Its maximum sampling frequency is 260kHz/channel. Offset and 40 gain values can be applied to improve the quality of data acquired.

Next figure shows the configuration used during the anemometer measurements: the IFA system, ISEL traverse system control, A/D converter, computer and an oscilloscope.



Figure 4.10 - Acquisitions systems: National Instruments and IFA, respectively.

4.2 Aerodynamic equipment

The measurements of the mean flow velocity profiles were performed using a pitot tube, while the hot-wire anemometer is used for mean flow (to compare with pitot tube) and turbulence intensity measurements.

4.2.1 Pitot Tube

The pitot tube is used to measure mean flow velocity profiles and the spreading of the jet. Furthermore, it was used as a reference velocity measurement to calibrate the hot-wire sensors. Two different transducer systems, coupled to the pitot tube, were used in these experiments: a micro-manometer for pitot tube, allowing velocities up to 180m/s and a Druck PDCR 820 transducer. Both data is digitalized using the National Instruments data acquisition board described previously.

Table 4.1 – Pressure and temperature channel allocation

Transducer designation	NI acquisition channel	Transducer Type
Transducer (Silencer)	2	Druck – 1 bar
Temp. chamber	3	1mV/C
Relative Humidity %	4	1mV/%
Transducer (Pitot)	5	Druck – 1 bar
Micromanometer pitot	6	Intern

For mean velocity survey using pitot tube, the data for each test point was acquired for 10 seconds. Different types of connectors as well as different pitot tubes were used during the measurements, to ensure consistency of the data. Next figure shows the two pitot tube used after the tests described at Appendix III. The pitot combined to the micro-manometer system is in the top, while the pitot connected to the Druck transducer is below. Theses system are shown in sequence.



Figure 4.11 - Pitot tube of the micromanometer (above) and pitot tube built during the experiments (below).



(a)



(b)

Figure 4.12 – (a) Micromanometer system. (b) Druck PDR800 series transducer

4.2.2 Hot-wire anemometer

Hot-wire anemometry is the main measuring system applied in this work. Single hot-wire anemometers are the most common sensors applied in flow measurements, for several

reasons: reduced size, relatively low price, high frequency response, simple to use. One of the limitations is that it has to be used for low turbulence intensities (up to 10%).

Table 4.2 – Pressure and temperature channel allocation.

Transducer designation	NI acquisition channel	IFA acquisition channel	Transducer type
Transducer (Silencer)	2	-	Druck – 1 bar
Tchamber	3	-	1mV/C
Relative Humidity %	4	-	1mV/%
Hot-wire probe	-	2	-
Temperature probe	-	A	-

Various sensors had been used in this work. Each probe has its specification for resistance and operation resistance given by the manufacturer. All of them were tungsten platinum coated wire type with a diameter of $3.8\ \mu\text{m}$. Unsuccessful measurements were done with a platinum triple hot-film sensor with $25.4\ \mu\text{m}$.

As a fluid flow passes over the heated sensor, the amplifier adjusts the voltage to the top of the bridge in order to keep it in balance. This voltage can then be related to the velocity of the flow. The bridge voltage is sensitive to temperature as well as velocity and so there is a need to attach a thermocouple circuit to the hot-wire sensor, enabling the measurement of the jet temperature. This read temperature can then be used by the software to correct the results to minimize the effect of the temperature of the jet. Next figure shows one of the single hot-wire anemometer used and the configuration with the temperature probe.

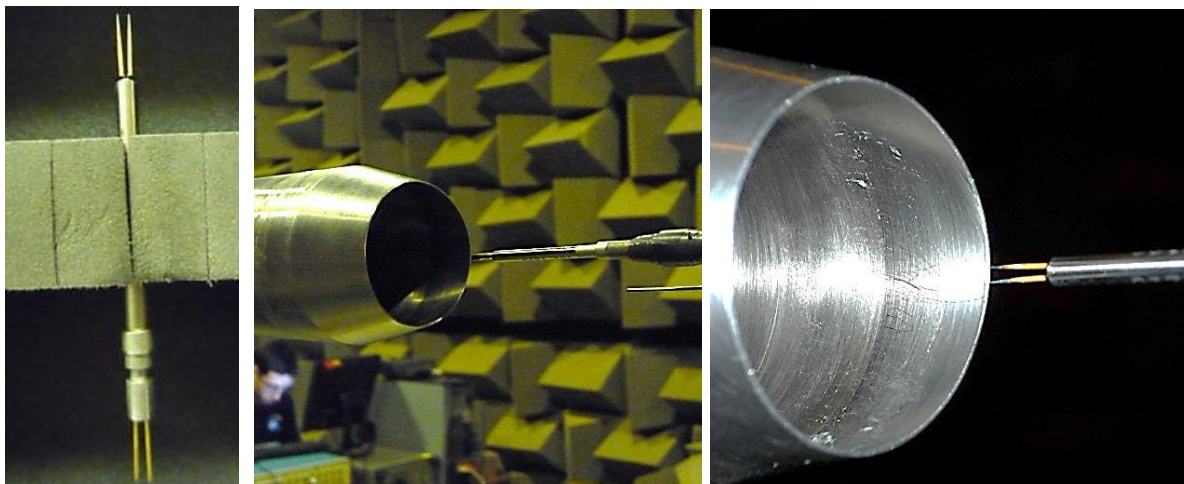


Figure 4.13 - Single hot-wire sensor.

4.2.3 Traverse system

A traverse system was used to move probes and sensors. This system, an ISEL traverse controller, allow 3 axis movement (updated during these experiments). It can be moved manually by a remote control or automatically and its accuracy is about 0.5mm. This device is compatible with the standard software Thermal Pro and connected with computer via serial interface, allowing movement by coordinates or by a matrix of many positions, which is useful for mapping measurements.

Major issues were faced throughout the project, resulting in a delay in the test matrix. The problems due to the traverse and the hot-wire anemometer system are explained in the Appendix III.



Figure 4.14: Traverse system ISEL 3 axis.

4.2.4 Sensors calibration

The pressure sensors are calibrated using a Druck Type DPI 610 pressure calibrator and a precision transducer power supply. This procedure was carried out at the start of each test campaign (Mach 0.25, 0.50 and 0.75), albeit the Druck PDR800 are substantially stable and have a good linearity (.04% of full-scale).

Firstly, it is determined the pressure range of the transducer will be operating. The maximum pressure desire is pumped to the calibrator and the associated voltage appear on the interface. The voltage and pressure values are recorded and the operator deflates slightly the calibrator, repeating the process until reach a relative pressure close to 0. The linear equation is obtained by these points.

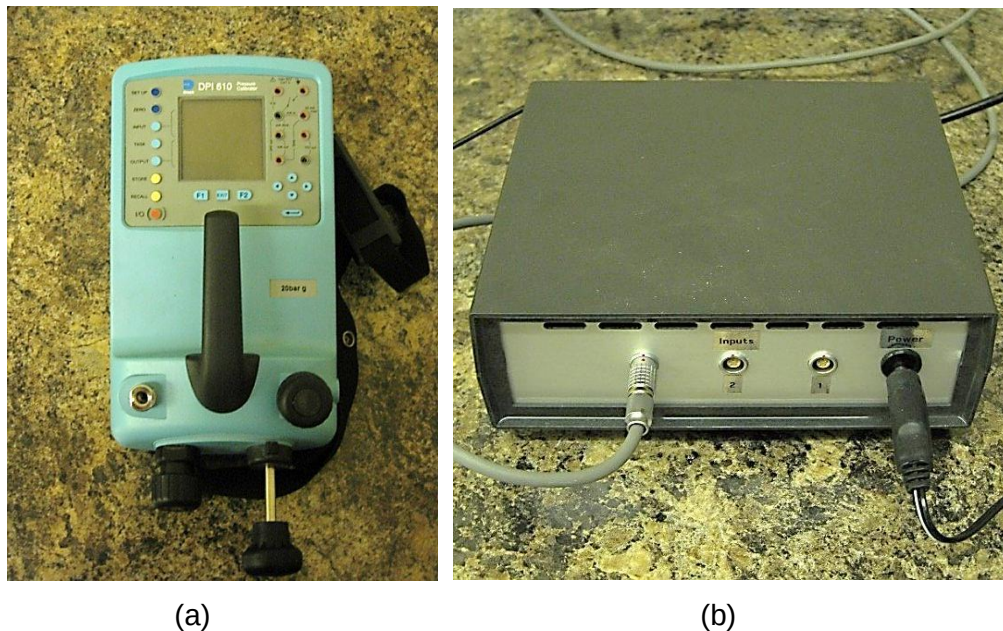


Figure 4.15 - (a) Druck Type DPI 610 pressure calibrator. (b) Calibrator power supply.

The hot-wire anemometer calibration was performed using data from the transducer on silencer. The software Thermal Pro allows this calibration by running the flow at different known velocities and acquiring the voltage from the bridge when the hot-wire sensor is into the potential core. The minimum and maximum velocity are required and it is important to the final curve calibration accuracy. Thereby, as the pitot measurements, the hot-wire probe calibration was also made before each campaign.

The two main screens of the software used to this calibration are shown below. Firstly, the screen where the velocities values are entered and secondly the final calibration curve generated by a fourth order polynomial.

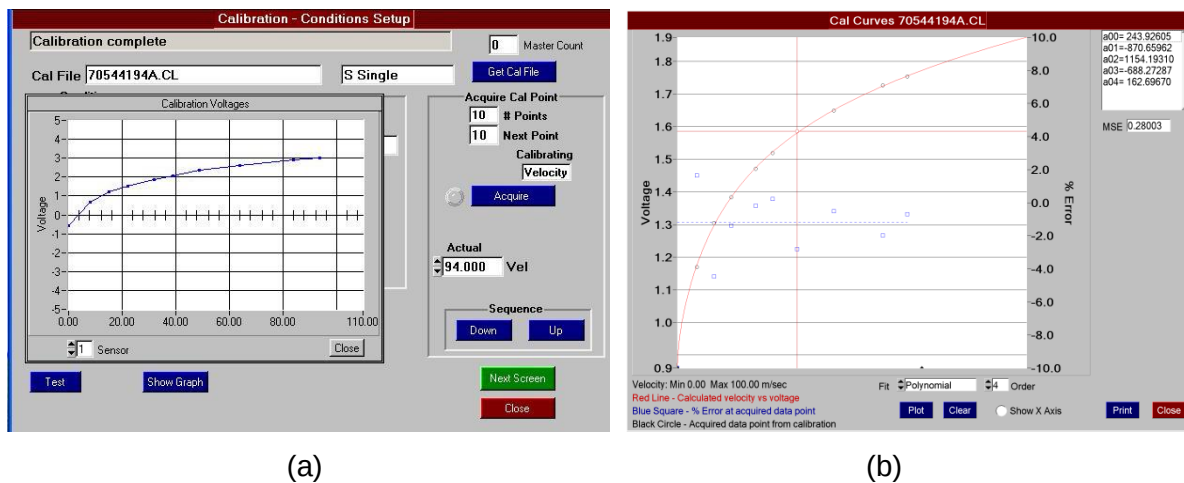


Figure 4.16 – (a) Points acquired during a hot-wire calibration. (b) Calibration curve by a fourth order polynomial.

4.3 Acoustic equipment

This section shows the equipment used to perform the acoustic measurements. It is mainly composed by microphones, preamplifiers and amplifiers. Far-field noise measurements were acquired using polar microphones covering 6 angles as shown in the Tab. 4.3.

Table 4.3 – Far-field microphone allocation

Microphone number	NI acquisition channel	Microphone polar angle θ	Microphone type
1	3	40°	1/4 " GRAS 40BF
2	4	50°	1/4 " GRAS 40BF
3	5	60°	1/4 " GRAS 40BF
4	6	75°	1/4 " GRAS 40BF
5	7	90°	1/4 " GRAS 40BF
6	8	110°	1/4 " GRAS 40BF

4.3.1 Microphones

Acoustic measurements were done with 1/4" GRAS Type 40BF microphones with a frequency range of 10 Hz to 100 kHz and dynamic range of 40 dB to 174 dB (reference 20 μ Pa). This is a precision condenser microphone for general purpose measurements in open acoustic fields and it is externally polarized. As a free-field microphone, it is for measuring

the sound pressure which existed before it was placed in the sound field pointing towards the sound source, and its disturbing effects are negligible for most application frequencies due the small dimensions. The normal sensitivity of the microphones used is 4 mV/Pa and it was checked before each experiment day.

The Fig. 4.17 shows the microphone with the grid protection and also it mounted in a preamplifier and a stand.

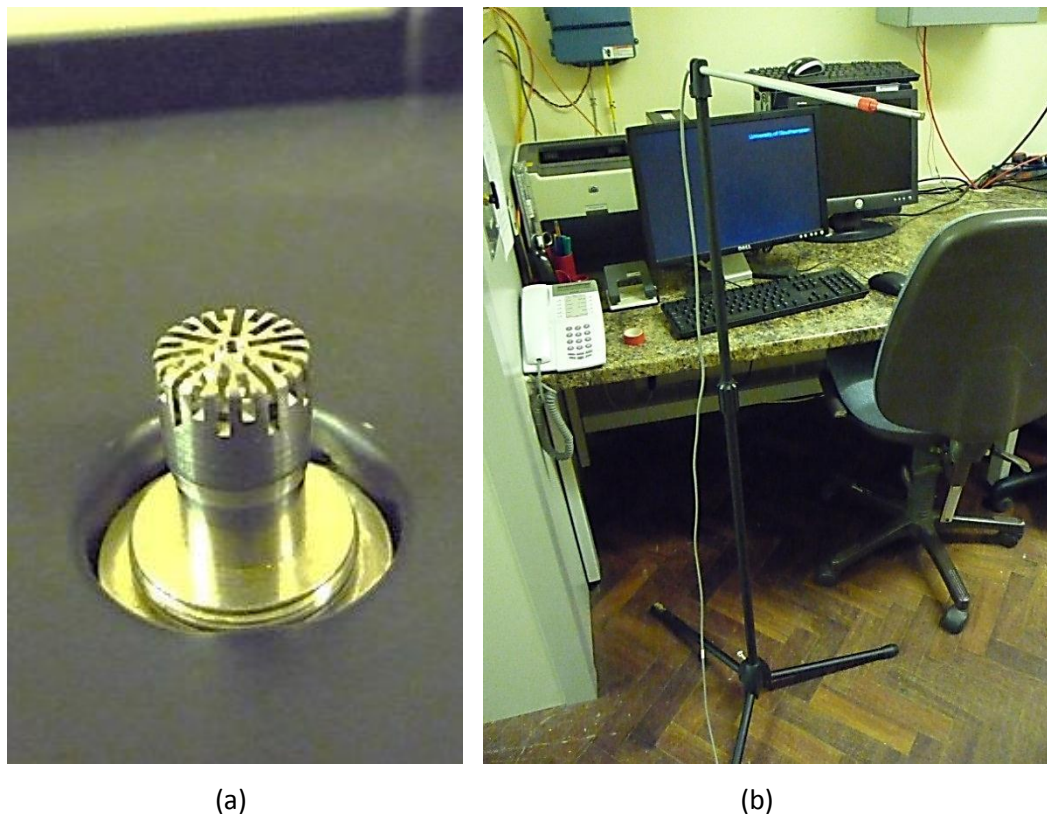


Figure 4.17 – (a) ¼ “ GRAS 40BF microphone. (b) Stand and preamplifier used.

4.3.2 Preamplifiers

The preamplifiers applied to this work are the B&K Falcon Range ¼” Type 2670, with full electromagnetic compatibility (EMC). It has low output impedance and high output current, allowing its use with long extension cables without loss of signal quality. The Falcon preamplifier is supplied with a 2 m fixed cable terminated with a LEMO connector for input at the instrument end.

The use of GRAS microphones and B&K pre-amplifiers is recommended as they have an excellent dynamic range and frequency response. Furthermore they are extremely stable with a linear response.



Figure 4.18 – Preamplifier Falcon Range 2670.

4.3.3 Amplifiers

The microphones were powered by NEXUS conditioning amplifier units with their HP filters set at 20Hz. These amplifiers were developed in association with car manufacturers and they are indicated to condenser microphones and sound intensity probes, among other applications. The configuration used has 4 channels, thus two amplifiers were needed. Wide range of filters and gains can be set up for specific tasks. To the present work, the standard configuration has fitted well.



Figure 4.19 – The amplifiers NEXUS used during this work.

4.4.4 Calibration procedure

Microphones were calibrated using a B&K Type 4220 pistonphone calibrator. This procedure was carried out at the start of each day test.

First of all, the microphone capsule is screw to the preamplifier and connected to power supply, in this case, to the NEXUS amplifier. The pistonphone calibrator is placed covering the microphone and it is turned on, producing a tone of approximately 124 dB at 250 Hz. Data is acquired to the acquisition system described previously and post-processed using Matlab scripts. It is checked if the signal is dominated by the 250 Hz tone and the sensitivity is compared to the datasheet from the last calibration performed.

The microphone protection grid was left attached when carrying out the calibration.



Figure 4.20 – (a) A pistonphone calibrator. (b) Configuration used during microphones calibration.

4.4 Experimental procedure

Initially, a test matrix was built with many possible measurements: mean velocity and turbulent intensity profiles, turbulent spectrum energy, radial length scales correlations, far-field and near-field surveys. Taking into account the time and equipment available, the final test matrix can be seen in tables 4.4 and 4.5.

The first table illustrates the aerodynamic experiments which were carried out. The columns represents the mean velocity profile (MVP) by pitot tube, the same using a single hot-wire anemometer, the turbulence intensity (TI) from a one-component hot-wire anemometer, turbulence intensity from a three-component hot-film and turbulent spectrum energy (TSE) also using a triple sensor hot-film, respectively. The Mach numbers are the same to each campaign, 0.25, 0.50 and 0.75.

Table 4.4 – Final matrix to aerodynamic measurements.

Mach number	MVP Pitot	MVP Hot-wire	TI 1 Comp.	TI 3 Comp.	TSE 3 Comp.
0.25	✓	✓	✓	✓	✓
0.50	✓	✓	✓	X	X
0.75	✓	✓	✓	X	X

The acoustic measurements were performed only in the far-field. Six different observer angles at nineteen Mach numbers were analyzed. Background acoustic measurements were taken during each session.

More information about the issues and changes in the initial test matrix are found in the Appendix.

Table 4.5 – Final matrix to acoustic measurements.

-	Angle θ (°)					
Mach	40	50	60	75	90	110
0.15	✓	✓	✓	✓	✓	✓
0.18	✓	✓	✓	✓	✓	✓
0.20	✓	✓	✓	✓	✓	✓
0.25	✓	✓	✓	✓	✓	✓
0.30	✓	✓	✓	✓	✓	✓
0.35	✓	✓	✓	✓	✓	✓
0.40	✓	✓	✓	✓	✓	✓
0.45	✓	✓	✓	✓	✓	✓
0.50	✓	✓	✓	✓	✓	✓
0.55	✓	✓	✓	✓	✓	✓
0.60	✓	✓	✓	✓	✓	✓
0.65	✓	✓	✓	✓	✓	✓
0.70	✓	✓	✓	✓	✓	✓
0.75	✓	✓	✓	✓	✓	✓
0.80	✓	✓	✓	✓	✓	✓
0.85	✓	✓	✓	✓	✓	✓
0.90	✓	✓	✓	✓	✓	✓
0.95	✓	✓	✓	✓	✓	✓
1.00	✓	✓	✓	✓	✓	✓

The Tab. 4.6 shows the acquisition time and the final frequency of each kind of measurement.

Table 4.6 – Acquisition time, number of samples and frequency used with each sensor.

	Pitot	Hot-wire	Hot-film	Acoustics
Acq. time (s)	10	20	50	10
Samples	10000	1000000	5000000	2000000
Frequency (kHz)	1	50	100	100

The velocity distributions were acquired along the jet axis to different radial positions and the workspace of mean velocity profile experiments is demonstrated in the Fig. 4.21. The nozzle centre is situated in “0”, the vertical axis ‘y’ represents radial variations in relation the radius of the nozzle (y/r) and ‘x’ is the jet axis normalized by x/D_j . The circles symbolize where the data were acquired. The dotted lines represent the estimated potential core and shear layer. Only for single hot-wire probes, just the points inside the shadow rectangle were acquired. Thus, for each Mach number analyzed, 963 points were recorded to pitot tube, whilst 583 to single hot-wire.

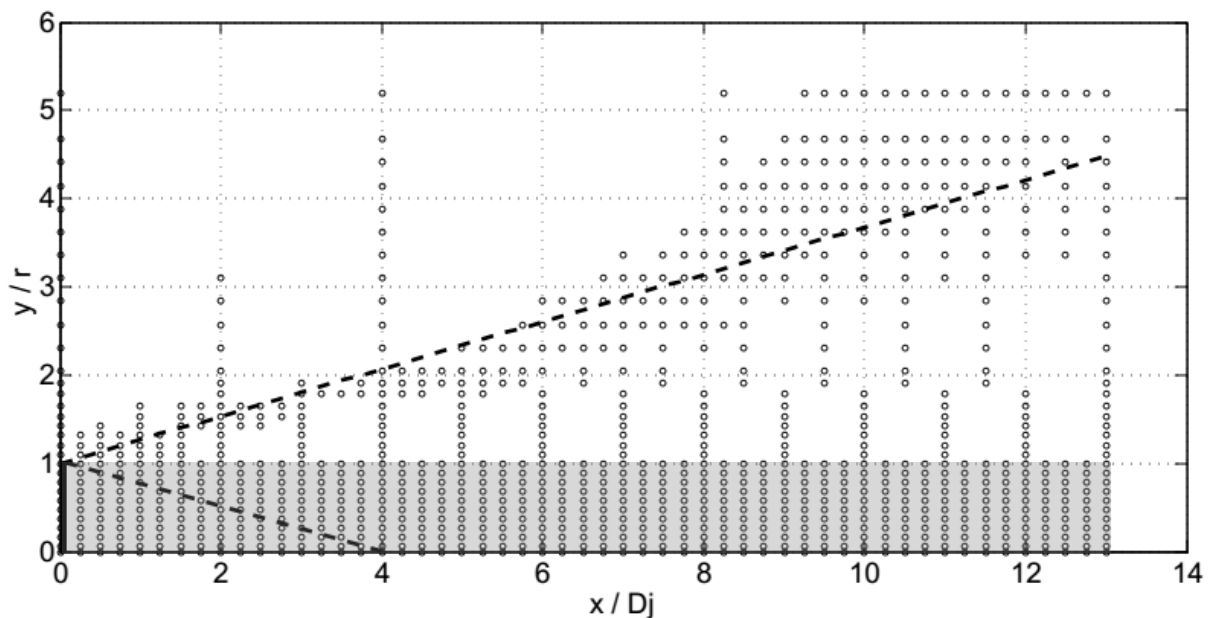


Figure 4.21 – Acquisition points along the region of the jet for aerodynamic measurements.

In order to acquire all the points to each velocity, a matrix of coordinates was used to move the traverse system automatically. Thus, after set values of velocity and sample frequency, the data were acquired continuously for many hours. The next figure shows a

sketch containing the path lines taken by the traverse to acquire the points shown in the Fig. 4.21. There are two different views: in front of the exit nozzle (left side) and the top view of the nozzle (right side). The first line acquired is the centreline (Cline), located in the middle of the nozzle. The acquiring data start at $x/D_j = 0$ and then the traverse moves downstream of the jet, until reach $x/D_j = 13$, the maximum position achieved. After acquire all 53 points within the centreline (from 0 to 13 D, with a 0.25 step), the traverse moves back to the origin and acquire the same points in the jet axis, but with a small offset in the radius position. That is called C1 line. There are nine intermediate lines between the centreline and the lipline. For pitot tube measurements, twenty lines beyond the lipline are also measured (S1 to S20).

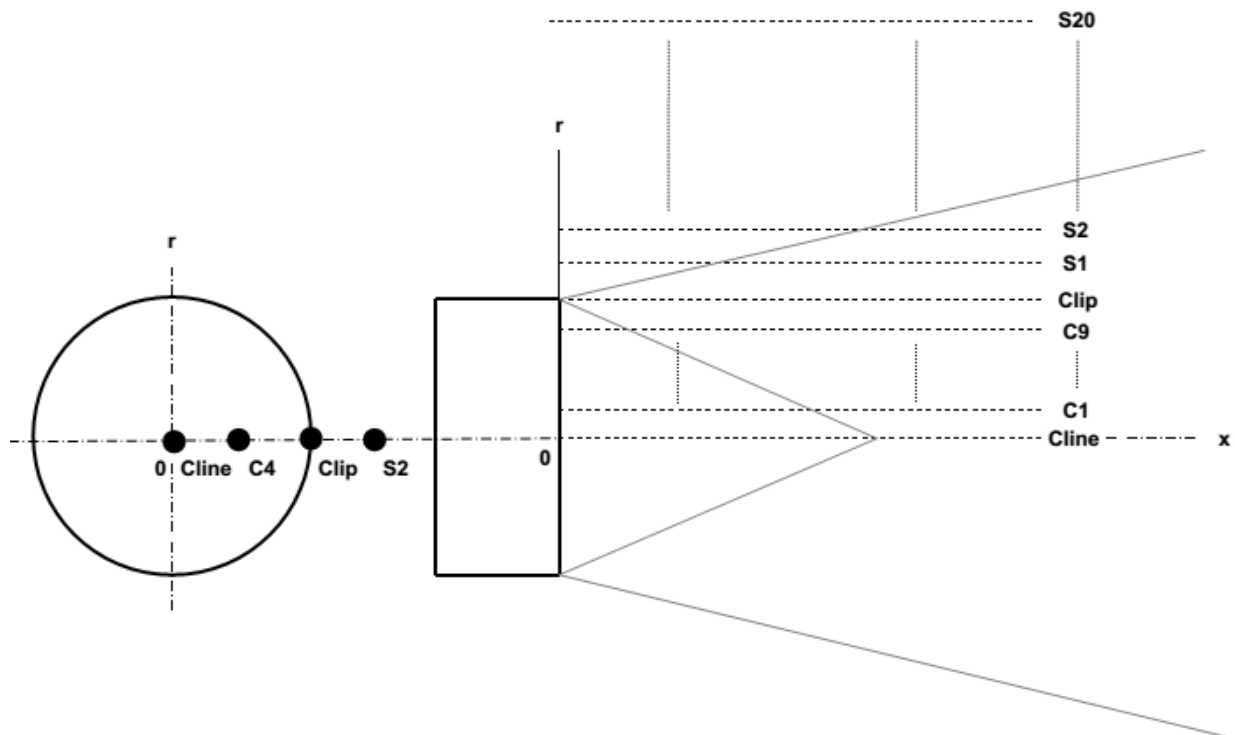


Figure 4.22 – Sketch of the measured lines.

The origins of the lines are shown in Tab. 4.7. The values are shown in millimeters. The $\frac{1}{4}$ " condenser microphones were mounted in the same plane as the jet axis. The stands were placed in a way that the microphones were disposed parallel to the jet axis, as showed in the Fig 4.23. All distances and angles were calculated by metric relations in triangles. The distances between the centre of the exit nozzle and the microphones are corrected to 1 meter. The microphones were orientated at 0° incidence, i.e. pointing to the centre of the nozzle.

Table 4.7 – Origin position (x,r) of the measuring lines (mm).

“C”		“S” (1 to 10)		“S” (11 to 20)	
Cline	(0,0)	S1	(0,20)	S11	(76.2,42.5)
C1	(0,1.05)	S2	(0,22)	S12	(76.2,45)
C2	(0,3.05)	S3	(0,24)	S13	(114.3,47.5)
C3	(0,5.05)	S4	(0,26)	S14	(114.3,50)
C4	(0,7.05)	S5	(38.1,28)	S15	(114.3,55)
C5	(0,9.05)	S6	(38.1,30)	S16	(114.3,60)
C6	(0,11.05)	S7	(38.1,32.5)	S17	(152.4,65)
C7	(0,13.05)	S8	(38.1,35)	S18	(152.4,70)
C8	(0,15.05)	S9	(76.2,37.5)	S19	(152.4,75)
C9	(0,17.05)	S10	(76.2,40)	S20	(152.4,80)
Clip	(0,19.05)				

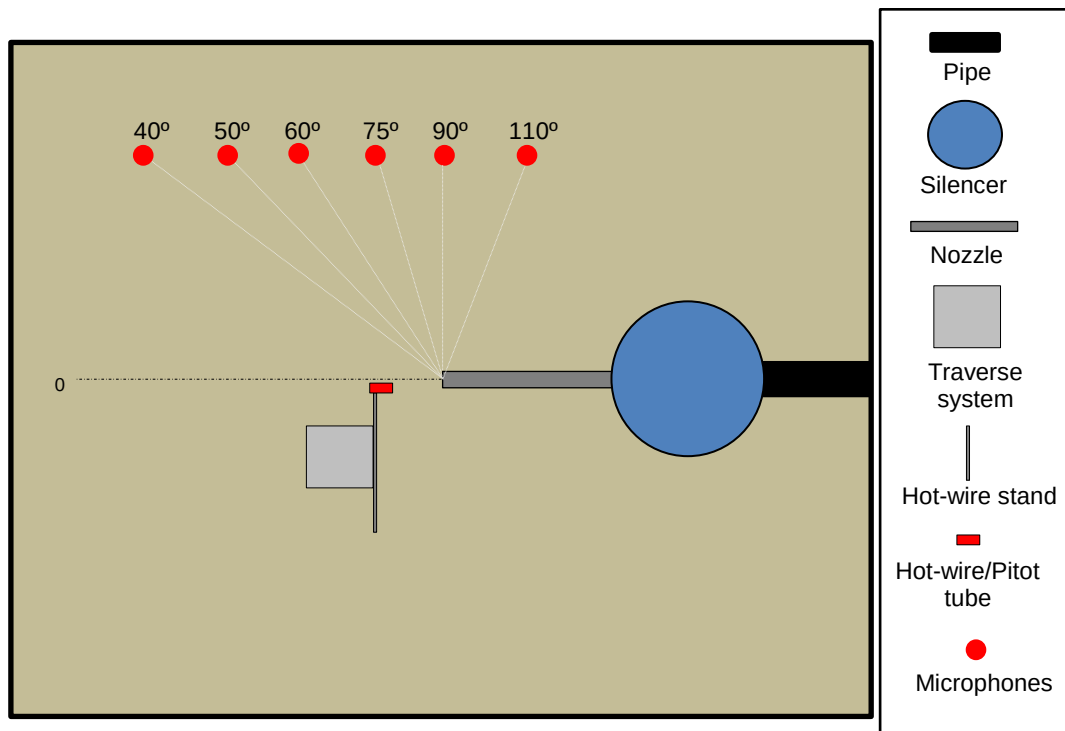


Figure 4.23 – Sketch showing the position of the microphones in each observer angle.

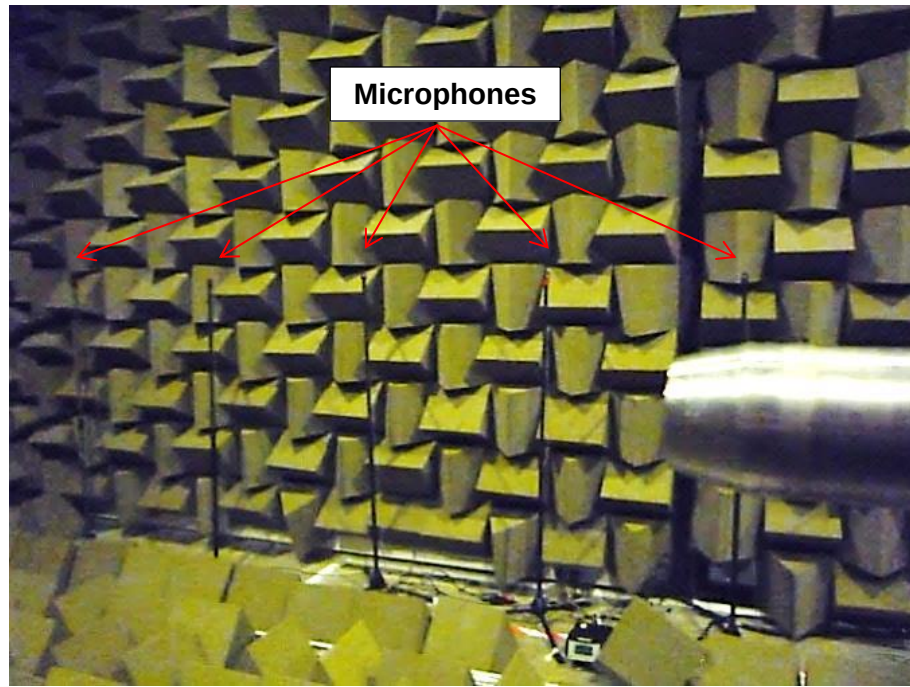


Figure 4.24 – Microphones position during the measurements.

4.5 Post-processing

The data acquired with both National Instruments and IFA acquisition systems were post-processed mainly by Matlab scripts and functions.

The pitot tube is used to map the region along the jet shown in the Fig. 4.21. As the jet is axisymmetric, the properties obtained by half diameter are mirrored to complete the velocity profiles and the contour plots. The raw data is a voltage signal and it is converted to the dynamic pressure (P_D) applying the linear equation obtained after the transducer calibration. According to Abramovich (2003), the static pressure in any region of the jet is equal the ambient pressure. Therefore, the total pressure is calculated by the equation:

$$P_T = P_D + P_{amb} \quad (4.1)$$

where the P_{amb} is acquired using the manometer inside the chamber.

The pressure ratio is calculated as follow:

$$PR = \frac{P_T}{P_{amb}} \quad (4.2)$$

Considering the isentropic condition, the temperature ratio is:

$$TR = PR^{\gamma-1/\gamma} \quad (4.3)$$

where γ is 1.4.

The final equation to obtain the Mach number is:

$$M = \sqrt{(TR - 1) / \left(\frac{\gamma - 1}{2}\right)} \quad (4.4)$$

The mean values to velocity in each point are now obtained by the arithmetic mean. As the flow is not constant along the measurements, the points must be corrected in order to plot and compare them. The procedure is detailed in Appendix II.

The post-processing of hot-wire anemometer data is substantially different from pitot tube measurements. The software used to acquire data is the Thermal Pro, which writes binary files containing the voltage signal. A Matlab script is used to convert this file and apply the calibration curve described previously, obtaining the velocity values. The mean velocity is obtained in the same process as the pitot data. The turbulence intensity for each point measured is obtained by the equation:

$$TI = \sqrt{\frac{u'}{U_0}} \quad (4.5)$$

where u' is the root mean square value of the velocity at one point and U_0 is the mean velocity value.

Finally, it is used the Welch's method (Welch, 1967) to estimate the power spectra, converting the signal from the time to the frequency domain. It calculates the periodogram by the Fourier transform, resulting in an array of power spectrum density by frequency.

The acoustic data is fully post-processed and analysed by Matlab scripts. The calibration is applied to the raw signal and the time domain data is then transformed to the frequency domain using a Fourier transform. The next step is to process all subsequent data through the narrowband spectra.

Beyond the narrowband, it is also achieved the Overall Sound Pressure Level for each Mach number and polar angle. It is obtained by numerically integrating the narrowband spectra with respect to frequency using a trapezium rule method across the entire range of narrowband frequencies.

CHAPTER V

EXPERIMENTAL RESULTS

The experimental results are shown in the present chapter. There are two main sections: the first one presenting the aerodynamic results and the second one with acoustic data analysis.

The aerodynamic section shows the results for mean and unsteady velocity, as well as an approach to the power spectrum density for a single jet under 0.25, 0.50 and 0.75 Mach conditions. It is shown the axial and radial velocity profiles for mean and unsteady flow.

The acoustics results are discussed in two ways: firstly, based in terms of different velocities to a fixed observer angle. Secondly, the opposite, the trend of the sound pressure level at different observer angles for a fixed velocity. Although the data acquired for this category of measurements were done for nineteen Mach numbers (0.15 to 1.00), the discussion is made for only four conditions, in order to simplify the graphs and consider the three aerodynamic measurements and Mach 1.00. Finally, a comparison and general discussion taking into account all measurements is presented.

5.1 Aerodynamics results

5.1.1 Mean velocity profiles

The mean velocity profile for a subsonic jet is well-established for many years. As stated before in Chapter 2, these profiles are discussed since the beginning of the twentieth century (Trüper, 1914; Förttmann, 1936; Abramovich, 1938).

This sub-section considers the mean velocity profiles acquired by the pitot tube and the single sensor hot-wire anemometer. The results are disposed in axial velocity profiles, radial velocity profiles and a jet characterization of the whole region measured.

5.1.1.1 Axial velocity profiles

The aerodynamic experiments were carried out originally to compose the axial profiles. Explanation about the disposal of lines during these measurements is found in Fig. 4.22 and Tab. 4.7. The next figures present the results for velocity distribution, comparing the lines measured in each Mach number analyzed. Since the trend inside the nozzle region (Cline to Clip) are similar and different from the trend out of this region (S1 to S20), the lines are grouped according with their trends, generating two graphs for each Mach number.

Figures 5.1 to 5.6 are extracted from pitot tube measurements. Firstly, Fig. 5.1 shows the normalized mean velocity from the centerline to lipline at Mach number 0.25, distributed along the jet axis domain, from 0 to 13 diameters. Each line is normalized independently, according to the formula:

$$\bar{U} = U_0 / U_{max} \quad (5.1)$$

where U_0 is the velocity measured in meters per second and U_{max} is the maximum velocity measured in meters per second along that line.

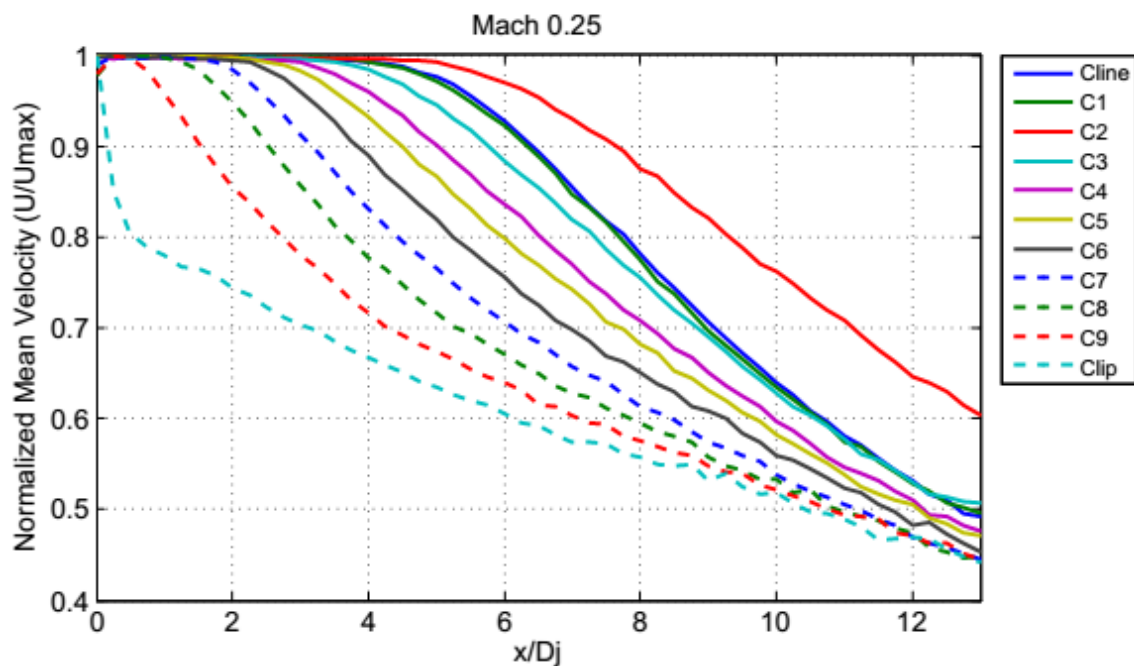


Figure 5.1 – Velocity distribution along the jet axis for different radial positions (Pitot tube, Mach 0.25).

The lines “Cline” and ”C1” represents the measurements along the axial line in radial positions 0 and 1.05 mm from the center of the nozzle. The velocity is expected to be maximum and unchangeable until 4 to 5 diameters from the exit nozzle along the centerline, since it is the potential core length (Abramovich, 1963). According to the Fig. 5.1, the potential core ends between 4 to 4.5 diameters downstream the jet axis.

The behavior of “C2” is unexpected. Since the potential core has a conical shape, the greater the distance from the centerline, the higher should be the velocity decay. It is observed from the other profiles, from “C3” to “Clip”. Although all measurements were corrected because the flow variation (Appendix II), the data from these two lines are very discrepant, since it occurred an instantaneous flow velocity increasing, probably related to the rise of pressure in the compressor for an unknown reason.

Keep moving in the radial position over the nozzle region (further the lipline), it can be seen a new trend in the axial profiles. Next figure shows this trend from “S1” to “S18”, again for Mach 0.25.

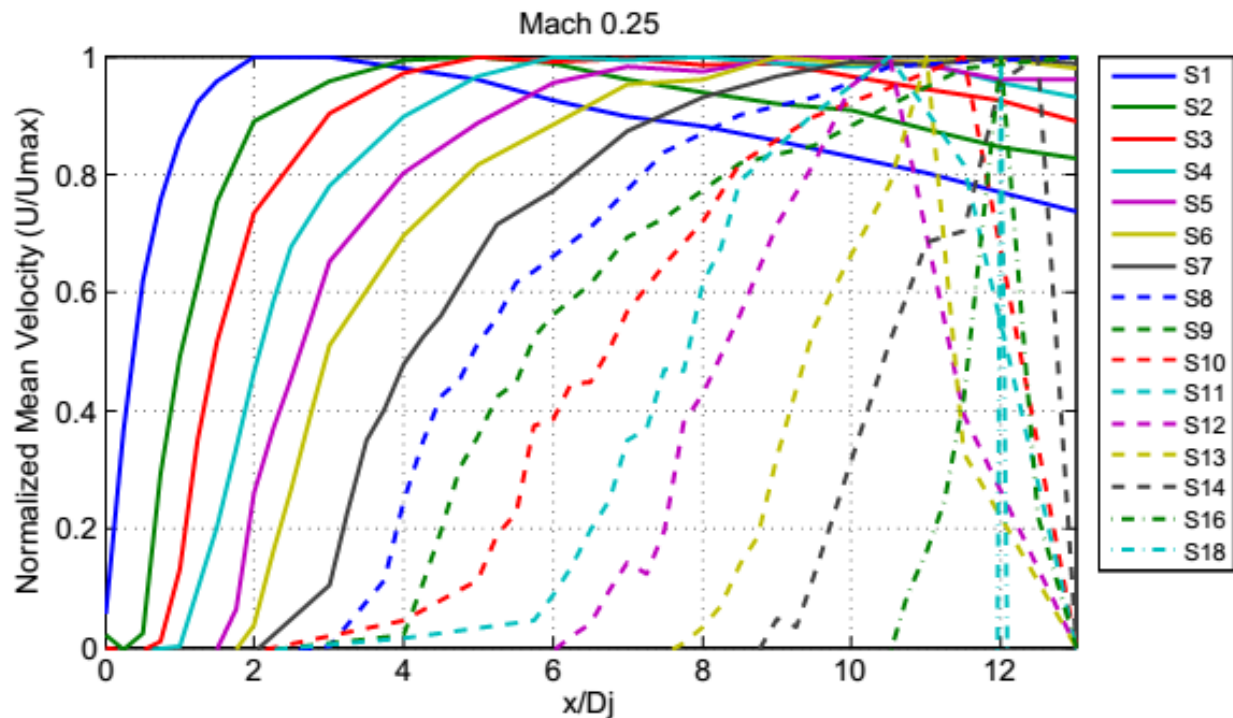


Figure 5.2 - Velocity distribution along the jet axis for different radial positions (Pitot tube, Mach 0.25)

The trend is clearly the expected. In the regions close to the nozzle, there is a sudden increase in the velocity as the sensor moves in the axial position. As the measurements get in lines far from the nozzle, the profile velocity is smaller and takes its maximum velocity at

higher axial distances. The trend shows clearly the shear layer between the jet and the stationary flow (ambient), located for each point where the velocity profile reaches the maximum value. The last results (especially after “S11”) the jet flow is practically all mixed with the ambient at certain point and the value of ‘u’ velocity component is close to zero.

Figures 5.3 and 5.4 show the same analysis as made before, but at Mach number 0.50. The profiles agree perfectly with what is expected for axial velocity profiles from a free jet. The potential core lasts in the same region, from 0 to between 4 and 4.5.

Finally, the same can be said to the Mach 0.75. Although the velocity is increasing in the conditions observed, the potential core length and the trend along the axial lines are very similar when it is analyzed in terms of normalized values.

Figures 5.4 and 5.6 also have shown a different trend in relation to the lines further from the centerline of the Fig. 5.2. Since the mean velocity in these cases is higher at all domain points, it takes longer distances to fully mix with the ambient fluid or to the pitot tube lose its accuracy (what can happen at low fluctuating flows).

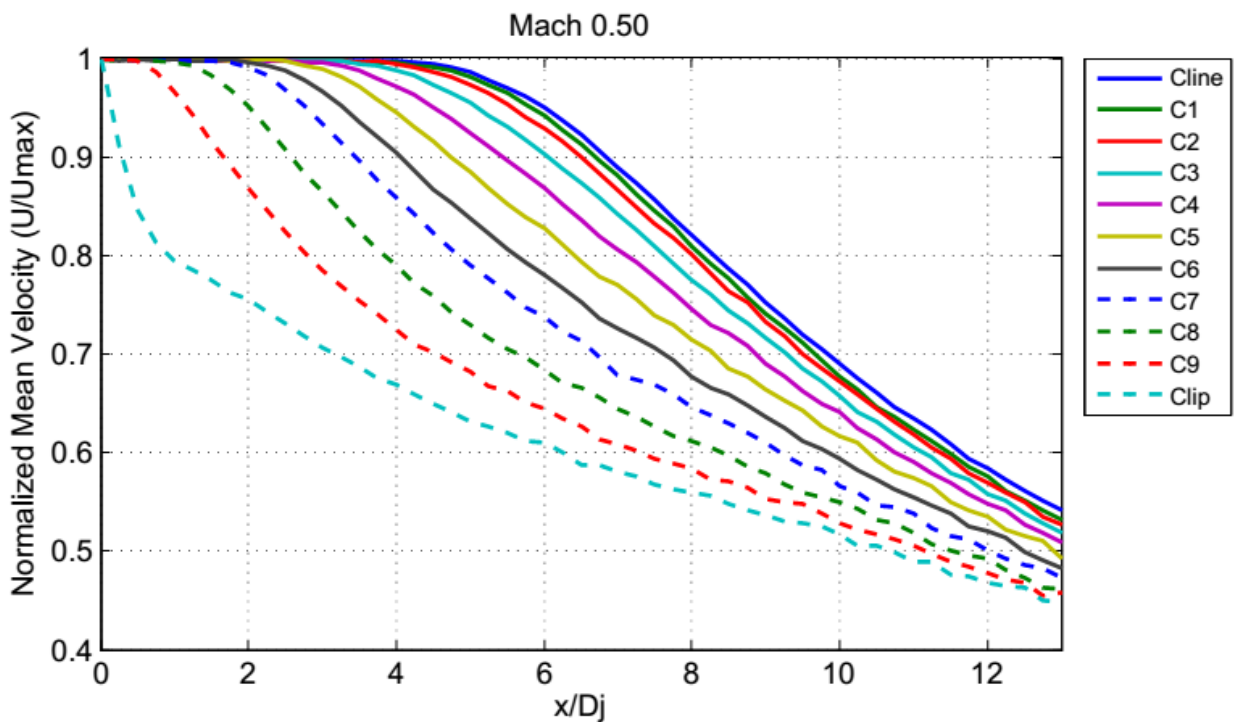


Figure 5.3 - Velocity distribution along the jet axis for different radial positions (Pitot tube, Mach 0.50)

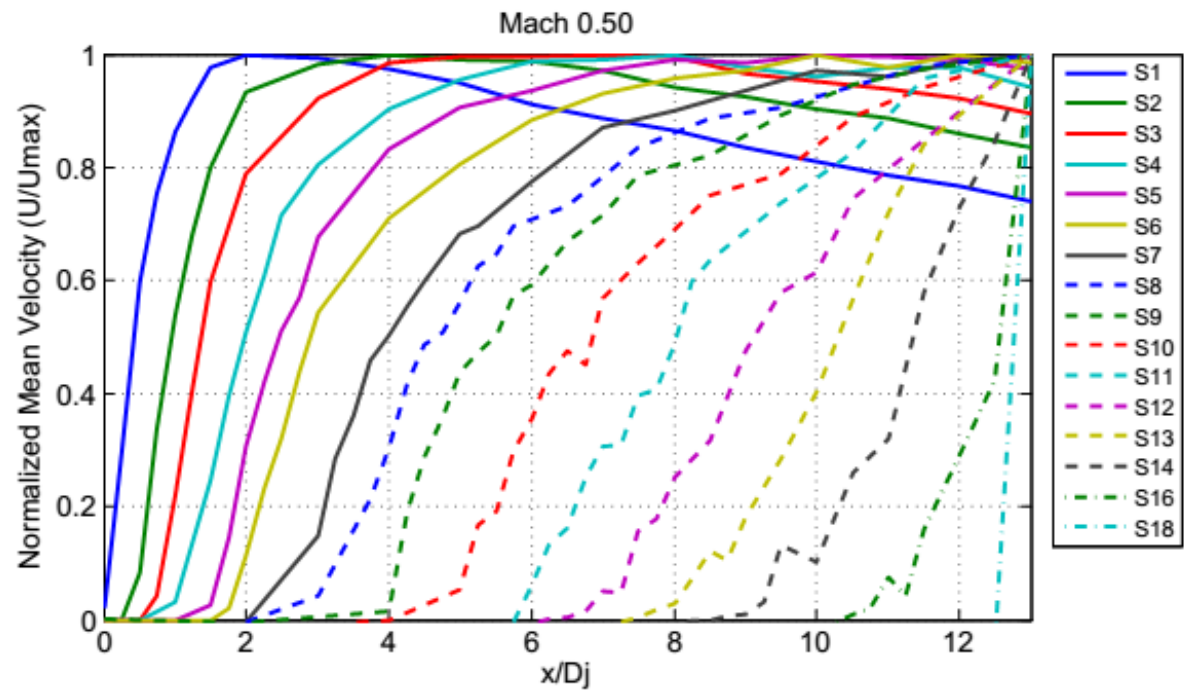


Figure 5.4 - Velocity distribution along the jet axis for different radial positions (Pitot tube, Mach 0.50)

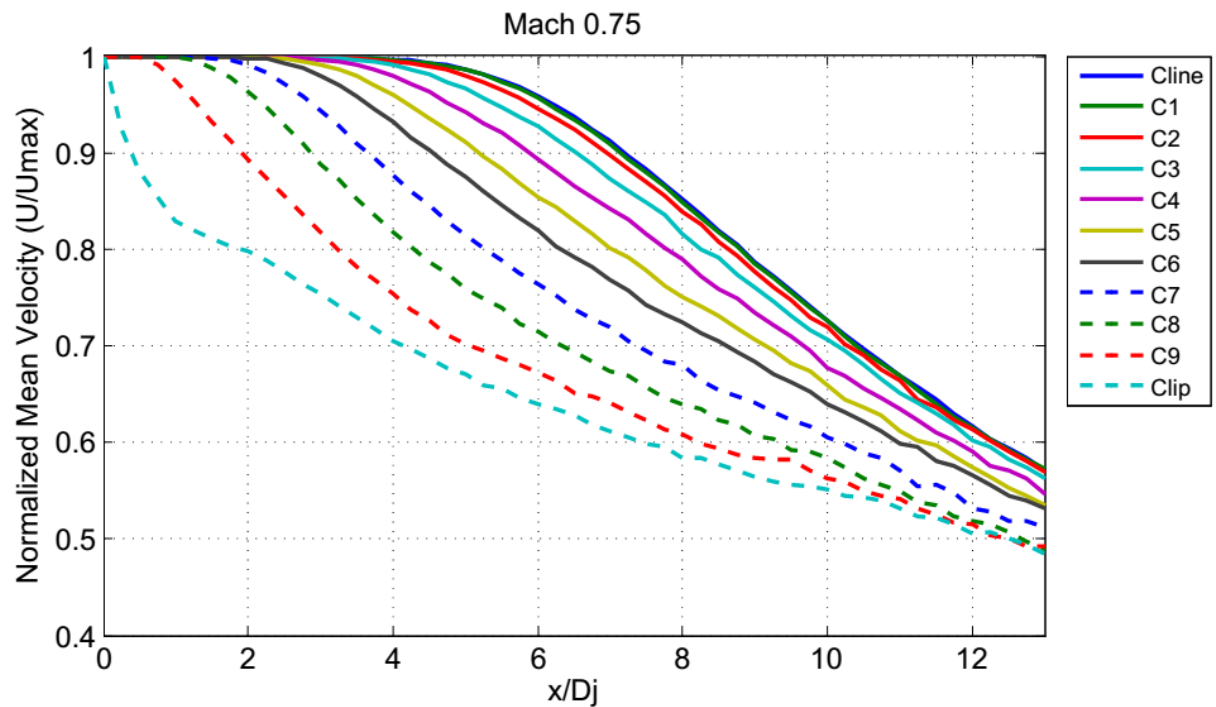


Figure 5.5 - Velocity distribution along the jet axis for different radial positions (Pitot tube, Mach 0.75)

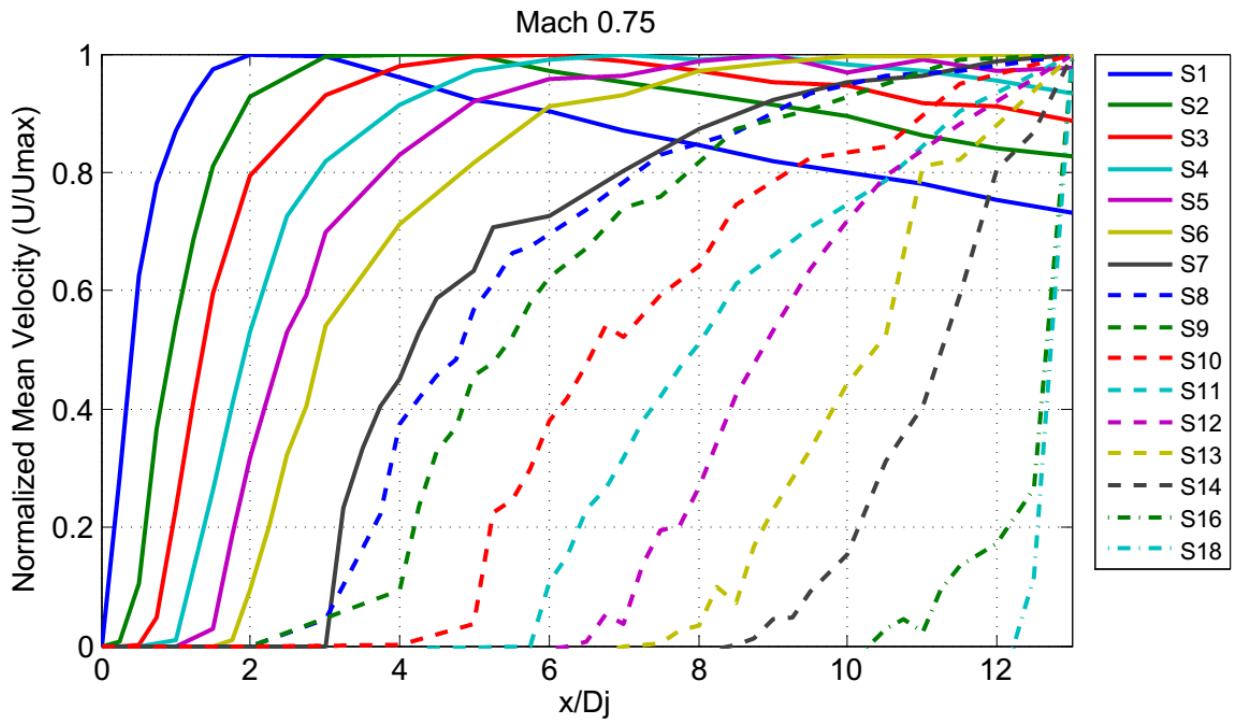


Figure 5.6 - Velocity distribution along the jet axis for different radial positions (Pitot tube, Mach 0.75)

Now the same sequence is shown for measurements using a hot-wire sensor. Firstly, a lesser number of axial lines were investigated in this campaign, due the high fluctuations above the lipline. The measurements were performed on the same points along the jet axis, but only for the radial positions within the nozzle radius. Thus, the figures 5.7 to 5.9 show the axial velocity profiles for Mach numbers 0.25, 0.50 and 0.75, respectively, from the center to lipline radial positions, acquired with a single hot-wire sensor.

Comparing the quality of the pitot and hot-wire techniques for the measurements discussed, it is clear that the pitot data present curves much smoother than the anemometer. The reason is that the latter is more sensitive to the flow variation. Furthermore, the hot-wire calibration curve, a fourth order polynomial, is more complex than the linear curve used by the pressure transducer. As the results had to be corrected to the unsteady pressure imposed by the compressor system, the accumulated errors are most evident in the anemometry system.

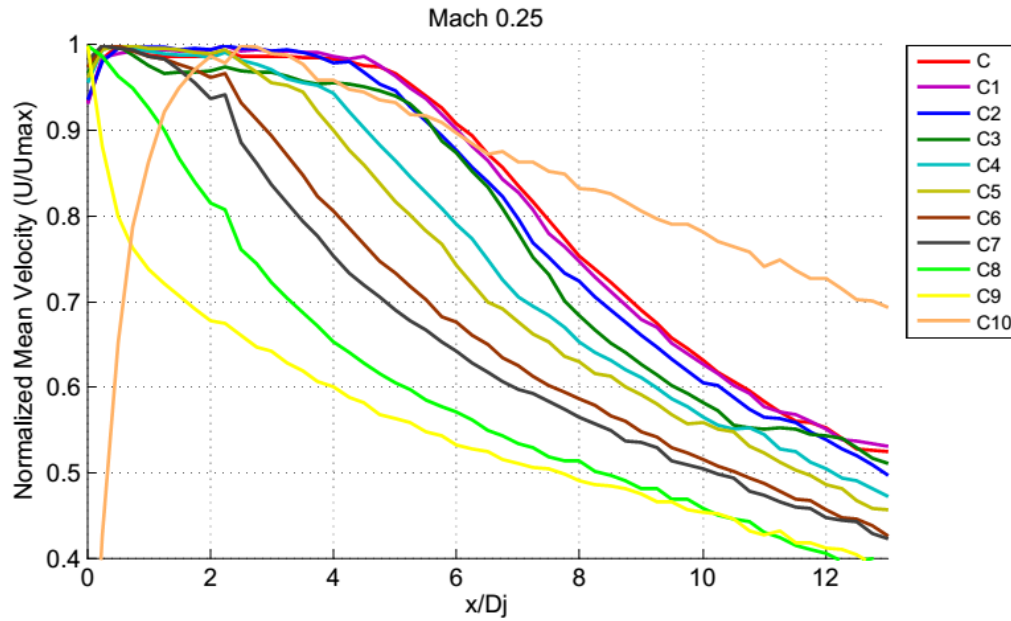


Figure 5.7 - Velocity distribution along the jet axis for different radial positions (Single hot-wire, Mach 0.25)

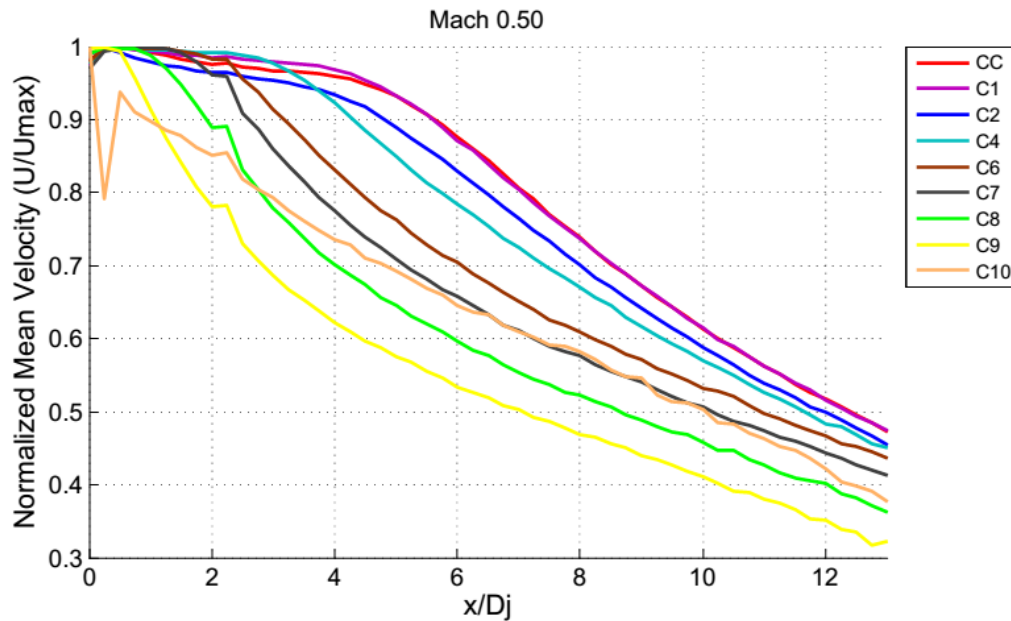


Figure 5.8 - Velocity distribution along the jet axis for different radial positions (Single Hot-wire, Mach 0.50)

Besides the above explanations and the errors from the air supply system, the profile trend is acceptable, with one exception: the lipline, called “C10” on Figs. 5.7 to 5.9, which is also the reason for the inexistence of further radial lines from this point. The errors associated with the measurements on this line along for the three Mach numbers are related to the high turbulence intensity on this line and it is commented in the next section.

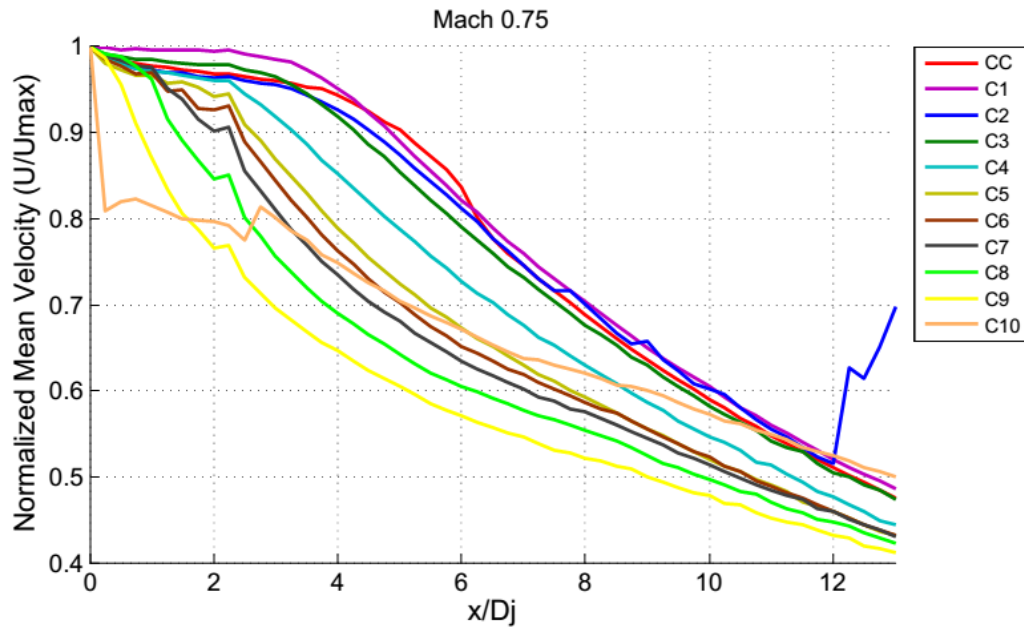


Figure 5.9 - Velocity distribution along the jet axis for different radial positions (Single Hot-wire, Mach 0.75)

In order to check the trend and the accuracy of the data shown above, the axial profiles obtained with each system are compared. The centerline for Mach conditions 0.25 and 0.75 are also compared to other experimental references. Figures 5.10 and 5.11 present this comparison.

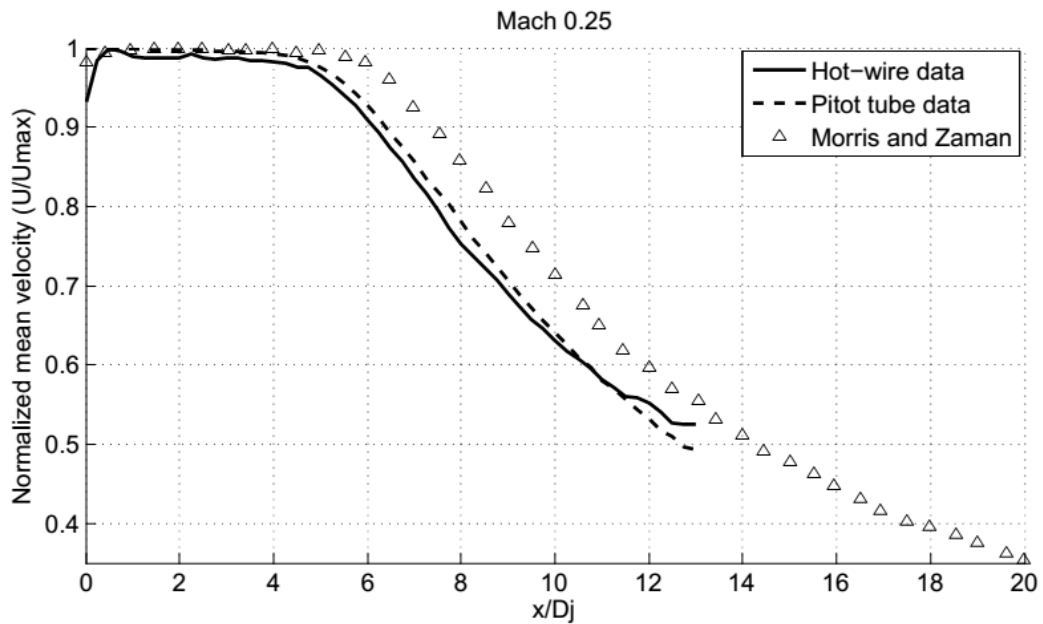


Figure 5.10 – Velocity distribution along the jet axis for centerline at Mach 0.25. — Hot-wire; -- Pitot tube; Δ Morris and Zaman, 2010 (Hot-wire technique, 2" circular nozzle).

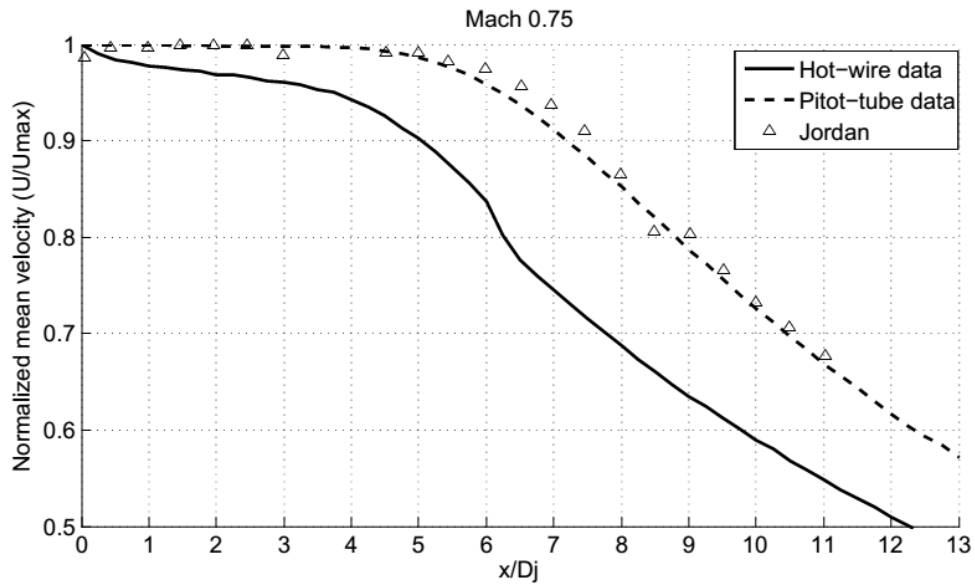


Figure 5.11 – Velocity distribution along the jet axis for centerline at Mach 0.75. — Hot-wire; -- Pitot tube; Δ Jordan, 2002 (PIV technique, circular nozzle).

It can be seen that at Mach number 0.25 the axial velocity profiles from the pitot and the hot-wire system are very similar. Far away around eleven diameters from the exit nozzle, the hot-wire results shown some inconsistency. It is believed that the cause is again the flow variation imposed by the compressor system. The work of Morris and Zaman (2010) shows only the results for Mach 0.25, alleging the fragility of the modern hot-wires probes with high frequency response to high and unsteady flows. The trend is confirmed, despite a presence of an offset.

The results for Mach 0.75 are compared with Jordan (2002). A similar trend and offset is viewed when it takes into account the hot-wire anemometry result. Therefore, the pitot measurements agreed very well with the reference. Since the theory says that the length of the potential core increases with the Mach number (Davies et al, 1962), the conclusion is that there is some source of error in the hot-wire measurement or data analysis. One of the possible causes is the dilatation of the sensor. Especially for Mach numbers 0.5 and 0.75, it was found an offset between several calibration curves of the sensor during these measurements, as discussed in the Appendix III. It makes sense to explain the difference presented in the Fig. 5.11, since the offset seems to start at four diameters downstream the exit nozzle, reaches its peaks around seven diameters and decreases until the last point measured in this work.

Comparing the results for Mach number 0.5 from pitot tube and hot-wire anemometer results from this work, a similar trend from the Fig. 5.11 can be seen.

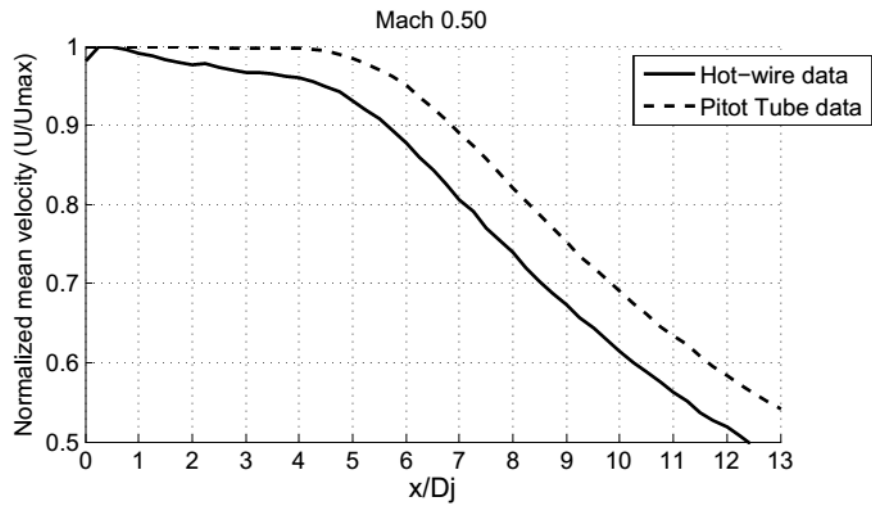


Figure 5.12 – Velocity distribution along the jet axis for centerline at Mach 0.75. — Hot-wire; -- Pitot tube.

The normalized velocity also allows the comparison of the profiles from different velocity conditions. Firstly, it is shown the profiles extracted from the lines “C1”, “C4”, “C7”, and “Clip”, from the pitot measurements.

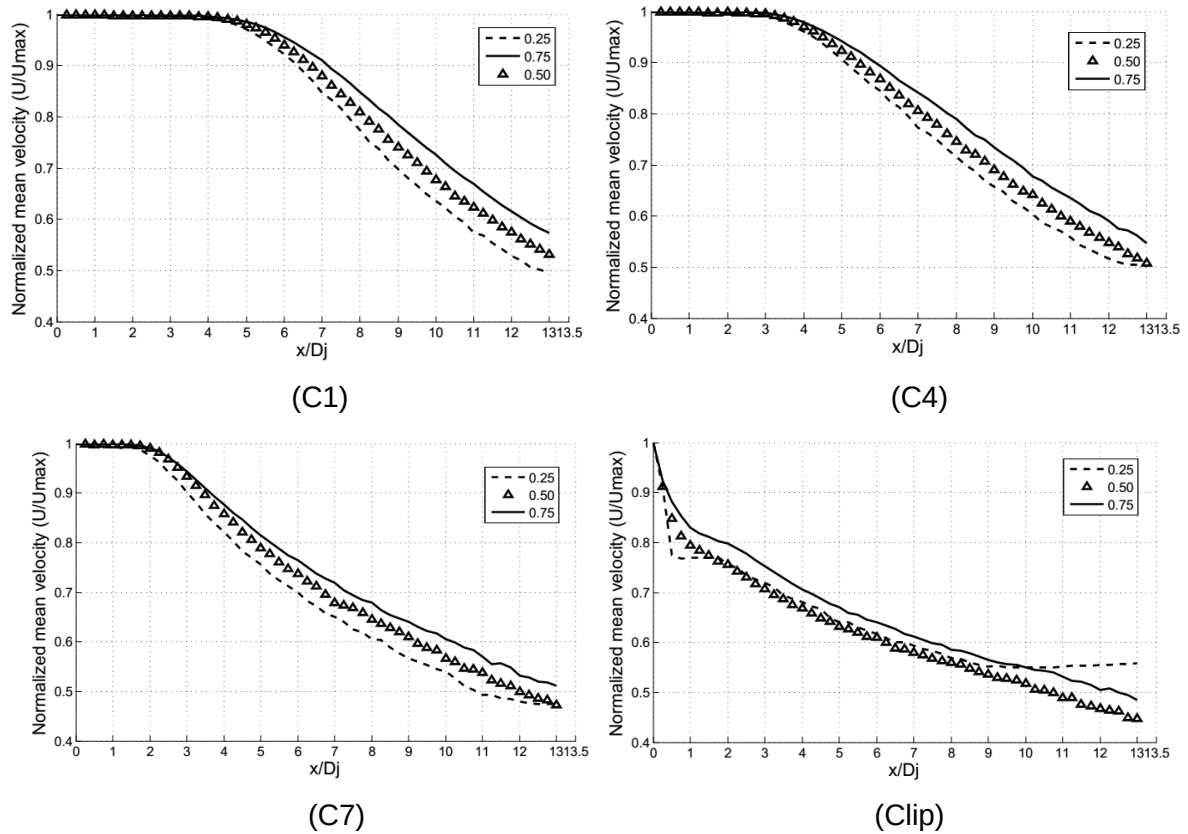


Figure 5.13 – Comparison of velocity profiles at different Mach numbers. -- Mach 0.25; ▲ Mach 0.50; - Mach 0.75.

It can be seen from Fig. 5.13 that an increase in the jet Mach number causes an increase in the length of the potential core. It was showed by Lau (1979) that the potential core comes to an end largely because the large-scale vortex pattern within the mixing region converges on the jet centerline during its travel downstream. It is believed that for higher velocities there is a higher vortex convection and this would result in the the jet centreline being displaced to greater distances downstream, as observed.

Next figure shows the same comparison as the previous one, however it can be seen axial lines outer the nozzle region, from S3 to S12.

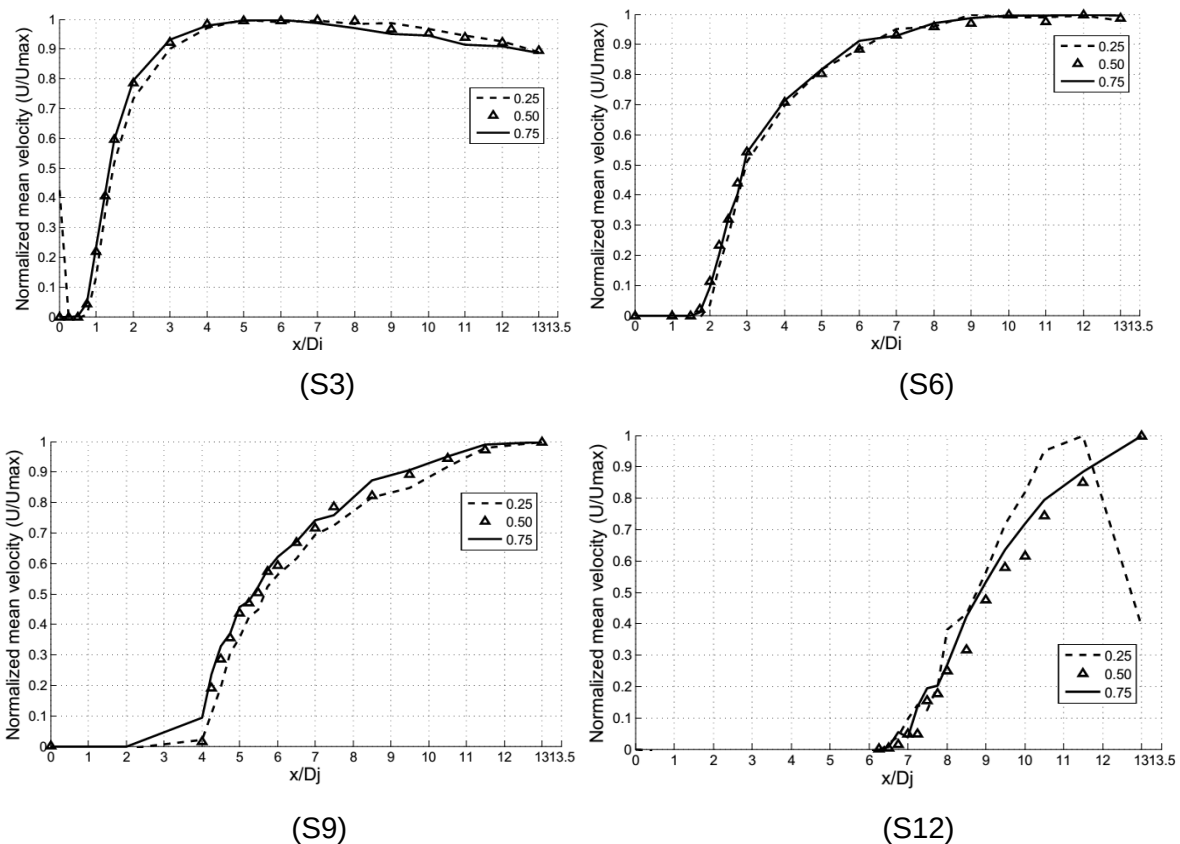


Figure 5.14– Comparison of velocity profiles at different Mach numbers. -- Mach 0.25; ▲ Mach 0.50; — Mach 0.75.

The measurements beyond the lipline are less sensitive to the Mach number rise than the previous region shown. It is explained by the same theory to the potential core, since the large-scale vortex are moving to the centerline.

The same comparison shown in Fig. 5.13 is made for the hot-wire anemometer measurements and is presented in the next figure. The trend presented is not the expected, with the potential core decreasing with the Mach number increase. Whereas the shape

agrees with the literature and the pitot measurements of the present work, some error is probably related to the unsteady properties of the wire at high velocities.

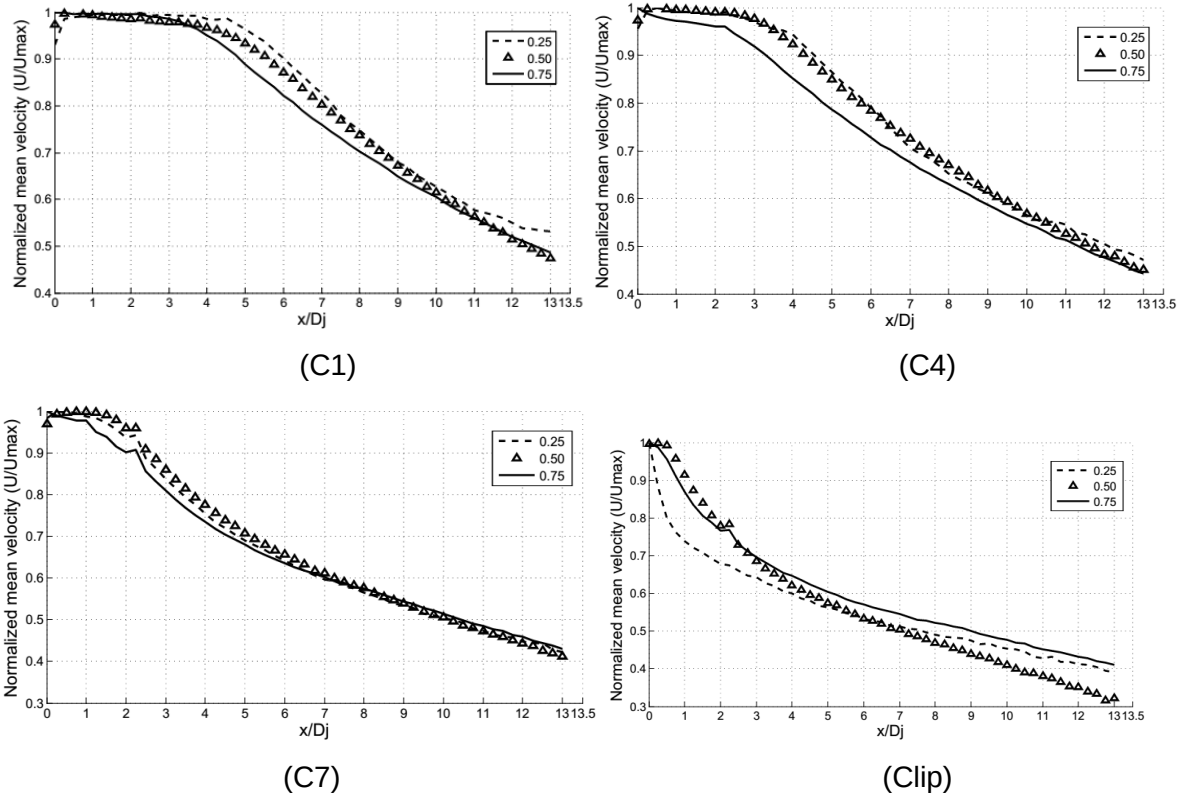


Figure 5.15 – Comparison of velocity profiles at different Mach numbers. -- Mach 0.25; ▲ Mach 0.50; — Mach 0.75.

5.1.1.2 Radial velocity profiles

Although the data were acquired following an axial string of points, radial profiles can be extracted since there are an enough number of lines (total of 31) from different radial positions. As the jet is assumed being axisymmetric, the data presented in this sub-section are mirrored.

Figure 5.16 presents the radial profile acquired for Mach 0.75 in different axial positions. The sensor used is the pitot tube. It can be seen the velocity decay as it moves downstream the jet. On the other hand, it also shows the jet spreading. The Fig. 5.17 shows the same condition, the difference is the velocity, normalized by the Eq. (5.1), where the U_{max} is selected in a radial line instead of an axial one. Results for the Mach numbers 0.25 and 0.50 have the same trend and they are suppressed at the present section. Appendix I shows further.

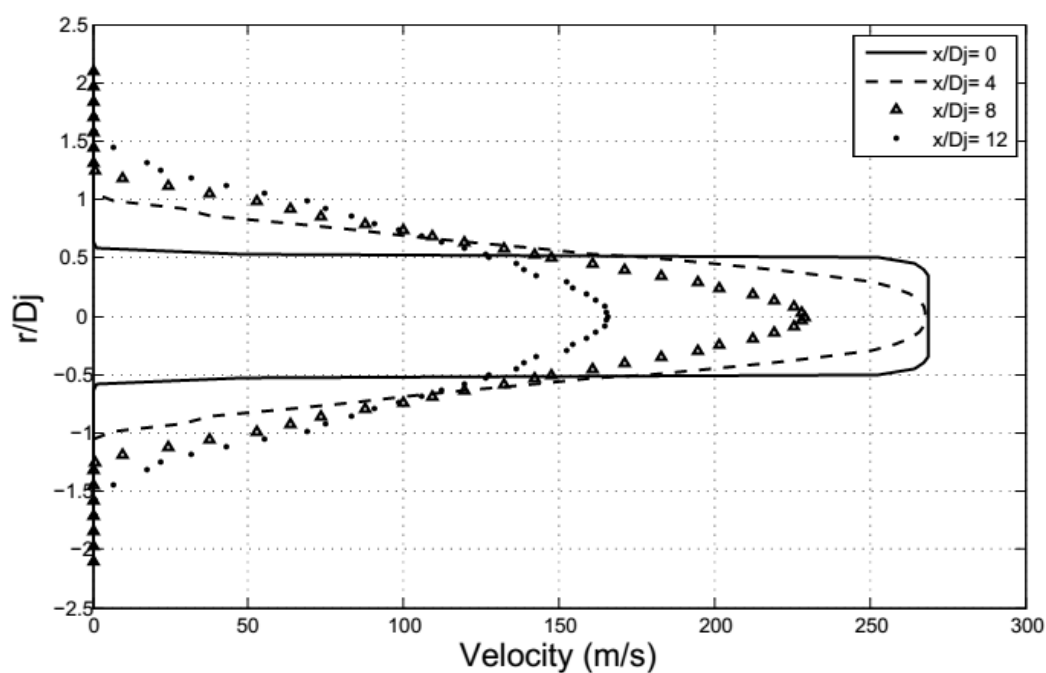


Figure 5.16 – Radial profile of the jet at Mach 0.75, acquired via pitot tube. — $x/D_j=0$; -- $x/D_j=4$; $\blacktriangle$ $x/D_j=8$; $\circ$ $x/D_j=12$.

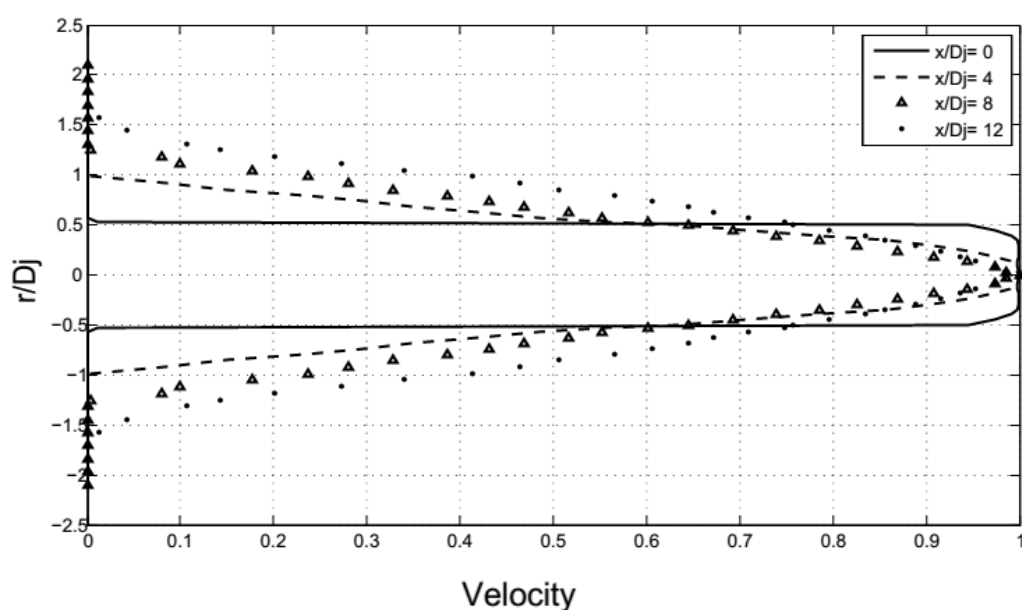


Figure 5.17 – Radial profile of the jet at Mach 0.75 in function of the normalized velocity, acquired via pitot tube. — $x/D_j=0$; -- $x/D_j=4$; $\blacktriangle$ $x/D_j=8$; $\circ$ $x/D_j=12$.

Finally for the pitot tube measurements, as the axial profiles, it is also possible to visualize the velocity profiles of the different Mach numbers, in different sections. Figures 5.18 and 5.19 shows the radial velocity profiles located at one and eight diameters away from the jet exit nozzle.

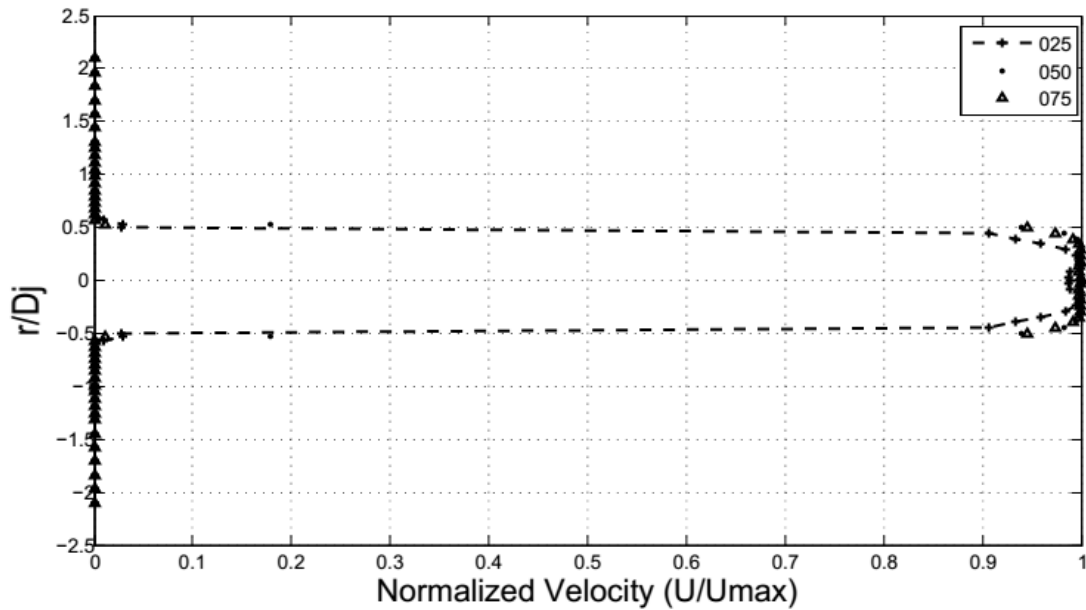


Figure 5.18 – Radial profile of the jet at distance $x/D_j = 1$ for different velocities, acquired via pitot tube. -- Mach 0.25; o Mach 0.50; ▲ Mach 0.75.

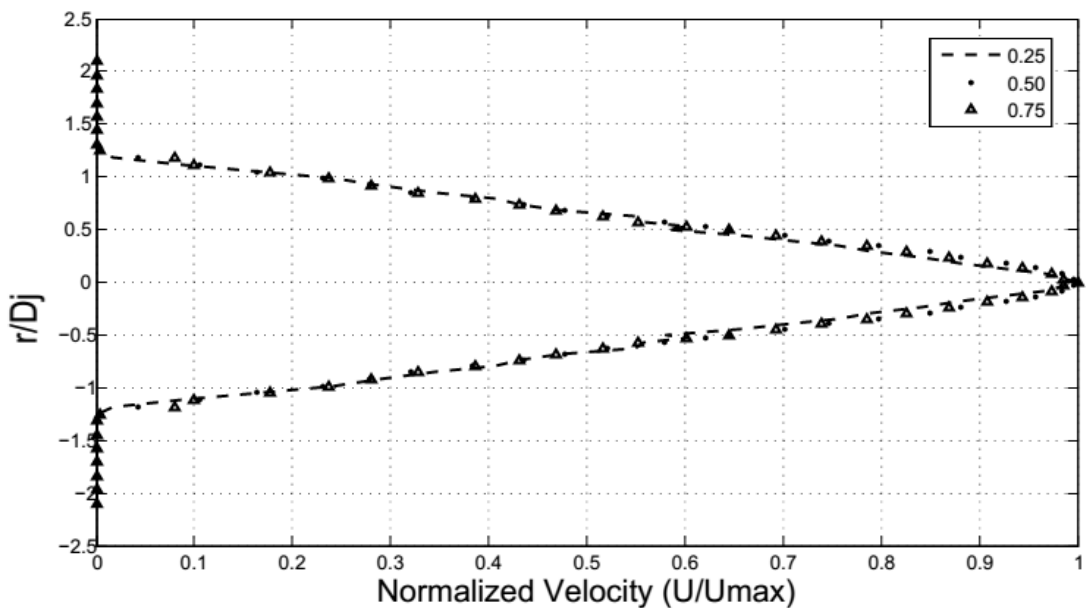


Figure 5.19 – Radial profile of the jet at distance $x/D_j = 8$ for different velocities, acquired via pitot tube. -- Mach 0.25; o Mach 0.50; ▲ Mach 0.75.

Moving to the hot-wire anemometer data, it is not possible to evaluate smooth velocity profiles from these measurements. The first reason is related to the pressure variation. It is discussed at the Appendix III, and has a crucial impact on the aerodynamics, mainly the hot-wire measurements. The Fig. 5.20 shows the flow behavior during thirty minutes, usually the

time spent to acquire the 53 points from one axial line for the hot-wire campaign in this work (25 seconds acquiring a single point and few seconds to write the binary file in the computer). As the points are distributed along the curve showed, it is simple to locate them and find a curve to correct or at list minimize this effect on the data measured. When it moves to analyses points radially, it is considerably more complicated to find a relation between the measurements.

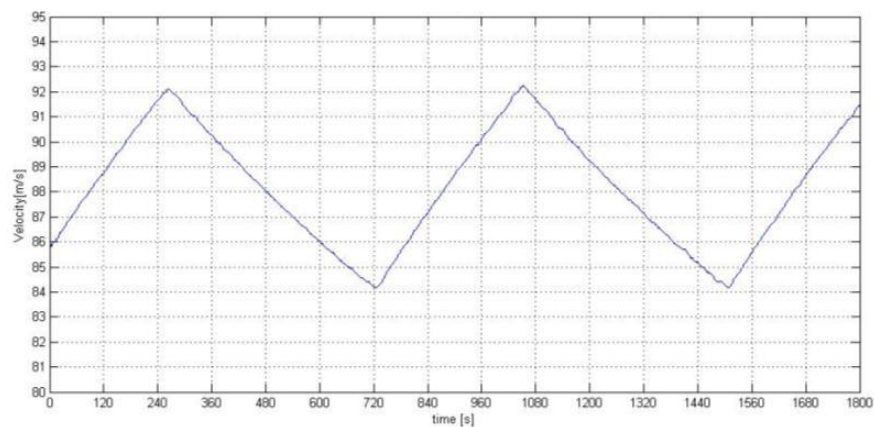


Figure 5.20 – Velocity (m/s) vs time acquired for 1800 seconds, showing the operating regime of the compressor.

Secondly, the turbulence intensities along and after the lipline are very high. The Fig. 5.21 shows various radial velocity profiles from hot-wire measurements.

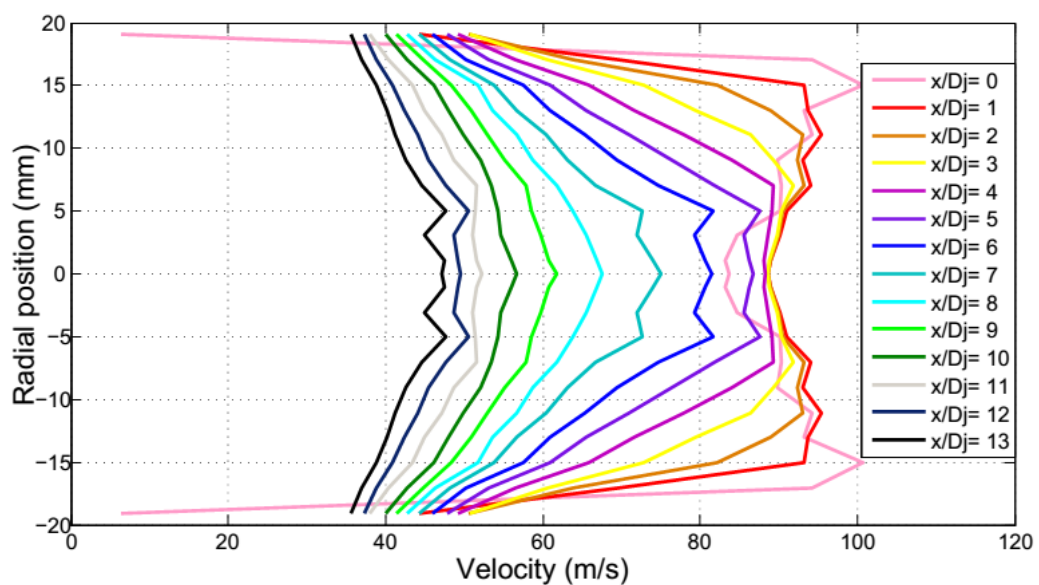


Figure 5.21 – Radial velocity profiles at Mach number 0.25 acquired with hot-wire anemometer. Positions $x/D_j = 1$ to 13.

5.1.1.3 Jet characterization

This sub-section is used to present a general view of the jet's velocity distribution. All lines measured are considered and, such as in the previous sub-section, the data is mirrored to better characterize the jet. Although it seems to be merely illustrative, it helps to summarize the information given on the previous sub-sections.

Figure 5.22 shows the velocity distribution from the exit nozzle to thirteen diameters downstream the jet axis, also covering two diameters from the center of the nozzle. It shows the results for the three Mach number analyses. These data were acquired by the pitot tube.

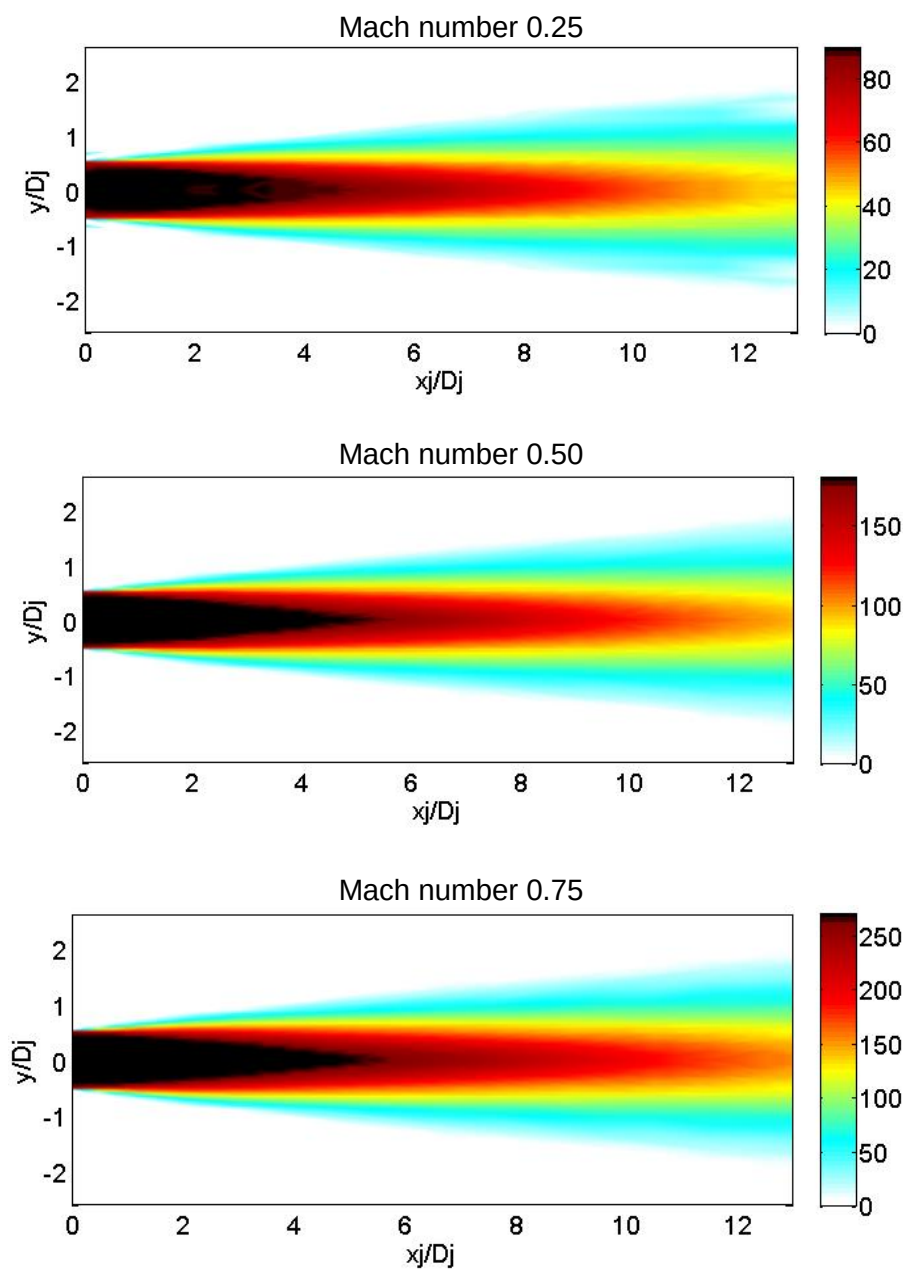


Figure 5.22 – Jet characterization with pitot tube data.

It is possible to see the potential core and the shear layer behavior along the imposed velocity regimes. The slight growth of the potential core with the velocity increases is evident, as well as the shear layer spreading, with the small thickness close to the nozzle.

The Fig. 5.23 presents the same graph style to the hot-wire measurements. The mean velocity information for these data is not accurate as the Fig. 5.22, for the reasons already stated.

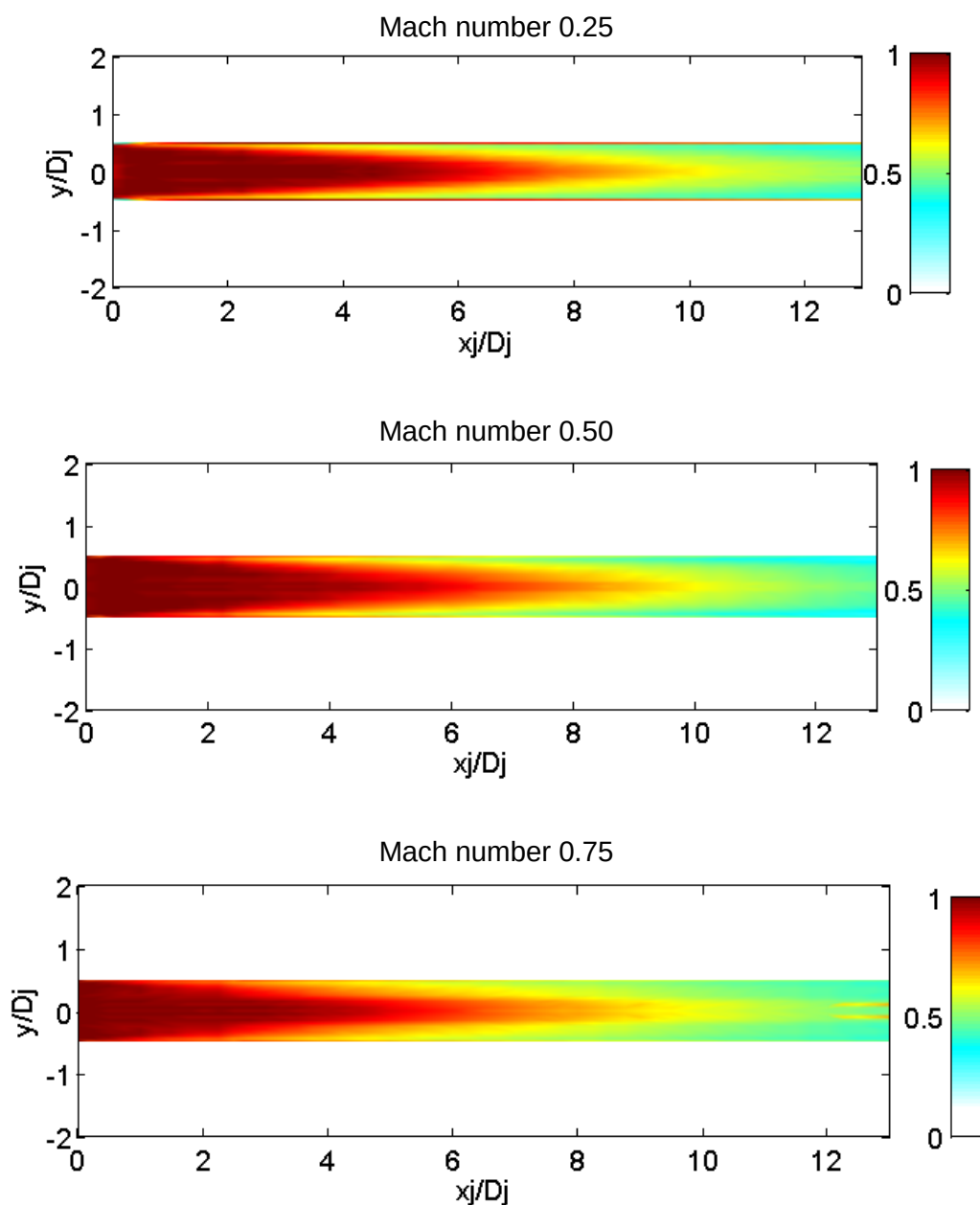


Figure 5.23 – Jet characterization with hot-wire data: (a) Mach 0.25; (b) Mach 0.50; (c) Mach 0.75.

5.1.2 Velocity fluctuation

The single hot-wire measurements were performed in a sample frequency of 50 kHz in order to obtain statistical results of the flow.

The turbulence intensity is related to the three components of velocity. The “u” velocity component is some orders of magnitude greater than the “v” and “w” components. Although it is a mistake in absolute values, the fluctuations of this jet axis component will be used to calculate an approach to the turbulence intensity. This sub-section shows the results for the unsteadiness or fluctuation of the jet axis velocity component, calculated by the follow equation:

$$u_{rms}/U_0 \quad (5.2)$$

One important point must be stated here. The hot-wire and hot-film anemometers are very used to measure flows, as mentioned before. To measure fluctuations, the manufacturers estimates that the reliable range to single hot-wire sensors is until 10 - 15% of the mean value. The hot-film is larger, until 20%. Along the shear layer of the jet, the maximum values of turbulence intensity expected for a subsonic jet are around 15% (Jordan, 2002).

5.1.2.1 Axial profiles

Figures (5.24), (5.25) and (5.26) show similar graphs to that on the figures (5.7), (5.8) and (5.9). Nevertheless, instead of mean velocity, values of unsteadiness or, such as approximated here, turbulence intensities are presented.

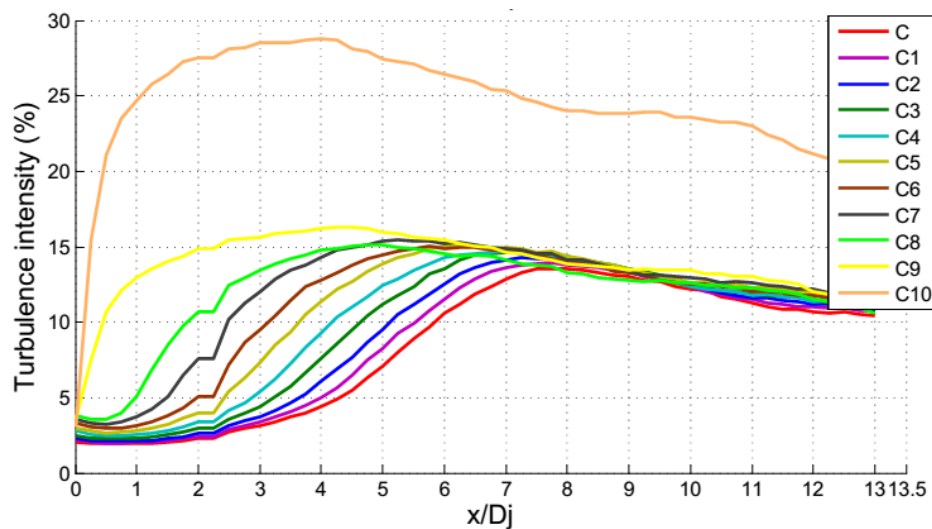


Figure 5.24 – Unsteadiness velocity distribution along the jet axis for different radial positions (Single hot-wire, Mach 0.25).

The results shown in Fig. 5.24 relates the turbulence intensity distribution from the centerline to the lipline of the jet. Initially, it can be seen that the unsteadiness of the flow is very low mainly until three diameters from the nozzle. By moving radially from the centerline ('C') to the lipline ('C10'), the turbulence intensity increases slightly and reaches its peak earlier, since it is crossing the shear layer between the potential core and the mixing region moving from a laminar flow with constant velocity to the turbulent layer.

In addition, with the end of the potential core, the transitional region arises and for the centerline the unsteadiness of the velocity grown until the theoretical end of this area, around eight diameters, beginning the self-preserving or fully developed region. The axial profiles met in this region.

As mentioned before, the operational range of the hot-wire anemometer has total influence on the curve 'C10', equivalent to the lipline. Even the previous lines, the turbulence intensity experienced in jet flows are high to these very small and sensitive hot-wires. For high velocities the same error has occurred to lines close to the centerline of the mixing layer, showed at Fig. (2.10).

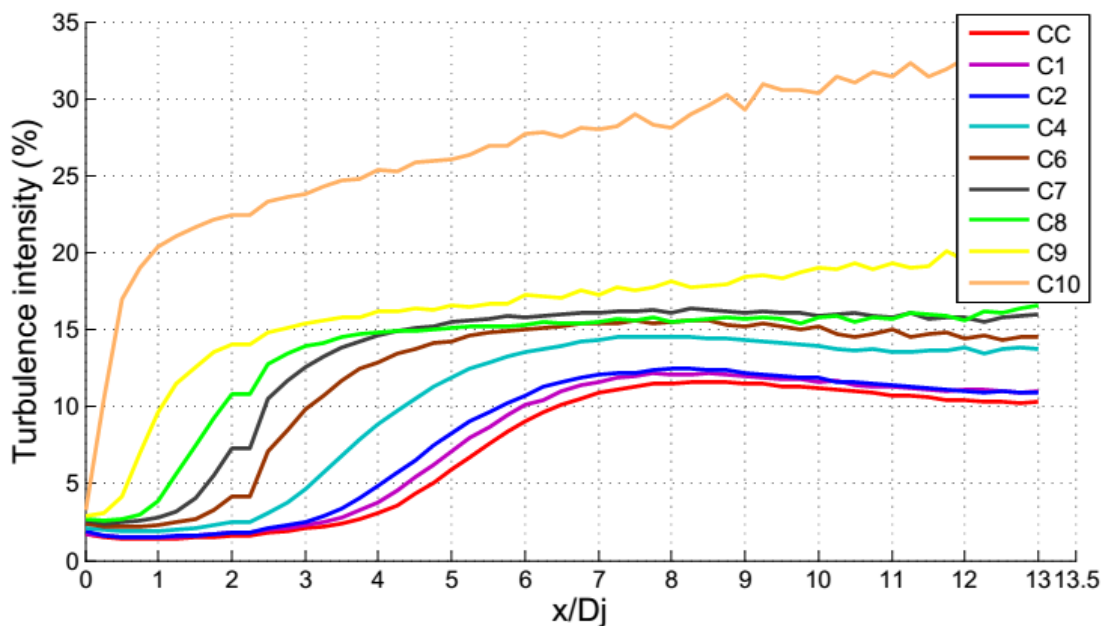


Figure 5.25 - Unsteadiness velocity distribution along the jet axis for different radial positions (Single hot-wire, Mach 0.5).

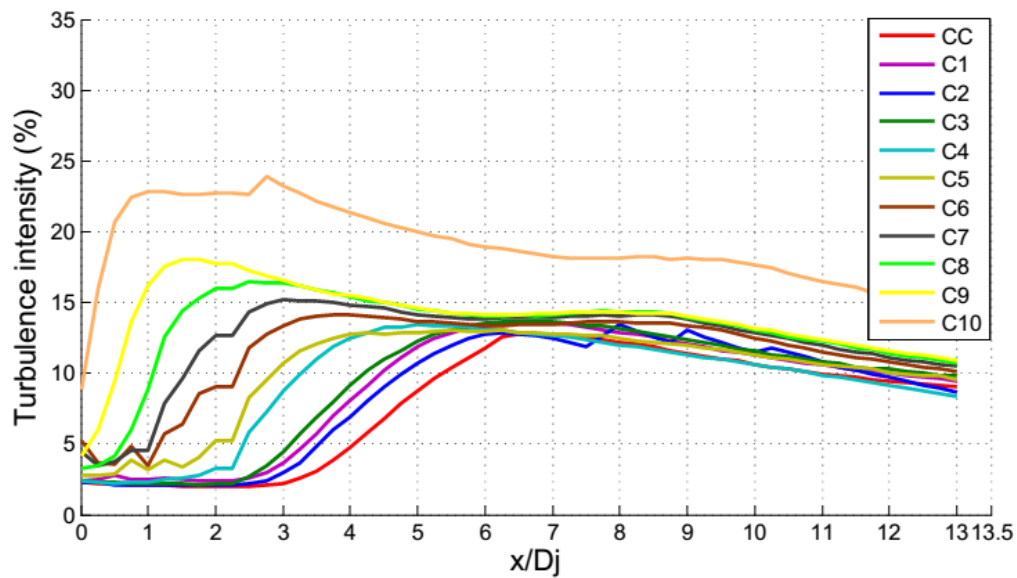


Figure 5.26 - Unsteadiness velocity distribution along the jet axis for different radial positions (Single hot-wire, Mach 0.75).

Such as done in the mean velocity profiles sub-section, the velocity fluctuation data are also compared to the literature, once again the centerline to Mach numbers 0.25 and 0.75. Figure 5.27 shows the comparison to the low velocity, from the work of Morris and Zaman (2010). The higher velocity is analyzed in contrast with Jordan (2002) and Mielke et al (2004) experiments.

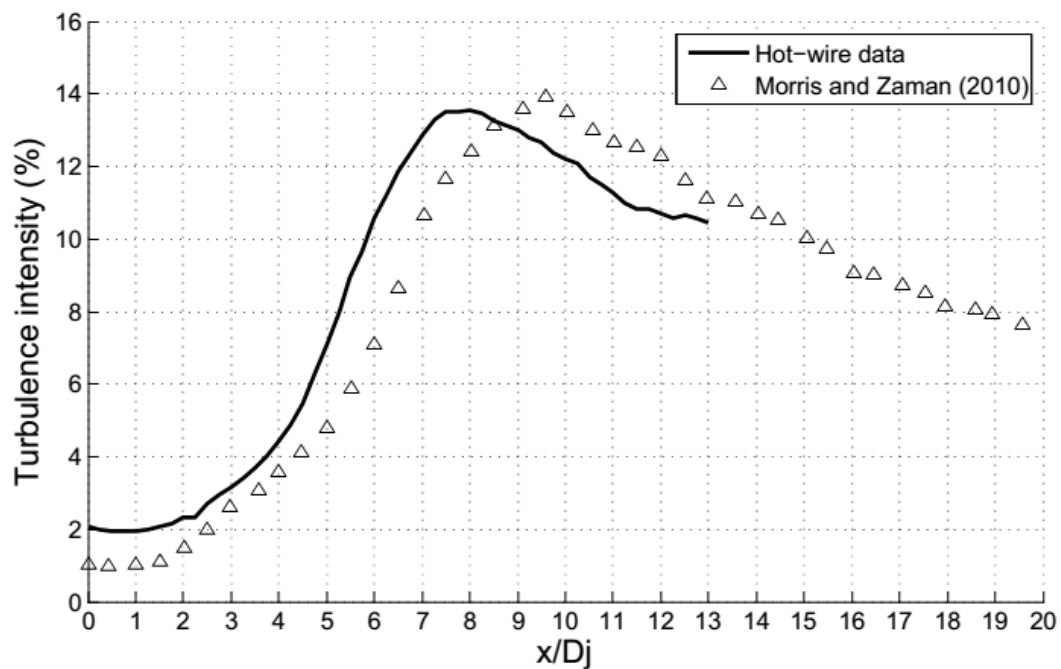


Figure 5.27 – Turbulence intensity along the jet axis for centerline at Mach 0.25. — Hot-wire; ▲ Morris and Zaman, 2010 (Hot-wire technique, 2" circular nozzle).

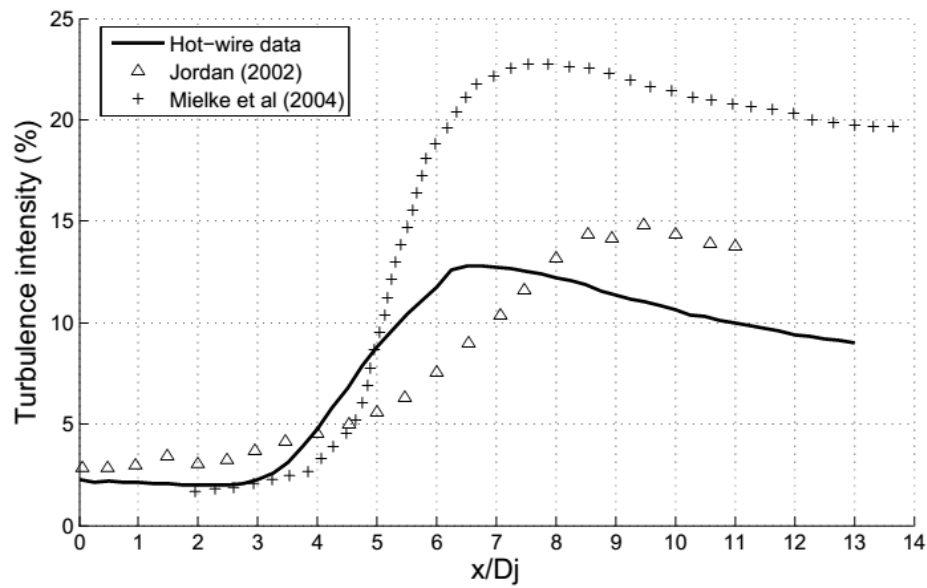


Figure 5.28 – Turbulence intensity along the jet axis for centerline at Mach 0.75. — Hot-wire; Δ Jordan, 2002; + Mielke et al, 2004 (Mie scattering technique, converging nozzle).

Figure 5.29 shows another intriguing result. As pointed by Lau (1979), the spreading rate of the turbulent shear layer decreased when the Mach number was increased, and that in turn this caused the stretching in the potential core, as already mentioned.

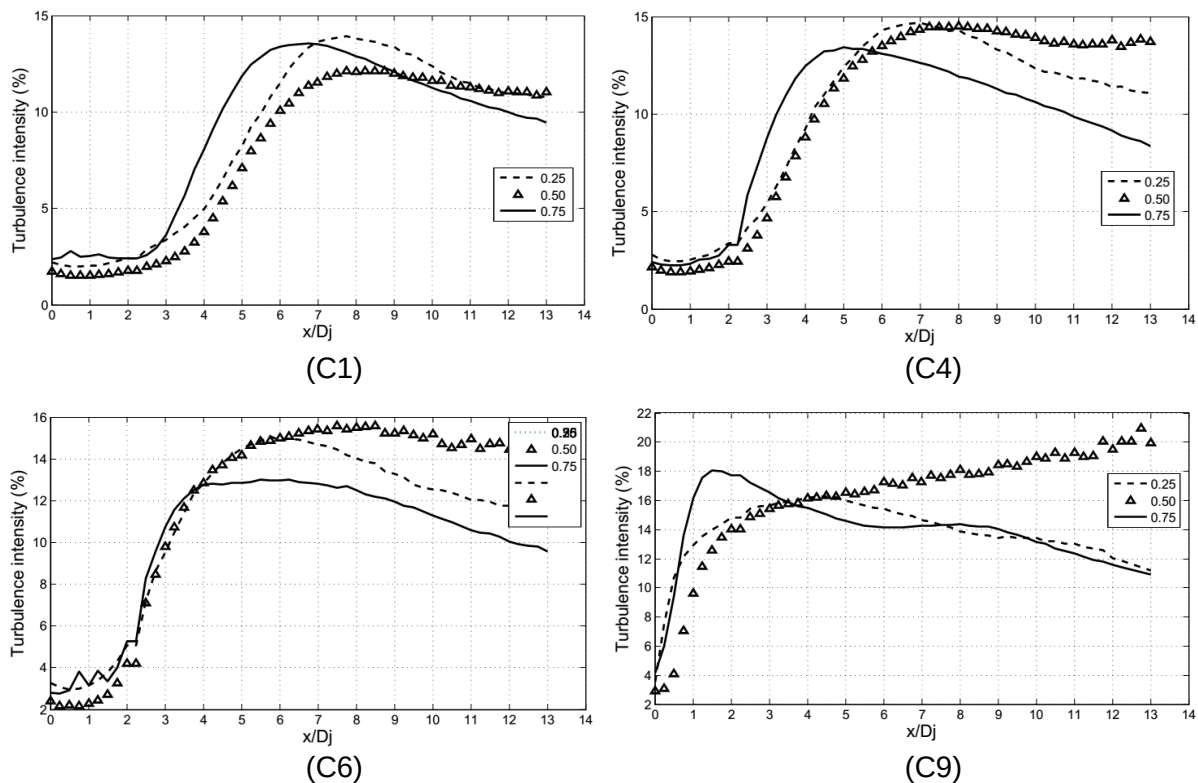


Figure 5.29 – Comparison of turbulence intensity profiles at different Mach numbers. -- Mach 0.25; Δ Mach 0.50; — Mach 0.75.

Although no substantial change could be observed, the general tendency was for the maximum axial and radial turbulence intensity, falling in the profiles distribution with increasing Mach number. It is clearly observed from the next figure taking into consideration the Mach numbers 0.25 and 0.75. Nevertheless, the intermediate value, Mach 0.50, this trend is not observed. Furthermore, the behavior of the curve after the transitional region is not following the pattern, since it does not decrease considerably and even increases close to the lipline.

5.1.2.2 Radial profiles

As this section uses only anemometry results, the radial profiles are not very smooth, but it shows an important tendency. It begins with high turbulence intensity along the lipline and “distributes” this property radially when it moves downstream to the jet. After eight to nine diameters it is in a fully developed region, keeping a constant distribution shape of turbulence intensity and decreasing slightly as it move forwards.

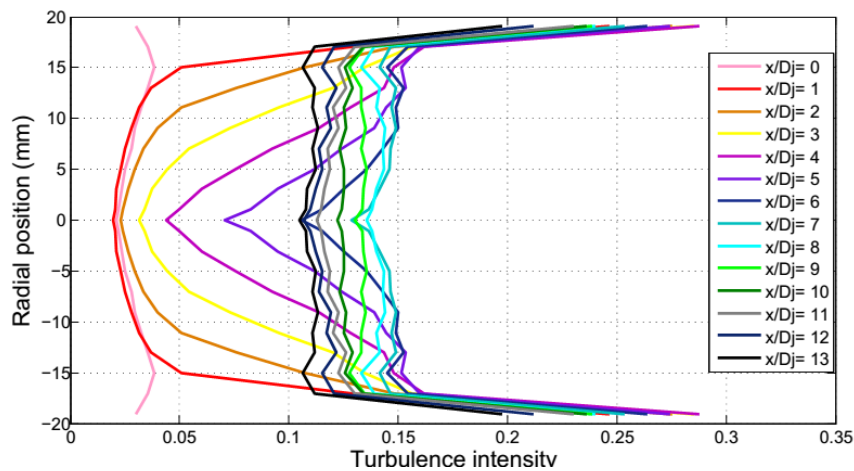


Figure 5.30 - Radial turbulence intensity profiles at Mach number 0.25 acquired with hot-wire anemometer. Positions $x/D_j = 1$ to 13.

Figure 5.30 shows the radial profiles for turbulence intensity when the jet is operating at Mach 0.25.

5.1.2.3 Jet characterization

This sub-section is used to present a general view of the jet's unsteady velocity distribution. All the previous description to the same sub-section addressing the jet characterization in terms of mean velocity is reiterated, now using the turbulence intensity information.

Figure 5.31 shows the unsteadiness velocity distribution from the exit nozzle to thirteen diameters downstream the jet axis, covering only half diameter from the center of the nozzle. It shows the results for the three Mach number analyzed, from data acquired by the anemometry system.

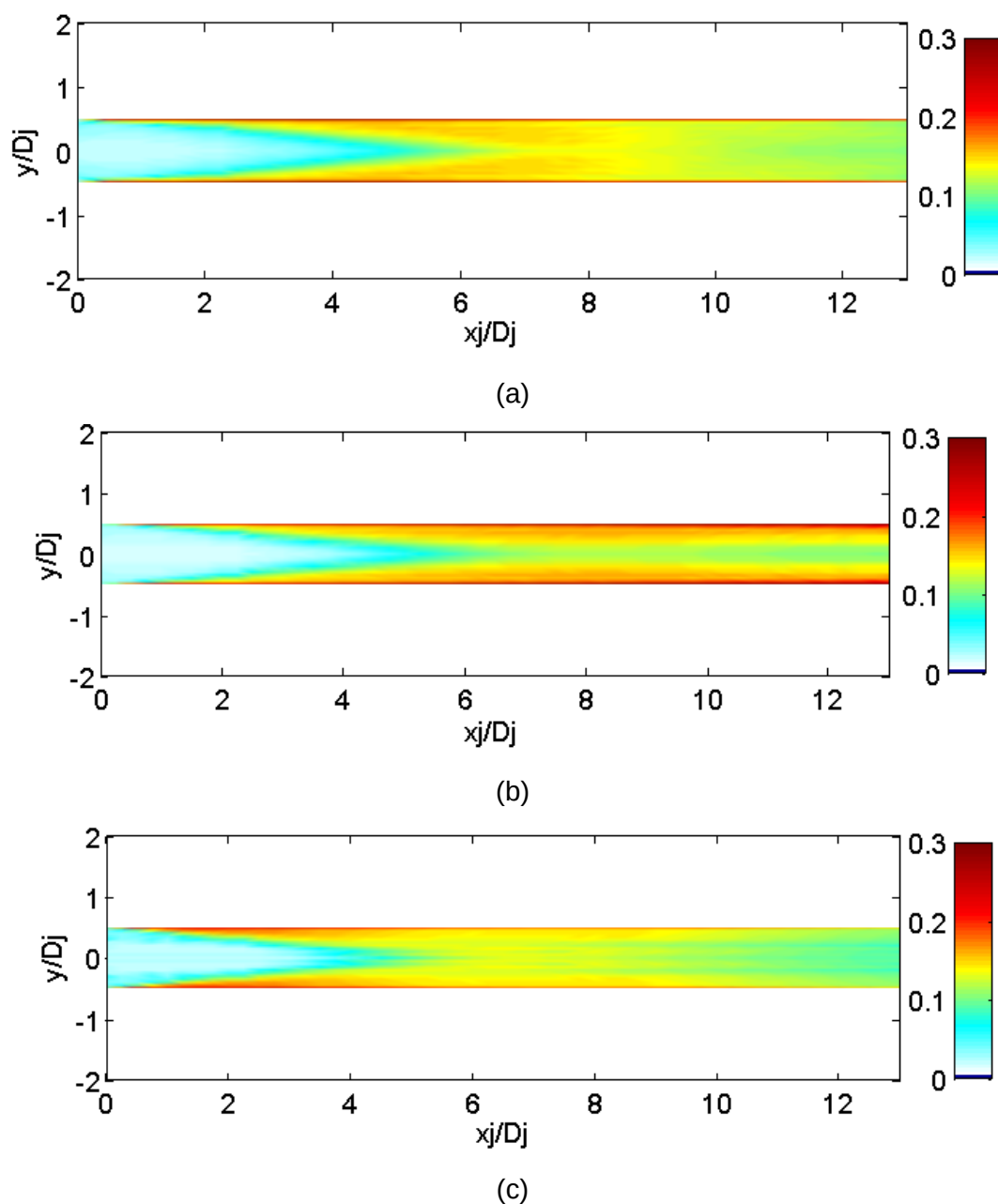


Figure 5.31 – Unsteadiness velocity distribution. (a) Mach 0.25; (b) Mach 0.50; (c) Mach 0.75.

5.1.3 Power spectral density

The power spectral density - PSD is a way to show the strength of energy variations as a function of frequency. The usual unit of PSD is energy per frequency, and the integral of the PSD over a given frequency range computes the average power in the signal. This spectrum is computed directly by a Fast Fourier Transform method - FFT or by computing an autocorrelation function and transforming it.

In the present work, the Welch's method (Welch, 1967) is used to calculate the PSD of the signal acquired by the anemometer. This method uses a FFT to obtain an estimation of the PSD based on time averaging over short modified periodograms (Welch, 1967).

Welch based on Barlett's method, which consists in split the original points into a number "n" of data segments of length "L", compute the periodogram by the discrete Fourier transform, and then compute the squared magnitude of the result dividing by the L. Finally, the result of the periodograms is time-averaged for the n data segments. The difference is that on the Welch's method, the system is divided into overlapping segments, which are windowed in the time domain before apply the discrete Fourier transform. It is considered an improvement on the standard periodogram and Bartlett's methods, since it reduces noise in the estimated power spectra when it reduces the frequency resolution.

The processing is done by the Matlab pwelch function, which returns the two-sided Welch PSD estimation. It was used a Hanning window and a sample frequency of 50 kHz (which is transformed in 25 kHz).

Still taking into account the fact that it is only one component velocity, some results to approximate the power spectrum density and compares with the power spectrum of turbulence are performed.

The Fig. 5.32 shows the result for some points along the "C1", "C4", "C7" and "C9" lines, for Mach 0.25. It shows that the PSD accompanies exactly the theory presented in the Chapter 2. The points inside the potential core have less energy than the points in the mixing layer. The low frequencies are responsible by the energy injection, whilst it is seen that the high frequencies are dissipating this energy.

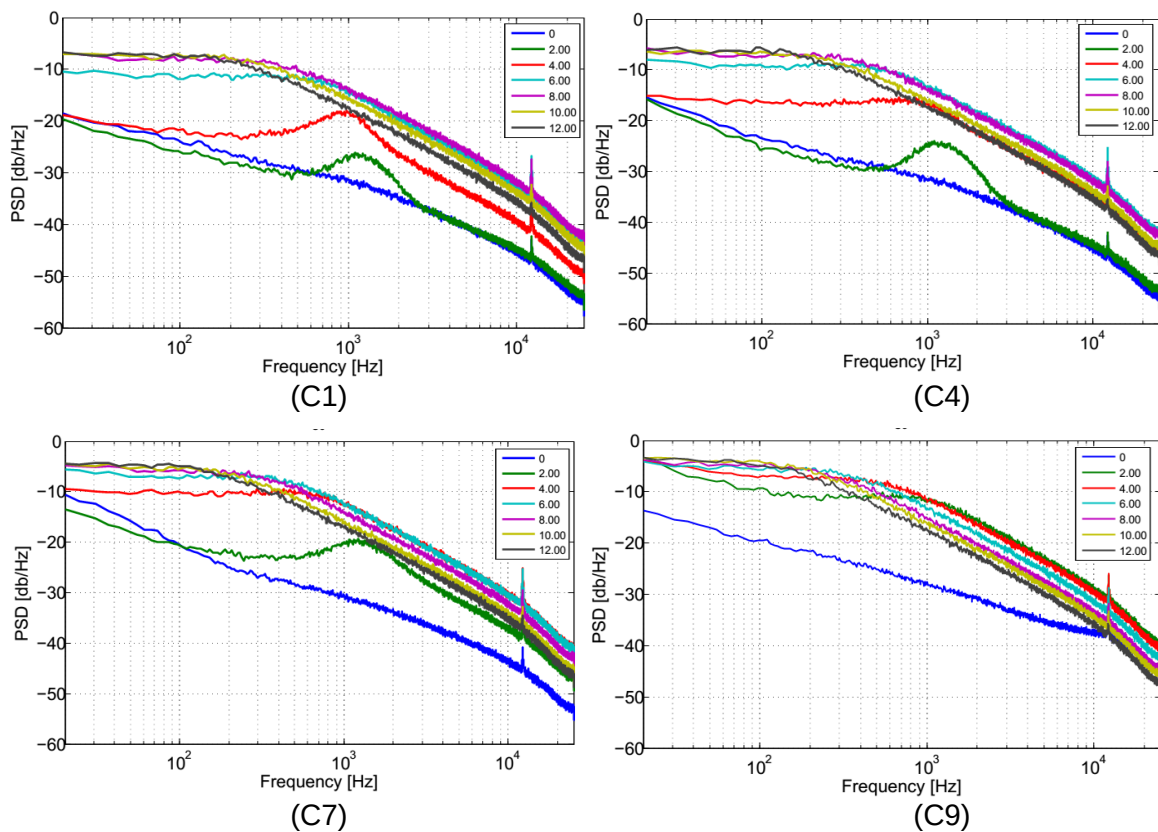


Figure 5.32 – Power spectral density in measurements at Mach number 0.25. $x/D_j=0, 2, 4, 6, 8, 10$ and 12 .

The same graphs are performed to the other Mach number conditions. Results shown in Figures 5.33 and 5.34 are related to measurements on the “C9” line, Mach numbers 0.50 and 0.75, respectively.

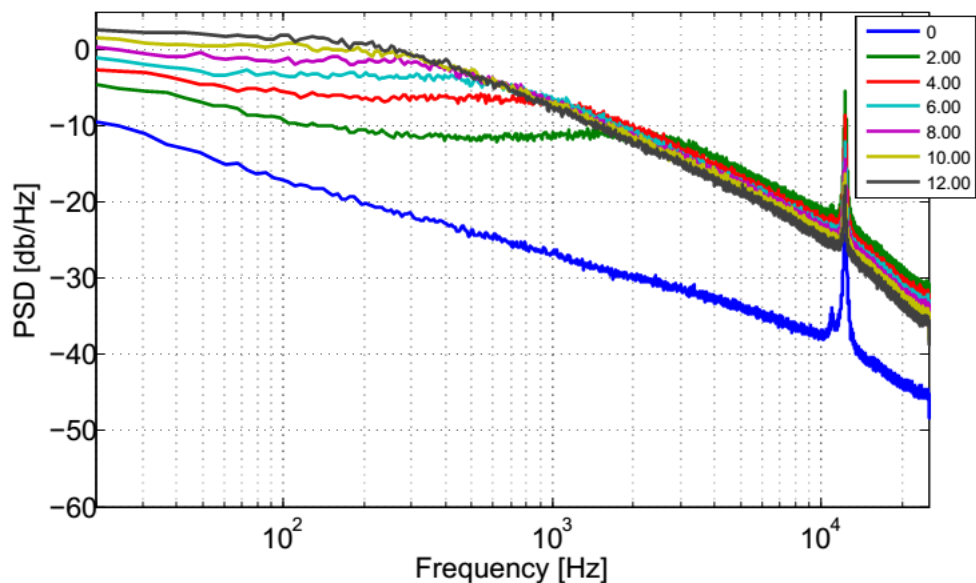


Figure 5.33 – Power spectral density in measurements at Mach number 0.50. $x/D_j=0, 2, 4, 6, 8, 10$ and 12 .

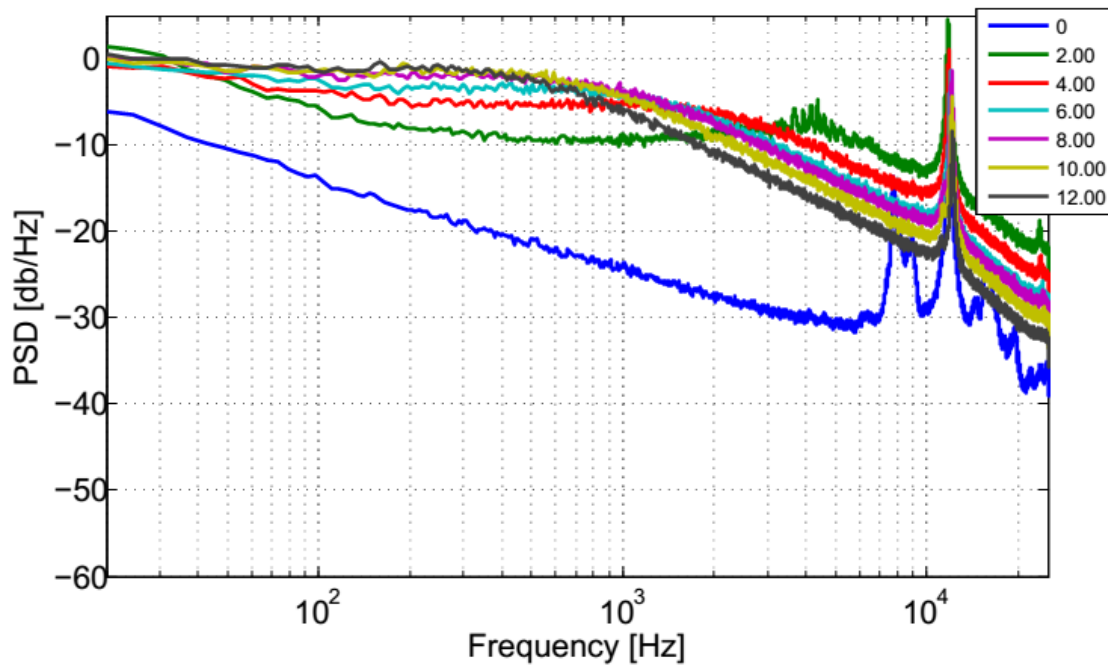


Figure 5.34 – Power spectral density in measurements at Mach number 0.75. $x/D_j=0, 2, 4, 6, 8, 10$ and 12 .

Both figures show a characteristic noise around 10 kHz. Actually, it is also viewed for the lowest velocity, and it spreads as the Mach number increases. It is assumed to be the interaction between the tonal noise produced when by the hot-wire anemometer into the flow and the support and even nozzle vibration, which is clearly more accentuated at high velocities.

5.2 Acoustic results

This section shows the results obtained in the acoustic campaign described in the Section 4.4. It is divided in two sub-sections, according to the analyses of the sound pressure level – SPL in for different velocities and for different observer angles. All results were corrected for the atmospheric attenuation and the observer distance for all angles is 1 m.

5.2.1 Sound Pressure Level vs Velocity

As mentioned, the narrowband sound pressure level was acquired for a microphone configuration of six observer angles and nineteen different velocities. This sub-section shows the results of the velocity trend acquired by each angle. The frequency varies from 300 Hz

(imposed by the anechoic properties of the chamber) and 80 kHz (although the sample frequency is 100 kHz, the filtering and post-processing takes 80% of this value).

Firstly, Fig. 5.35 shows the spectrum of sound pressure level for the microphone located at 90° , for all Mach numbers investigated. It is just placed to show the complete agreement of the measurements with what was stated in the previous chapters: the SPL increases with the Mach number increment. It is also observed that for low velocities there is an undesirable noise at very high frequencies.

The data from this figure and the same for the others angles are applied to compound the database used to the semi-empirical and numerical models in development at UFU.

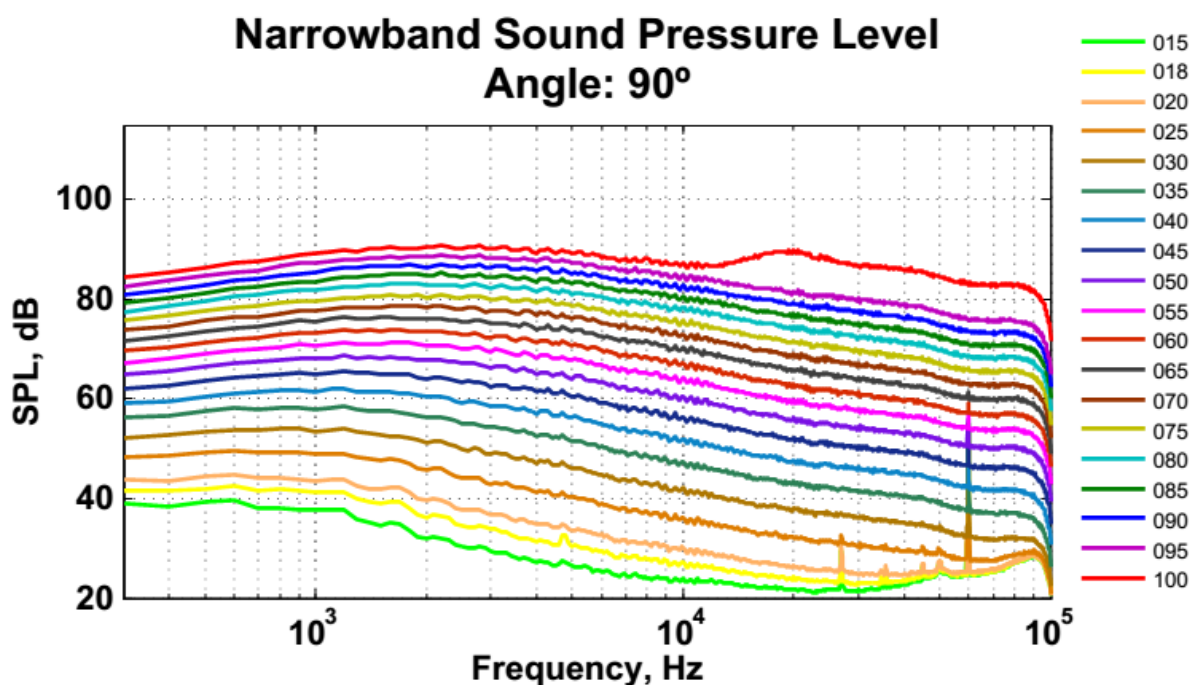


Figure 5.35 – Sound Pressure Level for different velocities at $\theta=90^\circ$.

Figures 5.36 and 5.37 present the SPL only for Mach numbers 0.25, 0.50, 0.75 and 1.00. It was chose only the lowest and highest angles, since the velocity trend is well established just with the Fig. 5.35. The increase in the Mach number means a higher Reynolds number, with more turbulent structures and scales. Independently of the observer angle, the fine-scale fluctuations and the large scale coherent structures fed by a flow with more energy must increase the SPL in all directions. When the observer is located at 90° or higer, these fine and large scales are not dominants in the noise produced, and the existence of shock waves are increasing the SPL at this angles due the refraction.

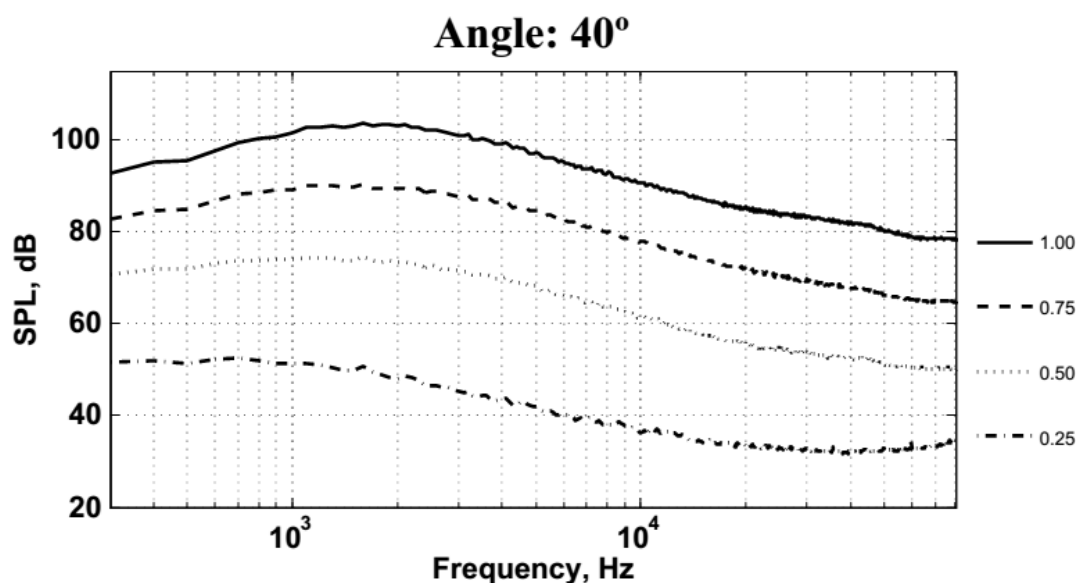


Figure 5.36 – Sound Pressure Level for different velocities at $\theta=40^\circ$.

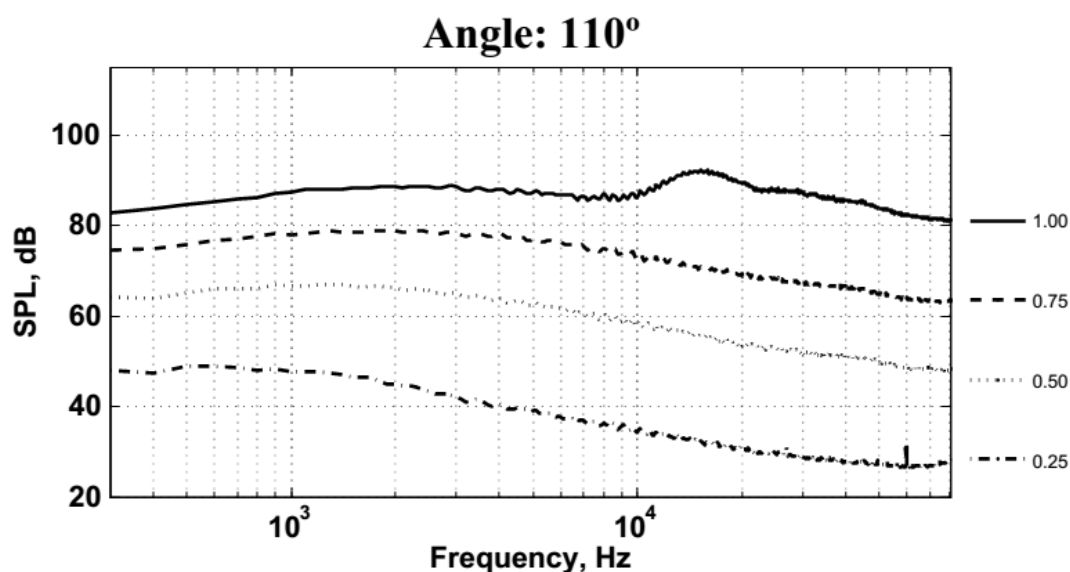


Figure 5.37 – Sound Pressure Level for different velocities at $\theta=110^\circ$.

5.2.2 Sound Pressure Level vs Observer Angle

The SPL pattern is now presented in observer angle comparisons. As stated in the Chapter 2, due the directivity of the sound and the effects overprint, the sound sources are convected downstream by the mean flow and the maximum noise is radiated at observer angles between 30 and 50°, what is found in the Figures 5.38 to 5.43. It also can be seen that the SPL difference between the observer angles becomes higher at low and moderate Mach numbers as the velocity increases. The opposite trend is checked to the high frequencies, even for just the subsonic conditions. The Doppler effect is more evident in high

Mach numbers as well the refraction, and it is distinct in the supersonic condition at Fig. 41, where the high frequency SPL is clearly influenced by the shock waves, specially to 90 and 110° angles.

Taking into account the overall sound pressure level – OASPL, the Figures 5.42 and 5.43 show the the same behavior as described previously. The Fig. 2.21 fits perfectly to explain the OASPL variation with the angle observed.

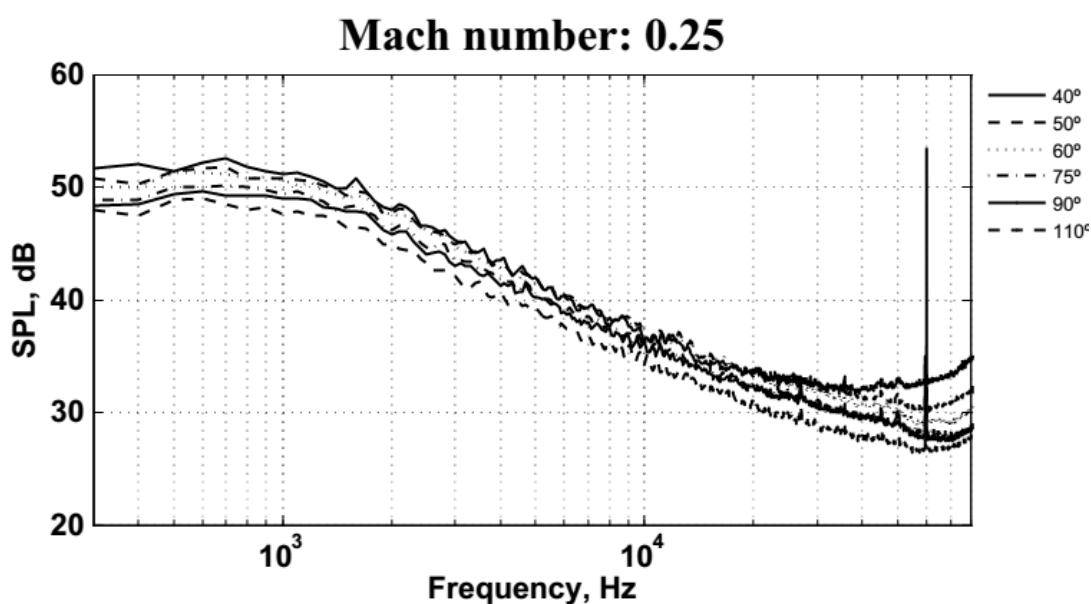


Figure 5.38 – Sound Pressure Level for Mach number 0.25 at six different angles (40°, 50°, 60°, 75°, 90° and 110°).

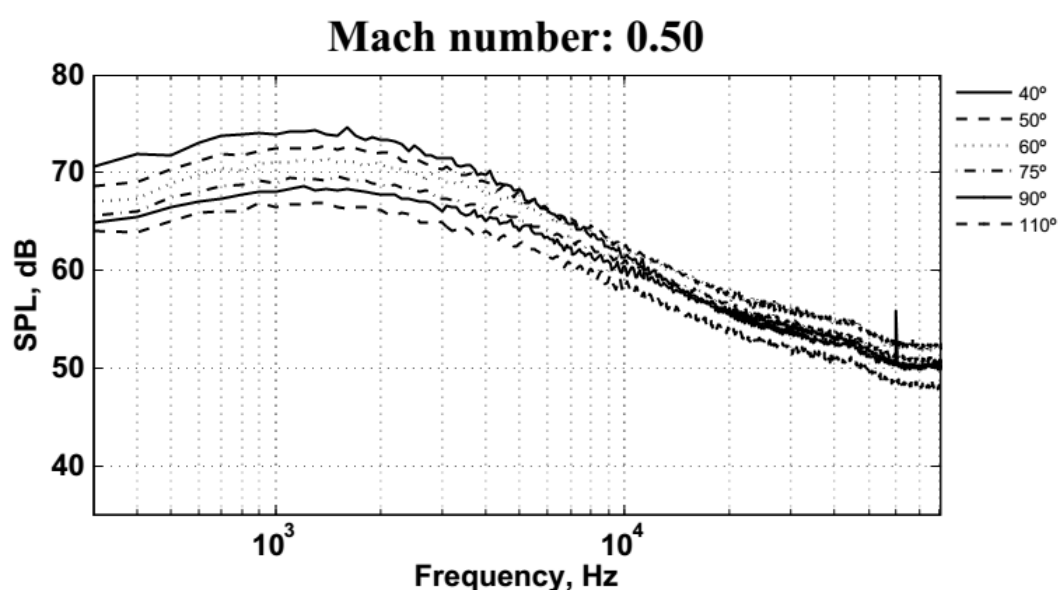


Figure 5.39 – Sound Pressure Level for Mach number 0.50 at six different angles (40°, 50°, 60°, 75°, 90° and 110°).

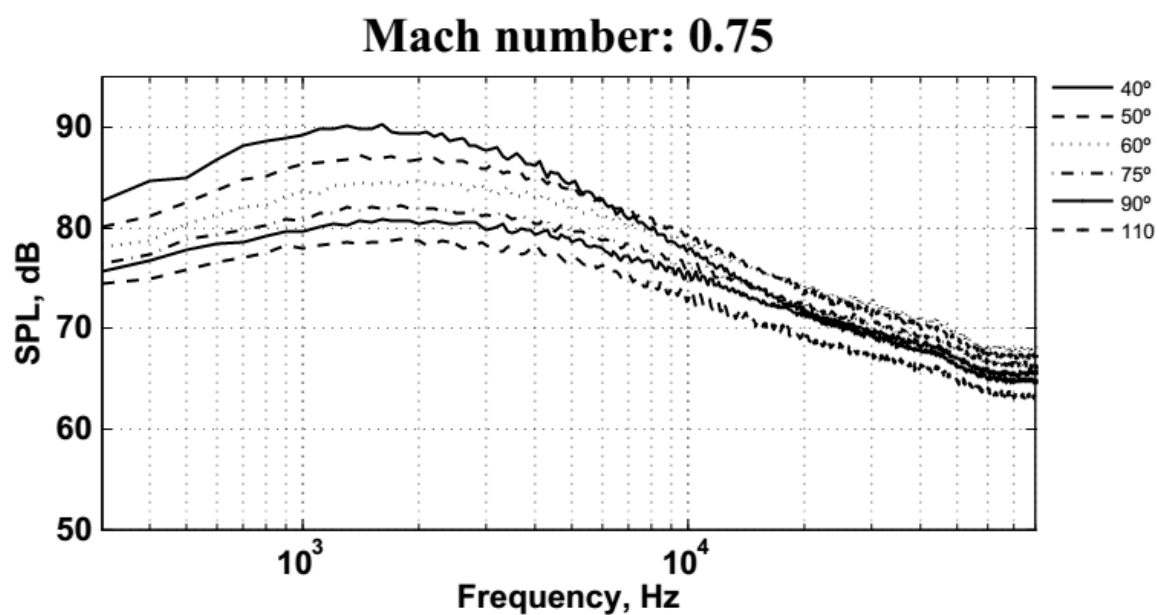


Figure 5.40 – Sound Pressure Level for Mach number 0.75 at six different angles (40°, 50°, 60°, 75°, 90° and 110°).

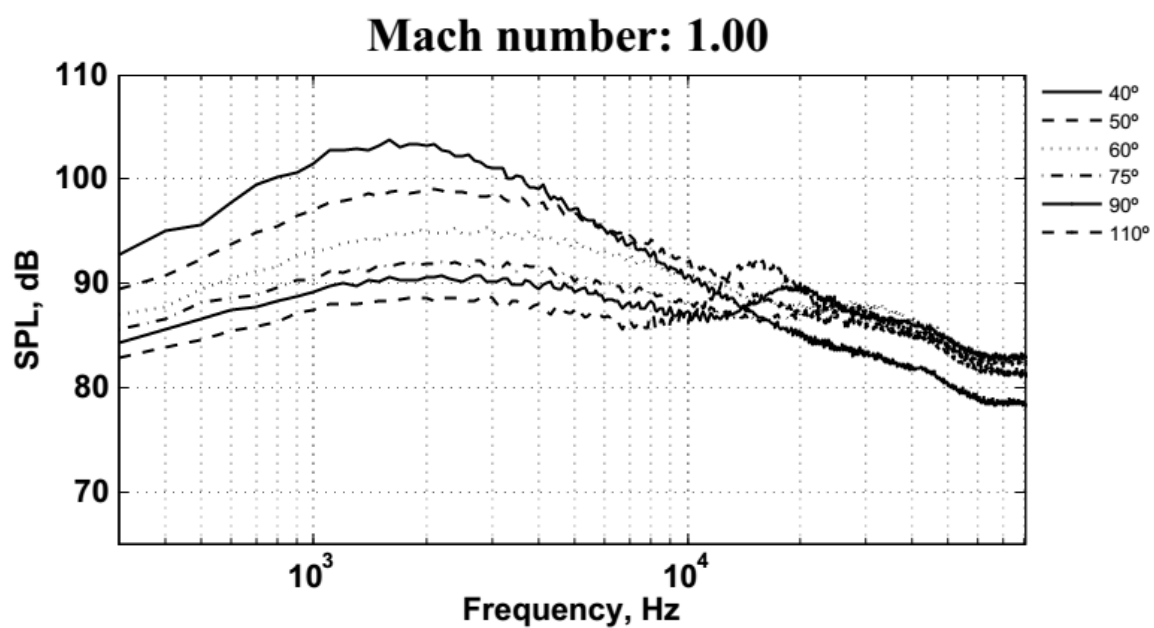


Figure 5.41 – Sound Pressure Level for Mach number 1.00 at six different angles (40°, 50°, 60°, 75°, 90° and 110°).

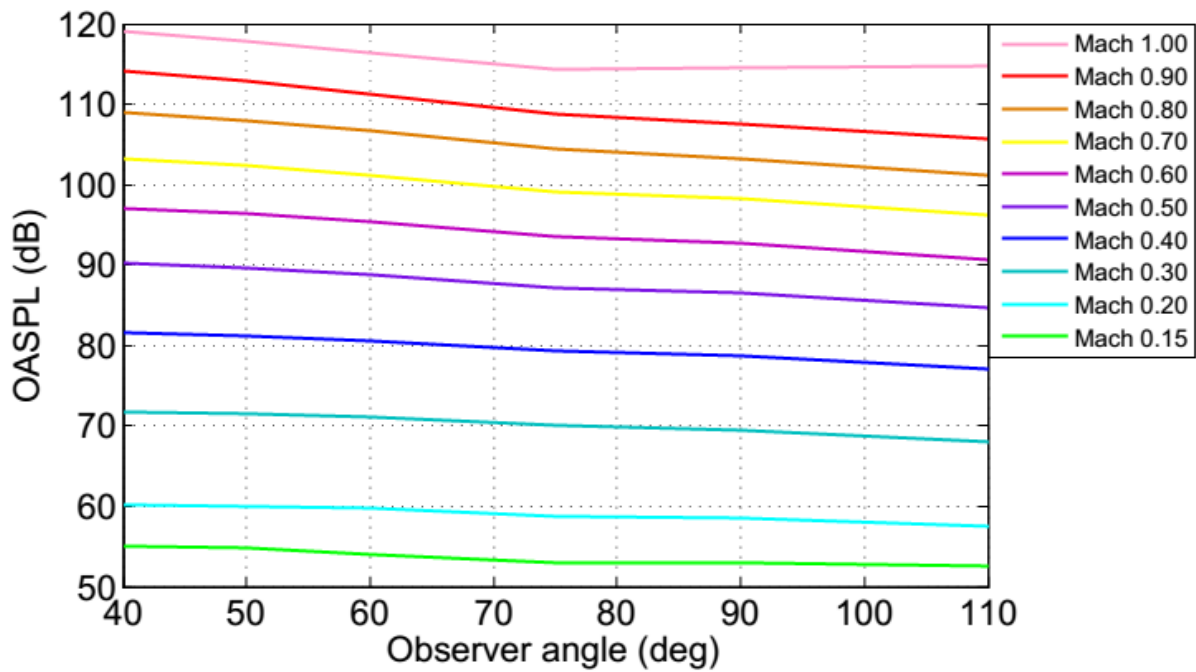


Figure 5.42 – Overall sound pressure level obtained by the integration of the SPL curves and its relation along the observer angles.

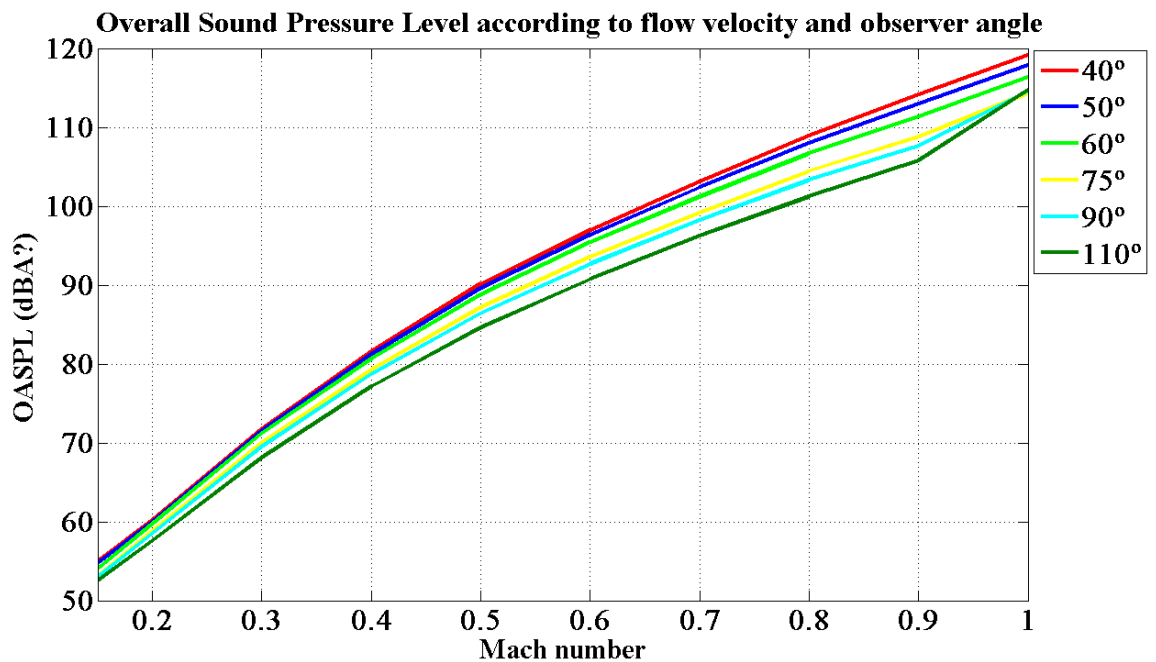


Figure 5.43 – The OASPL calculated vs Mach number, for the range of observer angles.

CHAPTER VI

CONCLUSION

The present work deals with the jet aerodynamics and acoustics exploring the basic theory related. The main goal was to study fundamental works, set up and run measurements from different systems and compare the results with the literature reviewed.

The jet noise issue has a distinct place on the aeronautical applications. The certification programs are imposing increasingly stricter limits and many researchers are devoting their efforts to mitigate the noise from aircraft. The engine is one of the most important noise sources, and it has been extensively investigated. As a result, the jet flow is one of the most searched topics of the last 60 years, and research involving extensive analytical, numerical and experimental methods.

Although many surveys have been done since the beginning of the twentieth century by the scientific community, the jet turbulent is an open field to new findings, such as the turbulent flows in general. The noise produced by a jet follows the same pattern, and despite the theory is well established, the models and considerations used are simplistic in many occasions. It is largely accepted that turbulence and noise are extremely correlated, which gives to the problem a particular degree of multidisciplinary.

Some rigs are shown and most of the parameters existing in an anechoic chamber equipped with jet rigs are described. Researchers have shown that the scale facilities have provided good data compared with integral scale experiments. This is viewed favorably by the UFU's team and the present work meets the objective of rise the first information to project and build a facility at this University.

A special anechoic chamber has been described: the Doak Laboratory, located at the ISVR. It also reports the equipment used to flow parameters control, acquisition systems and sensors. The instruments are divided in two groups: aerodynamic and acoustic. In the first one, it is mentioned the pitot tube and the hot-wire anemometry system. In the latter, high

precision microphones and amplifiers are reported. The experimental procedure showed is similar to many daily facilities, which will be useful hereafter.

The results are discussed in a methodical order. Firstly, it is presented the aerodynamic work, which compounds most of the efforts in terms of experiments, post-processing and analyses. It shows mean velocity profiles acquired by the pitot tube and hot-wire anemometer sensor. The experiments were carried out to several axial lines, and by combining these points it is also possible estimate the radial profiles, as well as a characterization of the subsonic jets regions. Through the anemometer data, it is also possible analyses the unsteadiness velocity, estimating the turbulence intensity in axial profiles and the power spectral density of the points measured. The profiles are compared with the literature for Mach numbers 0.25 and 0.75 presenting a good agreement, although at high velocities the hot-wire sensor seems to have some changes in its properties. Measurements for 0.5 Mach number are also performed.

Secondly, the acoustic results are shown to six observer positions for a wide range of velocities. The data is confronted to the theory showed in the chapter about the basic theory related to jets, and it shows a good agreement. The experiments done in this section are extremely simple in the way that many researchers are developing advanced techniques to jet noise measurements, but it is essential to the development of complex sets of experiments and insights about the jet physics, extremely important to the creation of semi-empirical methods. A database is created from these measurements.

6.1 Concluding remarks

The three regions of a subsonic jet: It is showed that the turbulence intensities acquired with a single component hot-wire anemometer can confirm the well-established concept of the dissipation, initial range and fully developed regions.

Relation between the jet velocity and the sound pressure levels: Both analytical and experimental works have shown the relation between the sound intensity and jet velocity. The acoustic experiments performed here reinforce this theory and allows a high resolution in interpolate and extrapolate data from subsonic cold jets at different observer angles.

Jet structures: With the power spectral density obtained by several points spread out the jet the theory presented about the fine and large scales is confirmed. Close to the nozzle it is found the smaller structures responsible for the dissipation of energy, whilst in the fully developed region the large coherent structures are present.

Hot-wire resistance: The modern hot-wire anemometer sensors have a high frequency response by having a reduced size, which is not quite attainable with other techniques. However, the system has an intrusive probe and it is restricted to low speed flows. During this research the sensor was placed into high flows and it did not show problems related to resistance, since the sensor was not damaged. However, the calibration curves showed that the sensor has changed its properties during the high velocities campaigns. It is believed that even for the reliable golden wire the system has physical modifications, probably related to the wire dilatation. In addition, the turbulence intensities exceeds the range specified by the manufacturer (T. I. up to 15%).

6.2 Future works

After all, the aerodynamic and acoustic study presented in this work could be highly enriched with length scale correlation information. Since it is proposed to study the noise produced by a jet through the turbulent properties, the correlation measurements and its techniques keep being developed and has helped to solve the turbulent flows statistically.

Experiments with two-point measurements using two single hot-wire anemometers are a good option to space and time correlations. In addition, the triple sensor hot-film anemometer can be used to set up the turbulent kinetic energy spectrum and compare with the PSD technique used to measure the spectrum at a single point in the present work. These experiments are planned to complete the present work in the future.

Correlation curves for analytical and numerical methodologies are also planned from the results of this work. The database for the SPL in function of Strouhal number is also desired, since it can be used to semi-empirical theories or even be an initial point to the development of a new one.

Finally, the experimental procedure presented for a free jet can also be extrapolated to other configurations. Fundamental works as described here must be applied to different nozzle, coaxial jets and mainly for installed jets, for example in jet – wing interactions.

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APPENDIX I

The Appendix I is used to exhibit the secondary and additional results or split some plots to improve the visualization and make the main text easier to read.

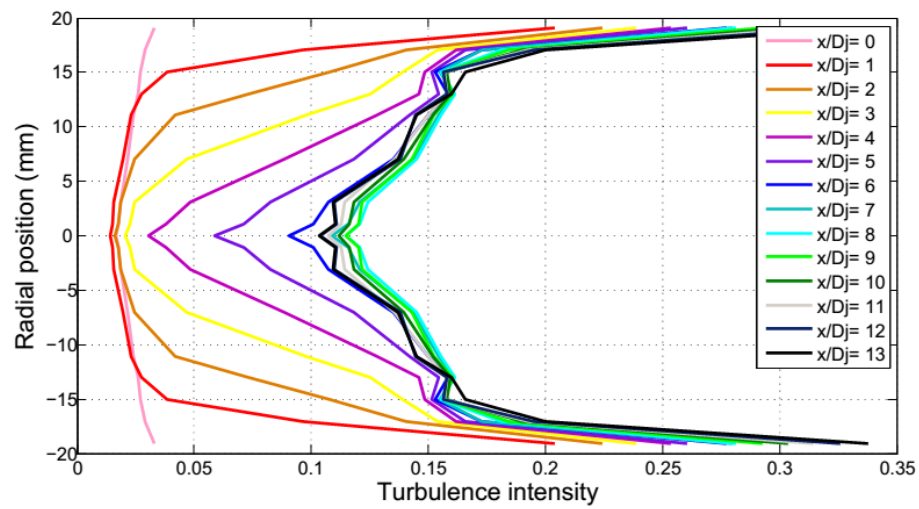


Figure AI.1 – Radial turbulence intensity profiles at Mach number 0.50 acquired with hot-wire anemometer. Positions $x/D_j = 1$ to 13.

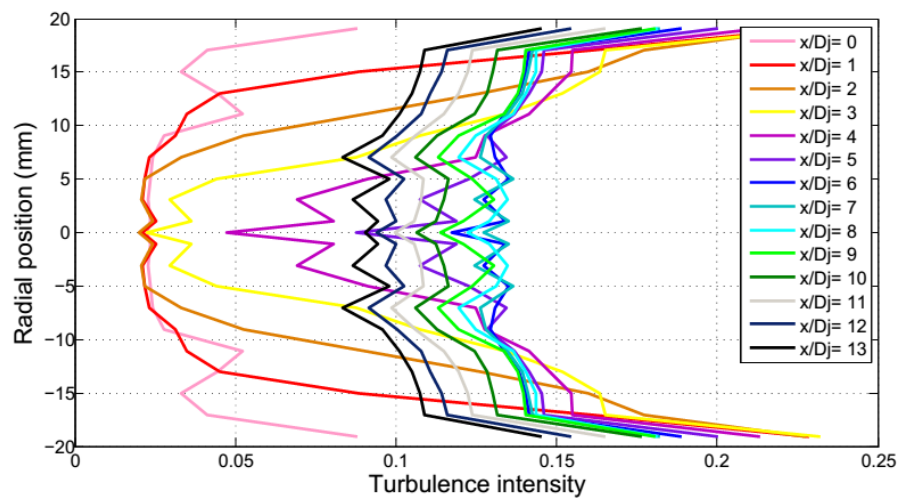


Figure AI.2 – Radial turbulence intensity profiles at Mach number 0.75 acquired with hot-wire anemometer. Positions $x/D_j = 1$ to 13.

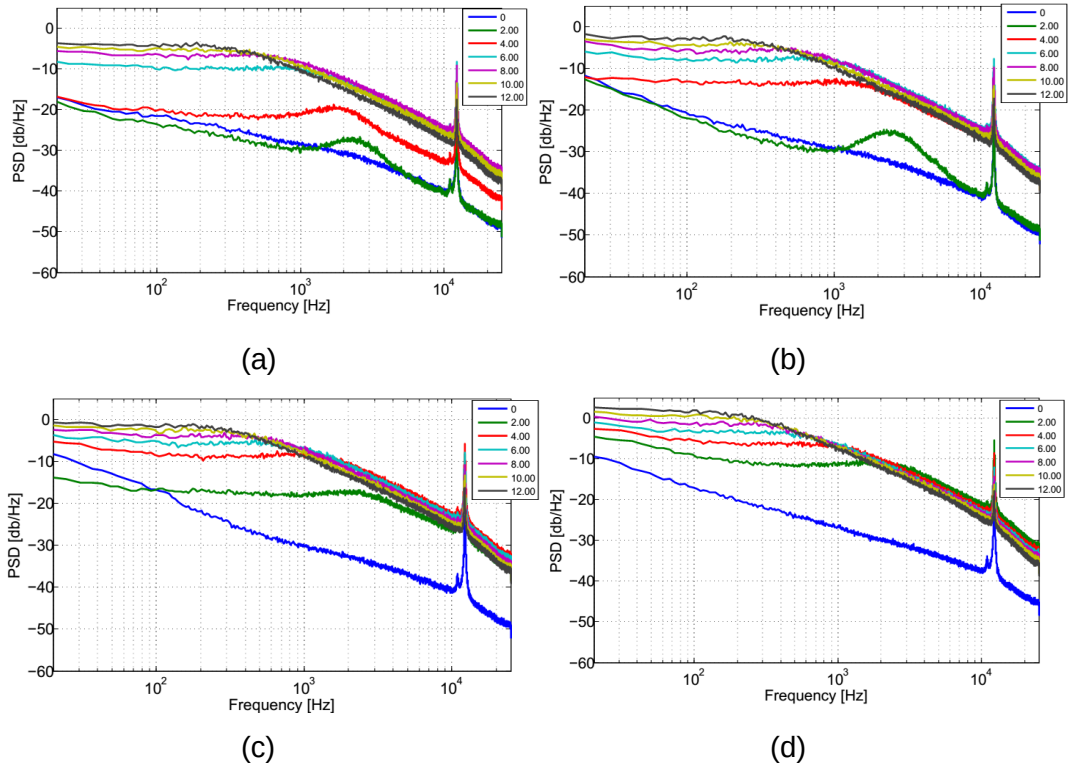


Figure A1.3 – Power spectral density in measurements at Mach number 0.50. $x/D_j=0, 2, 4, 6, 8, 10$ and 12 . (a) C1; (b) C4; (c) C7; (d) C9.

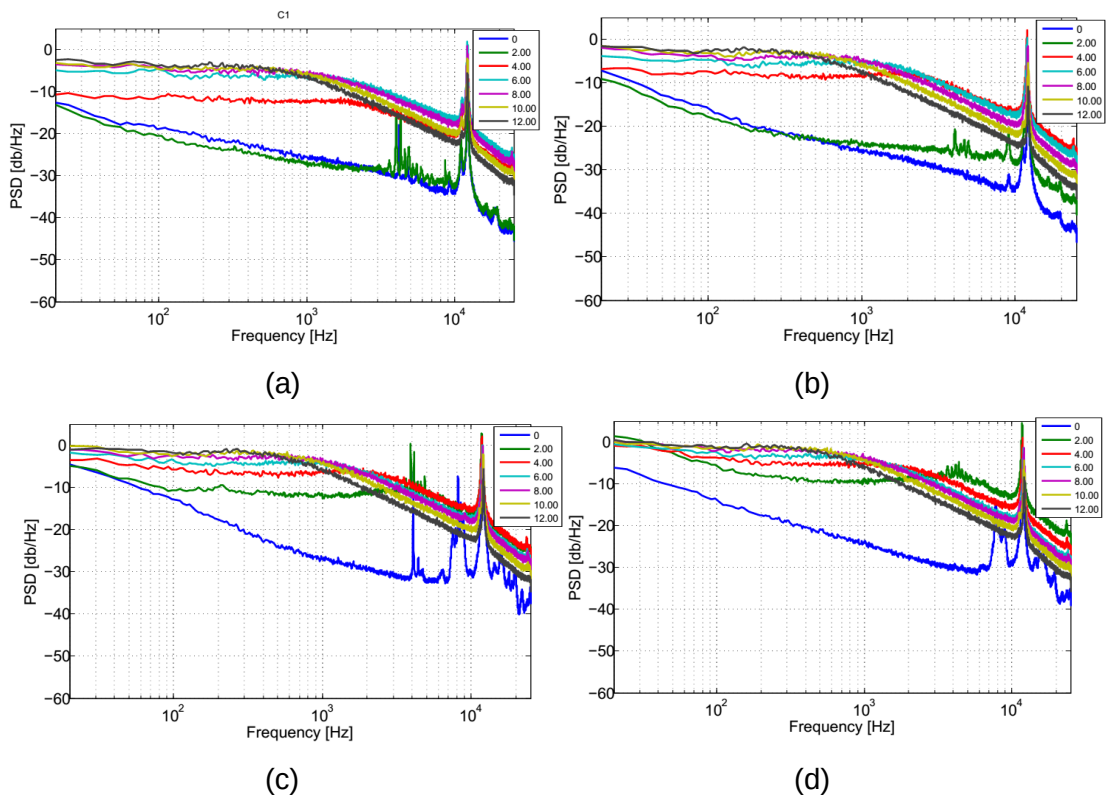


Figure A1.4 – Power spectral density in measurements at Mach number 0.25. $x/D_j=0, 2, 4, 6, 8, 10$ and 12 . (a) C1; (b) C4; (c) C7; (d) C9.

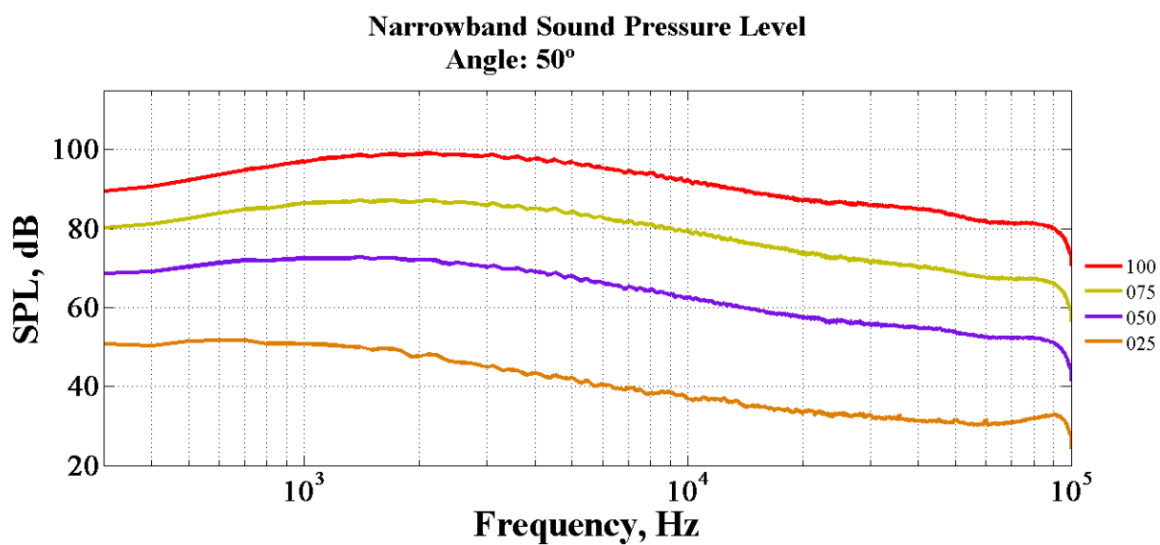


Figure AI.5 – Sound Pressure Level for different velocities at $\theta=50^\circ$.

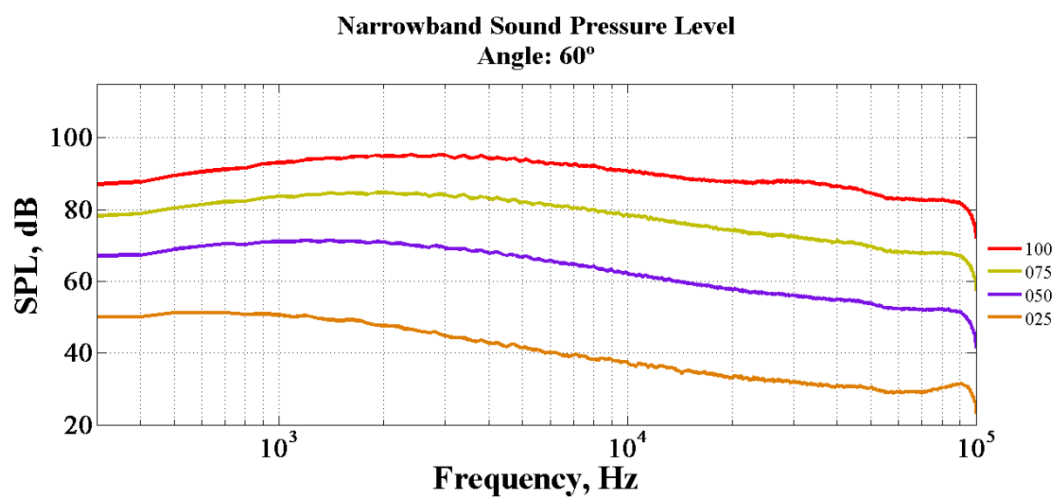


Figure AI.6 – Sound Pressure Level for different velocities at $\theta=60^\circ$.

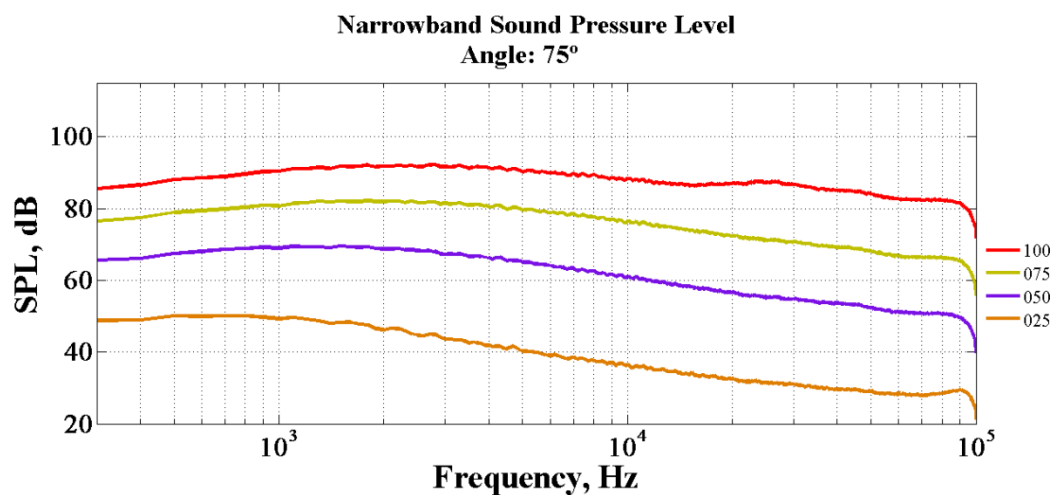


Figure AI.7 – Sound Pressure Level for different velocities at $\theta=75^\circ$.

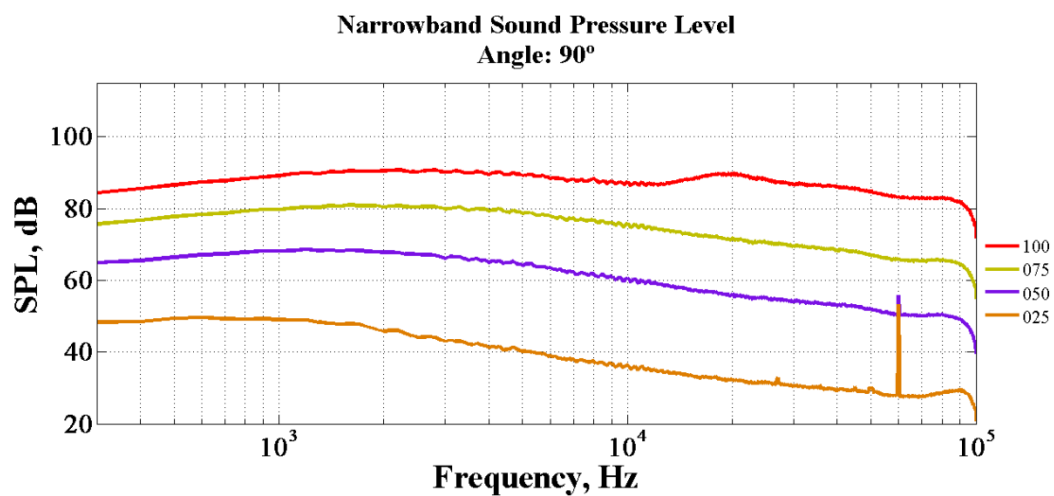


Figure A1.8 – Sound Pressure Level for different velocities at $\theta=90^\circ$.

APPENDIX II

The Appendix II demonstrates the procedure to data correction to the aerodynamic measurements, since there is a flow mass variation during long measurements. Figures All.1 to All. 3 show the real velocity measured with pitot tube (light blue), the velocity measured with a transducer on silencer, i.e., upstream the jet (dark blue) and the corrected velocity for this variation (the red one). Mach numbers are 0.20, 0.50 and 0.75, each one just for three jet lines: centreline, lip line and intermediated line (between the other two). For this text it is shown only one plot for Mach number, since it is merely illustrative.

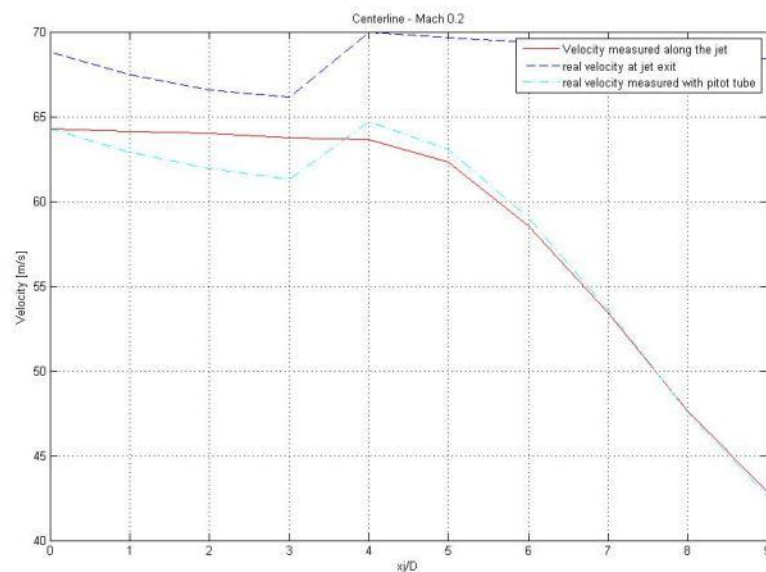


Figure All.1 - First results along the centreline jet axis, for Mach 0.20

Figure All.1 represents the velocity values for Mach 0.20 along the centreline. It is important to note the low resolution for these measurements, so just highlighting the trend and the correction factor used.

As said before, the flow variation for the final experiments had a maximum of 5m/s and that variation had a linear behaviour. This correction only eliminates peaks or small variations resulting from the increasing or decreasing of the flow velocity of a measured point

to another. It is used the velocity of first measured point as a reference and is made a 'correction factor' for the other points by dividing the reference value by the velocity measured upstream. The 'correction factor' multiplies the velocity measured by the sensor, whether pitot tube or hot-wire. Figure AII.2 exemplifies this process.

$V_{upstream1}$	$V_{upstream2}$	$V_{upstream3}$	$V_{upstream4}$	$V_{upstream5}$
$V_{sensor1}$	$V_{sensor2}$	$V_{sensor3}$	$V_{sensor4}$	$V_{sensor5}$
○	○	○	○	○ ...
1	2	3	4	5 ...

$$V1 = V_{sensor1};$$

$$V2 = V_{sensor2} * (V_{upstream1} / V_{upstream2});$$

$$V3 = V_{sensor3} * (V_{upstream1} / V_{upstream3});$$

$$V4 = V_{sensor4} * (V_{upstream1} / V_{upstream4});$$

$$V5 = V_{sensor5} * (V_{upstream1} / V_{upstream5});$$

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Figure AII.2 – Scheme used to fix the flow variation

Fig. AII.3 has shown other two cases, for lip line with Mach 0.50 and the intermediated line with Mach 0.75, respectively.

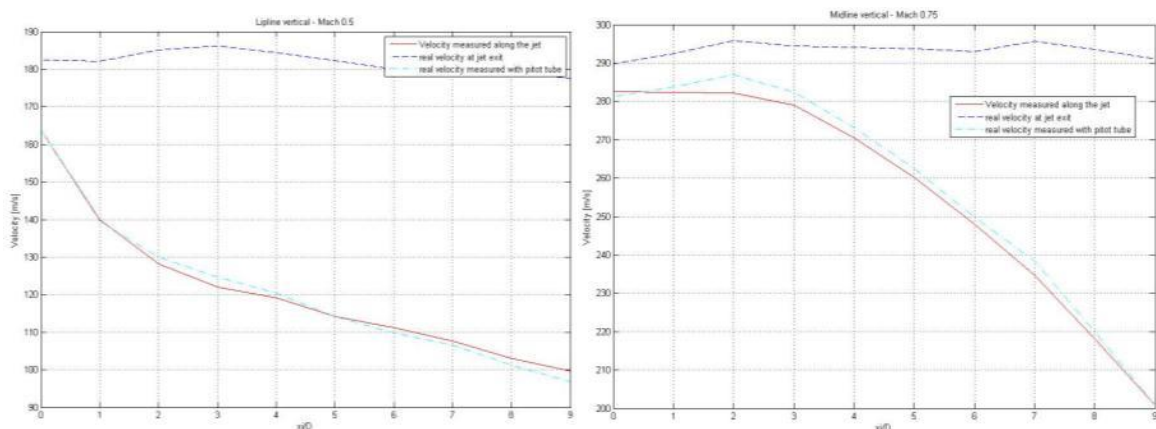


Figure AII.3 - First results along the lip line and intermediated line jet axis, for Machs 0.50 and 0.75, respectively.

APPENDIX III

Appendix III contains some issues found during the measurements. It was decided to show since most part of the problems faced in this work should be common in this kind of measurements, thus someone could be interested.

Unsteady flow

During the first measurements, one fact was clearly influencing the results: the flow velocity variation. To acquire data during ten minutes or more (some hot-wire measurements needs about more than one hour running) this action is not desired. Figure AIII.1 shows this variation.

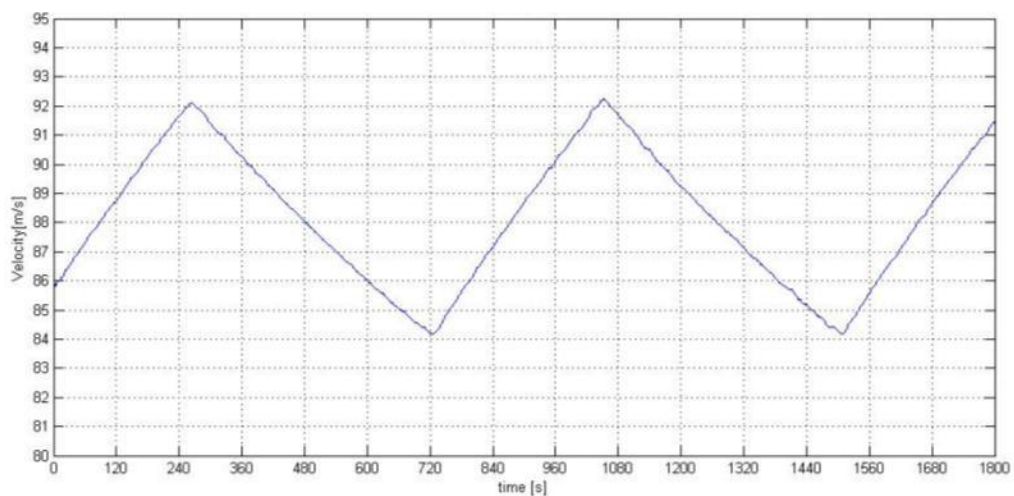


Figure AIII.1 - Variation of the flow velocity with the time.

The solution to this problem or, at least, a smoothing, is to use the compressors air system operating at high-pressures. When the figure above shown the velocity decreasing it means that the compressor is turned off and the flow is running out the system. The lower peak represents the minimum pressure acceptable in the tank storage, so the sensor turns the compressors on and the velocity increases until the high peak, which is due the maximum pressure set by the air supply system control. This process is unavoidable, unless

the system has an electronic valve. However, when a high work pressure is used, the difference between the maximum and minimum values of pressure and, consequently, exit velocity, are accurate enough to use simple corrections. The magnitude of the velocity is likewise important: low velocities show small variations and high velocities increase the speed process and the amplitude variation, shown in the Figure AIII.2.

For this work, the domestic pressure means 100 PSI and the high pressure 200 – 250 PSI. The Mach number 0.3 had less than 10 m/s of difference during a test with domestic pressure. To high velocities, 0.75 Mach, values around this fluctuation magnitude are obtained just using 250 PSI. Figure 9 shown a comparison of this situations for Mach numbers 0.2, 0.3 and 0.75, Domestic pressure (100 PSI) and high pressure (200 PSI).

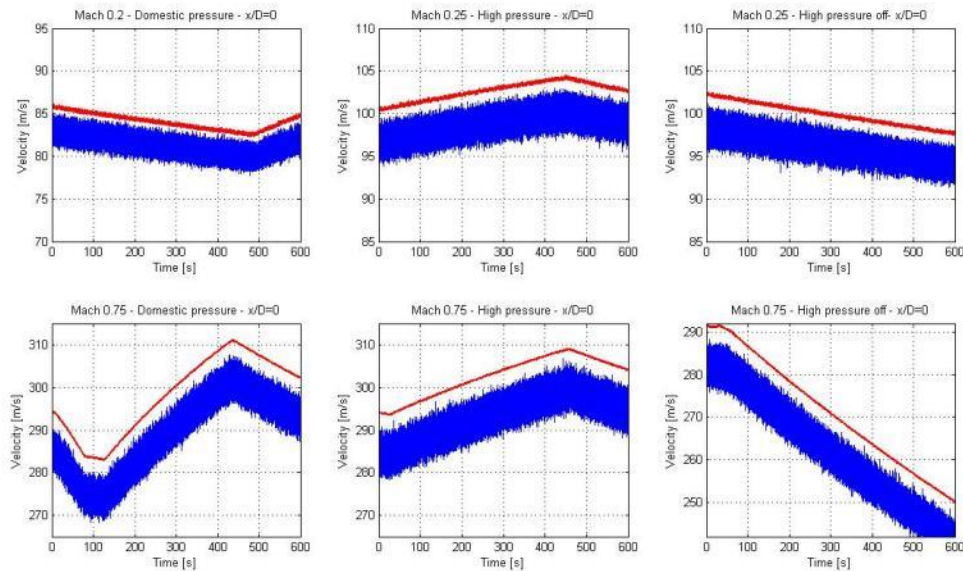


Figure AIII.2 – Velocity variation during ten minutes of experiment. Top: Mach 0.2. Bottom: Mach 0.75. First column: Domestic pressure (100 PSI). Second column: High pressure (200 PSI). Third column: Compressor turned off at 200 PSI.

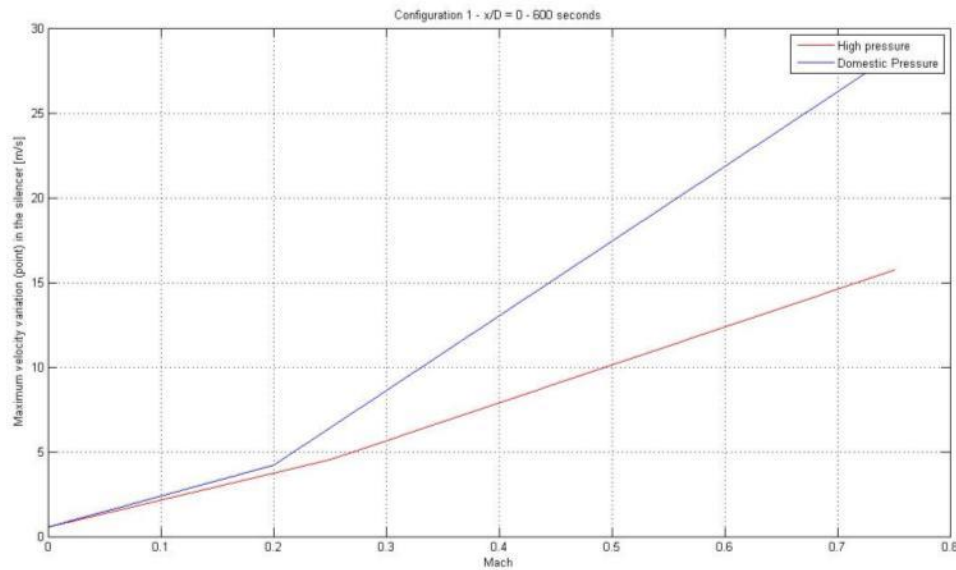


Figure AIII.3 – Behavior of different velocities (Mach 0.2, 0.3 and 0.75) at domestic (100 PSI) and high pressure (200 PSI).

Velocity offset between the transducers on pitot tube and the transducer on silencer

This question was found when the velocities just before the exit nozzle was compared with the velocities measured on the pitot tube. Next figure shows two examples.

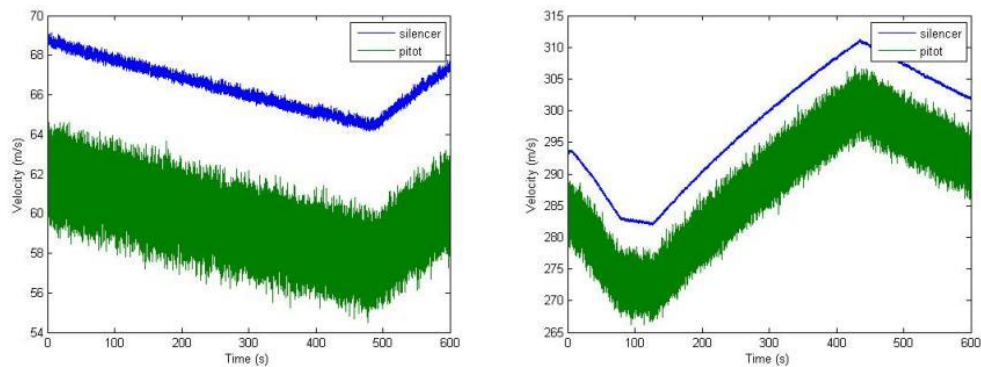


Figure AIII.4 – Low and high velocities measured by the pitot tube and the pressure transducer upstream on silencer.

Some procedures were performed to find the reason of this difference. The tubes were swapped and checked with bubbles, as well the connectors and other pitot tubes also were tested. An important point was evidenced when the figure above shows the gap of velocity between the two sensors is larger as the velocity is larger. It leads to some leakage at some point of the experiment. Furthermore, the transducers were several calibrated and lots of

configurations (swapping pitots, tubes, connectos, transducers, cables and calibrators) were tested (Figure AIII.5). It does not matter which transducer and system is, always the sensor on silencer will present the major value. Below, some equations from transducers which the statistics can be reliable.

Transducer on silencer: $y = 12698x + 1283$, $y = 12356x + 2815.2$, $y = 12712x + 1177.2$.

Transducer on pitot tube: $y = 12772x + 435.71$, $y = 12726x + 1052.8$, $y = 12548x + 2183.5$, $y = 12366x + 2771.7$.

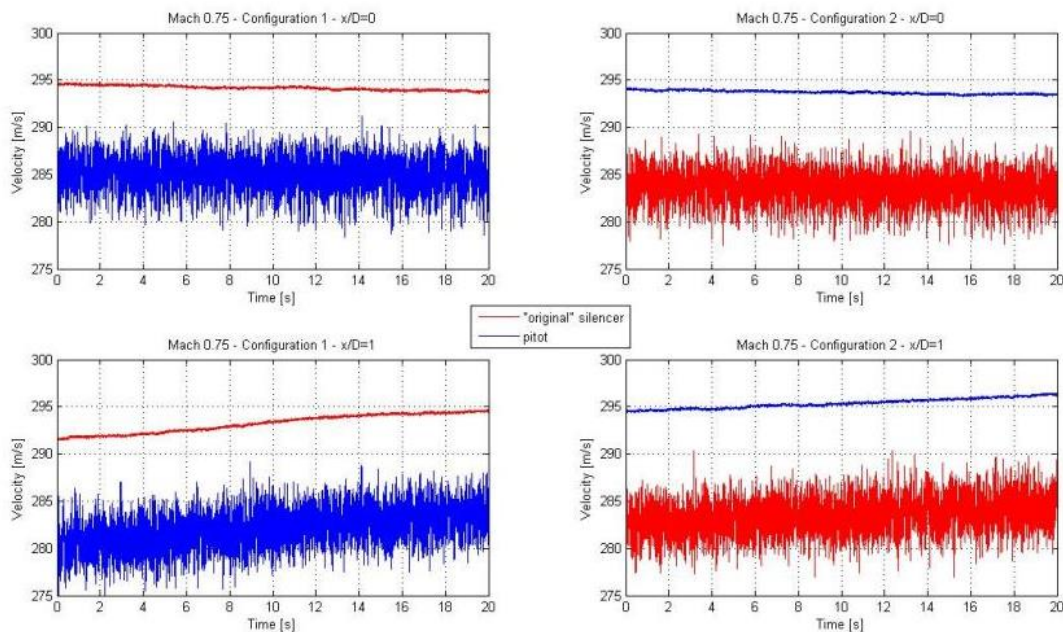


Figure AIII.4 – Different configurations showing the difference between the sensors. Configuration 1: Transducers on its place. Configuration 2: Swapped transducers places.

After all, discarding problems with the transducers, transducer calibrations and the tubes, only the pitot and some leakage between the silencer and the nozzle was taking account. A new pitot tube system was provided by QinetiQ, and the results on the Figure AIII.6 leads to differences around 7 to 8 m/s at high velocities using a simple transducer, and less than 5 m/s using a micromanometer system.

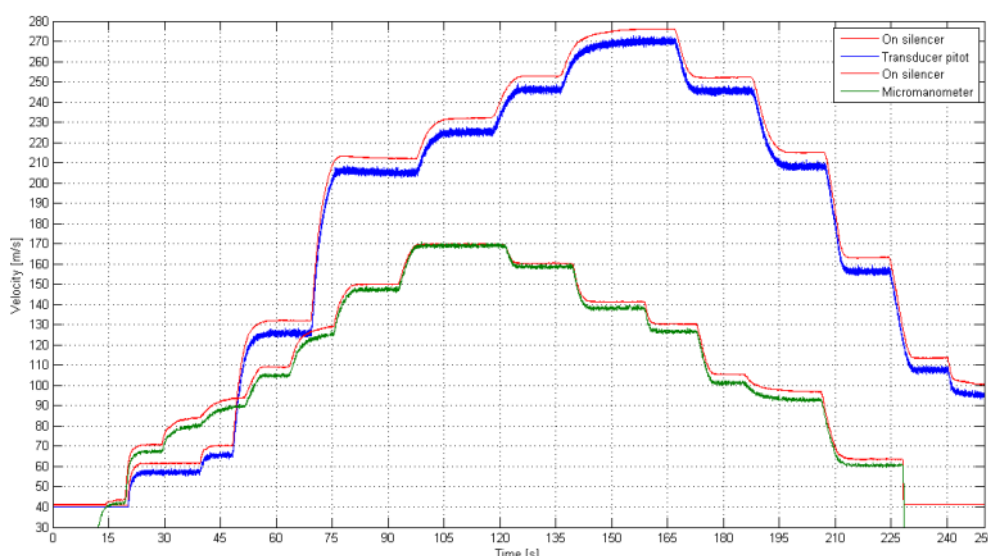


Figure AIII.6 – Difference between the velocities on the silencer (red) and the pitot tube using a single transducer system (blue) and a micromanometer system (green).

Traverse issues

The traverse system is used to move the sensors and probes. It is an automated machine which operates with associated software. The TSI company, contracted to supply the hot-wire and traverse system, offer the software Thermal Pro. This program acquires the hot-wire data in binary files, post-processes and plot the graphs. Furthermore, the traverse system can be moved manually or automatically by a matrix of points to course.

The system moved very well in X and Y axis, but not in Z. The first TSI consulting found that there were only two cards on traverse channels and it was exceeded. After upgrade the system and put three channels, the axis Z keep in conflict with the program. It had no reason to move, sometimes working, sometimes not. A new consulting from TSI the answer was an incompatibility between the software and the traverse system. In other words, only a new version of the software (which had no prediction to occur) could solve the problem.

Some months after, some students from University of Santa Catarina, in Brazil, confirmed that the same system (Traverse ISEL, hot-wire anemometry system by IFA, provided by TSI) works very well in the three axis.

At long last, once our experiments were carried out in a horizontally line (always on the centre, without move vertically), the “zero” was set manually and the Z axis remained static during the campaigns.

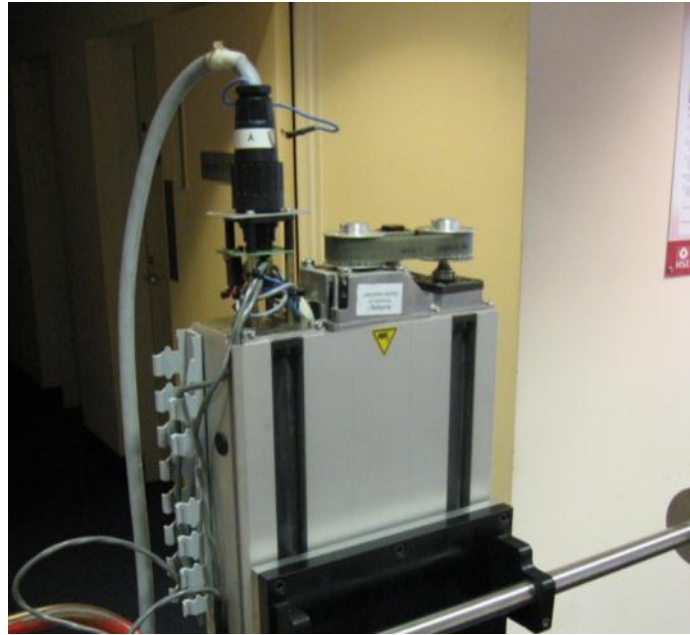


Figure AIII.7 – Z axis moved manually.

Hot-wire measurements: Gain and offset

A parenthesis about the hot-wire measurements that got some time during the tests. The first data from this experiments can be seen on Figure 15. The trend of the curve looks like similar to the expected, both to values of mean velocity and unsteady velocity (fluctuations divided by mean at each point measured).

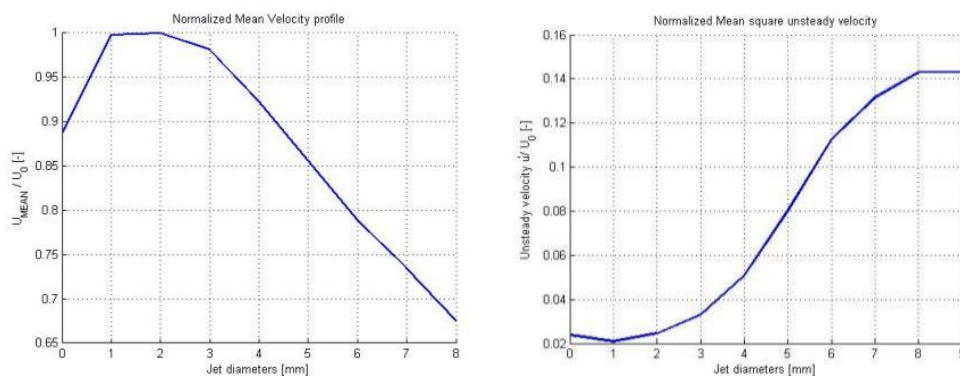


Figure AIII.8 – Results along the centreline of the jet to mean velocity (left) and unsteady velocity (right).

Lots of measurements were carried out after this apparently good result. Looking to the raw data, a bad surprise was found: the signal was getting out of the range (-5 to 5 volts), like next figure.

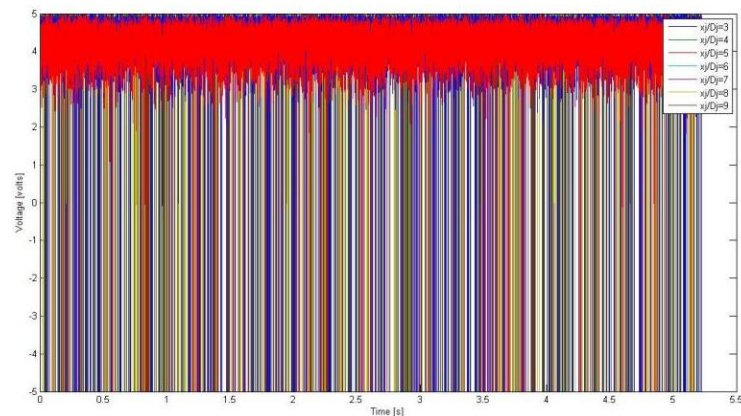


Figure AIII.9 – Raw data acquired during the centreline measurements. The different colours represents the points measured away the nozzle. The variables are time measured ('x') and signal in terms of voltage ('y').

The results from the lip line showed the same. A good trend about the mean and unsteady velocity, but the data are not reliable. Next figures demonstrate this statement.

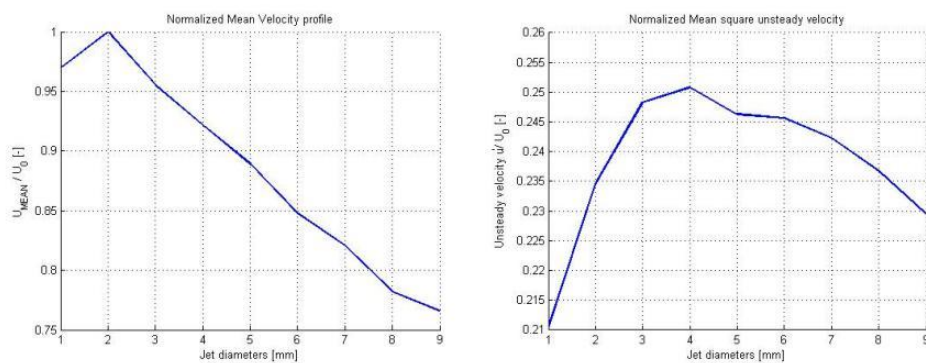


Figure AIII.10 - Results along the lip line of the jet to mean velocity (left) and unsteady velocity (right).

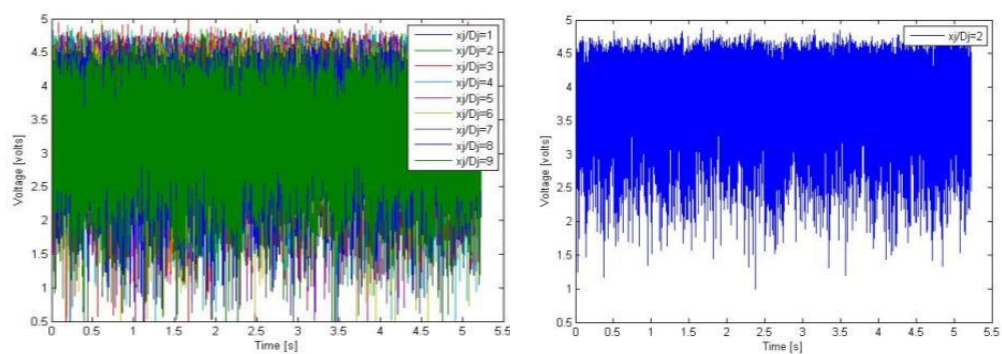


Figure AIII.11 - Raw data acquired during the lipline measurements, similar to figure AIII. 9. Despite here the data looks like inside the work range, a better look in just only one point (right plot) show the real biased signal.

The solution to this case is simple, is just work with the correct values of gain and offset. What was being made is choose the suggestion given by the software. The procedure following the manual was done correctly, thus the problem should be in the interpretation of the software or some hardware damage. The hot-wire sensors were calibrated manually for a gamma of “gains” and “off sets” and for each experiment an optimization analysis was made. The data acquired were as best as possible.

Anemometer system (channel 1)

Even getting reasonable data, the investigation to understand the problem about the gain and the offset continued. After compare the three hot-wire channels with a step-by-step send by the TSI, the channel 1 shown some irregular behaviour. Looking this channel, the sensitivity of the probes were really small. Figure AIII.12 show that a variation of 80 m/s in velocity generate less than 1 V in voltage, even to high gains.

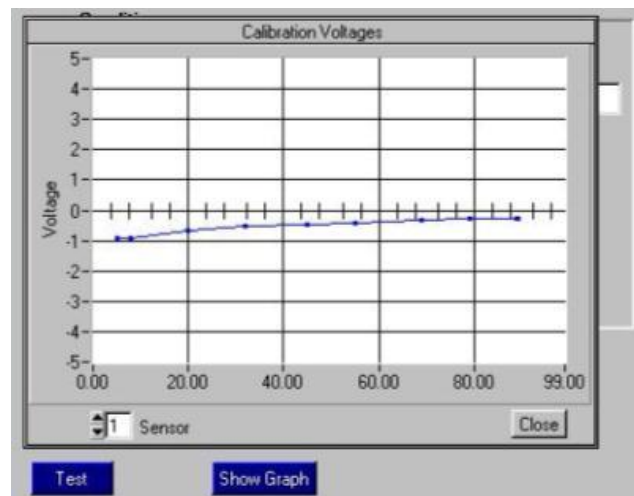


Figure AIII.12 – Variation of the voltage during the calibration procedure carrying on the channel 1.

The TSI noted the problem and should exchange the channel. Meanwhile, the experiments were done using the channels 2 and 3. Single hotwires use just one channel by time, correlation measurements uses two channels and only the triple hot-wire should be a problem, specifying the three channels.

Next figure presents the comparisons between the channel 1 and channel 2 during the same calibration procedure.

Calibration - Data Table
Probe 70544194A printed at 10-04-2011 15:44:17

Cal Point	Bridge Voltage	Bridge Voltage	Bridge Voltage	dP	Actual Velocity	Temp
1	0.8596			0.00	18.90	
2	1.1697			8.00	19.15	
3	1.3051			15.00	19.14	
4	1.3838			22.00	19.04	
5	1.4707			32.00	19.06	
6	1.5188			39.00	19.08	
7	1.5859			49.00	19.08	
8	1.6491			64.00	18.96	
9	1.7269			84.00	18.71	
10	1.7538			94.00	18.62	

Calibration - Data Table
Probe 70544194CHANNEL1S printed at 10-04-2011 15:57

Cal Point	Bridge Voltage	Bridge Voltage	Bridge Voltage	dP	Actual Velocity	Temp
1	0.1620			0.00	18.65	
2	0.1999			2.00	19.09	
3	0.2238			17.00	19.25	
4	0.2332			23.00	19.10	
5	0.2450			33.00	19.01	
6	0.2547			42.00	19.09	
7	0.2638			50.00	19.15	
8	0.2778			69.00	18.91	
9	0.2851			84.00	18.76	
10	0.2960			102.00	18.47	

Figure AIII.13 – Data calibration from channel 2 (left) and channel 1 (right).

A final test was made and give a curious result: if the calibration begin when the jet is at high velocity (tests used around 100 m/s) the sensor sensitivity works well, until low velocity. It lead to think the sensor has some problem to heat transfer at low to moderate velocities. However, the question is why the sensor works correctly when the system was turned on with jet steady at high velocity and does not work if the fluid begins to flow after the system, even coming at any velocity.

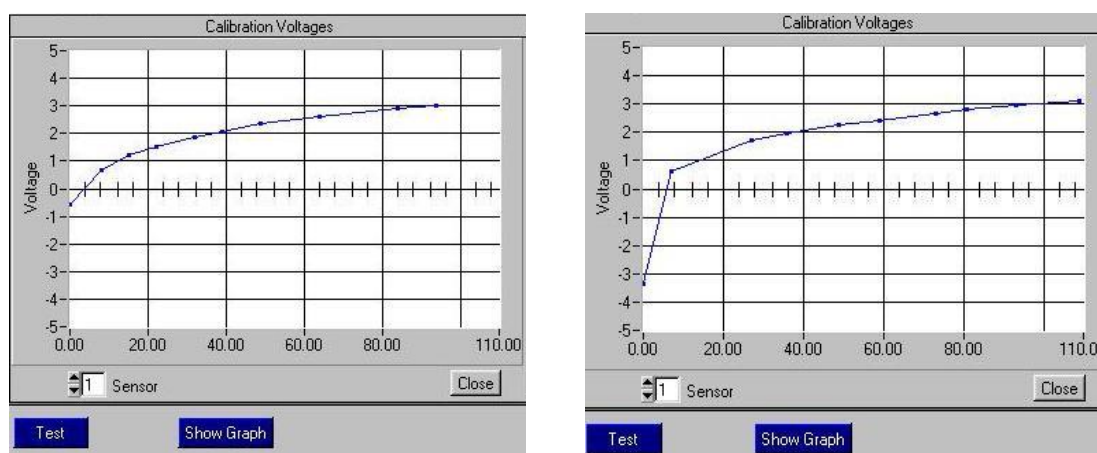


Figure AIII.14 – Characteristic calibration from channel 2 (left) and a calibration from channel 1 when the high velocities were measured first.

Hot-wire calibration

Another point taken into account is about the “decalibration” of the sensors during the experiments. Early in the day, before begin the tests, a calibration of all sensors were made. Other two calibrations along the day, one at noon and other in the end of the day, and often the results were slightly different.

There were not cases found in the literature, but the suspicion is related to the dilatation of the wire after be exposed to high velocities for long time. This work also was a survey about the hot-wire resistance, since most part of the literature works with Mach 0.3 or lower. A typical day of these experiments reported here put the sensors working about eight hours per day, with a one hour pause in the middle of the day, with velocities between 10 and 270 m/s.

Figure AIII.15 exemplifies this consideration.

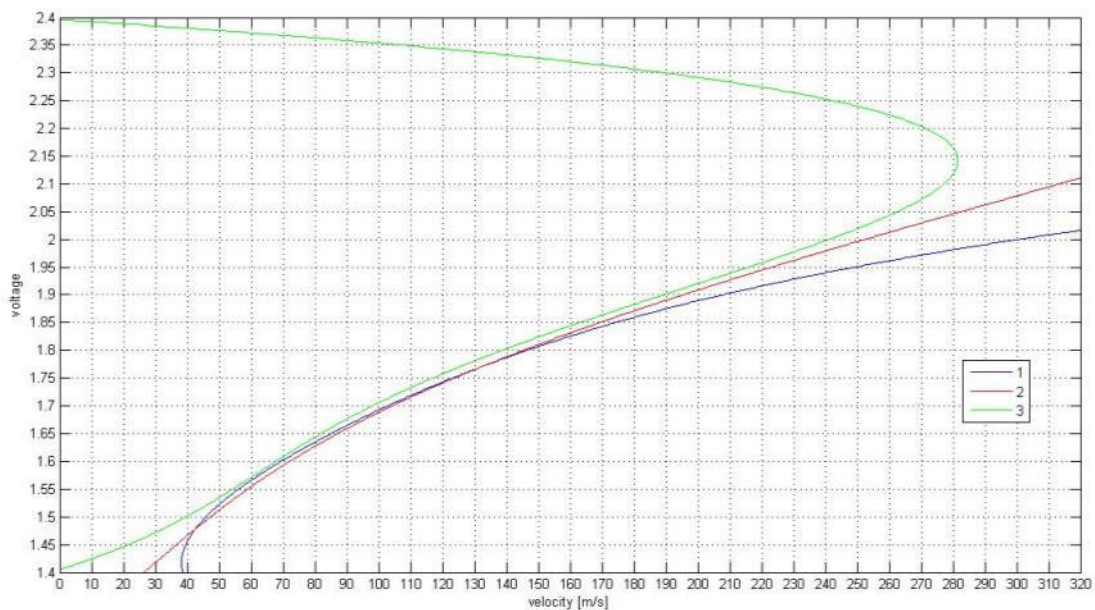


Figure AIII.15 – Different calibrations to hot-wire sensor. Velocity range: 50 to 270 m/s (which explain the bad tendency of the green curve after 270 m/s). Curve 1 – blue: Calibration at 7 am. Curve 2 – red: Calibration at noon. Curve 3 – green: calibration at 6 pm.

This does not represent a big problem, but to be more accurate, an semi-empirical curve was adopted, just interpolating the results two by two. Moreover, the calibration was made using the velocity calculated from the transducer on silencer and inserting this value on hot-wire calibration software, which means in a result approximated.

Radial correlation length scales measurements

For this campaign, a support should be design and built. This experiment needs two sensors working simulstaneously. The supports from manufacturers are just to single measurements. The only way is to project and to build it at the University. During this work lots of sketches were made, like Figures AIII.16 and AIII.17.

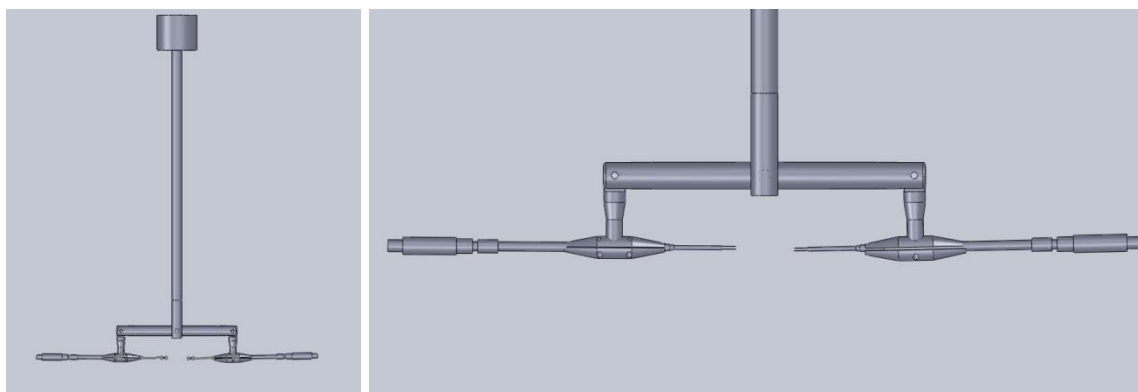


Figure AIII.16 – Sketch of the proposed system. Left: system with the bar, support and hot-wire sensors. Right: Zoom in the region support/sensors.

The support can be moved by a rotation of its pieces, giving the range distance on the sensors necessary to the correlations.

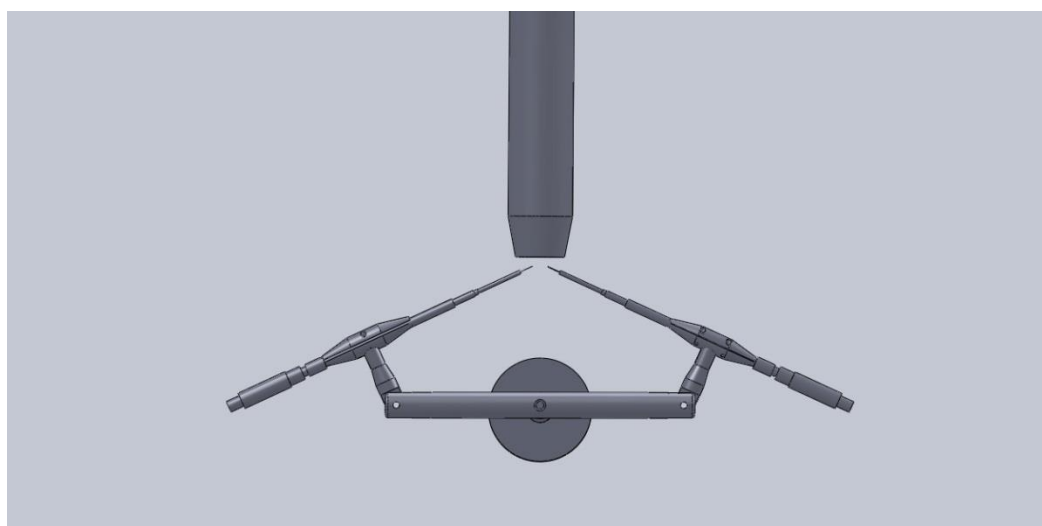


Figure AIII.17 – Sketch of the proposed system. A top view with the nozzle.

The problem with this configuration are the restrict kind of correlations (only radial and azimuthal correlations, not along the x axis) and the control of the distances between the sensors. This control is very important to obtain reliable data and avoid the sensors to shock at small distances.

A new and simple sketch was being designed, but it had no time to be made during this work.

Triple sensor measurements

The triple sensor measurement has significant differences from the single sensor. The data are acquired using three channels for all points measured. The calibration also is more complex than the other one, requiring more attention and procedures. The post-processing is, obviously, different as well. Despite the fact the experiments are too much expensive and not too easy, the results obtained are really important to studies about aerodynamic of jets.



Figure AIII.18 – Triple hot-wire sensor used to this work.

As stated before, the current anemometer system has three channels and the first one was defective. It got some weeks to the TSI fix it, and just after the experiments of this nature were carried out.

The Figure AIII.18 is good to explain another difficult issue: there is no commercial support available to the sensor. The long thin bar is a problem to fix and avoid undesirable vibration. A special support should be made, what was not, since there was no enough time.

Since the three wires do not form exactly the three perpendicular axis, calibration comes from an related equation, resulting in moves of rotating during the process, impossible for the equipment available. The high costs involved in hiring a company for this task took this job to do the experiments using a default calibration from the manufacturer.

Despite all these factors previously mentioned, some experiments were carried out during the last week of measurements.

Turbulence spectrum and turbulent kinetic energy (3 velocities components)

The experiment using the triple sensor data at Mach 0.25 should get the true results for turbulence intensities and turbulent spectrum and kinetic energy. Again, the incorrect calibration of the sensor affects this data, but the red points showed in the Figure AIII.19 were acquired and are copied to enable a new post-processing.

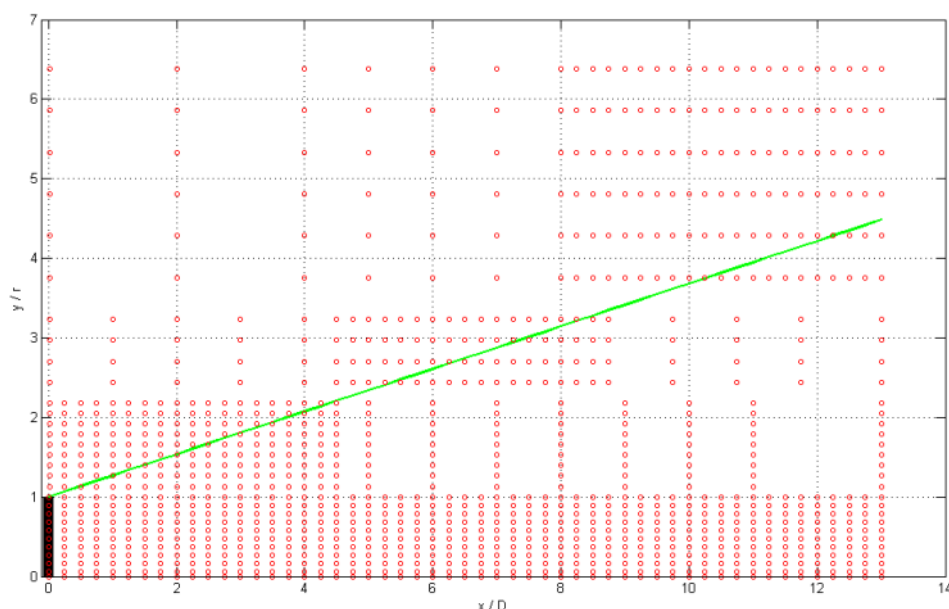


Figure AIII.19 – Points of the campaign using triple sensor hot-film.

Triple sensor data

A new program routine to post-processing the triple sensor data was written. The data were acquired in a sample frequency of 100 kHz to do the turbulence analysis in the small scales of flow. Nevertheless, each point measured by the three channels simultaneously created a binary file extremely large. This file has an special format to save the data in values of voltage. A program is used to convert this value using the calibration curve to get the values of velocity, turbulence intensity and others. The simple computers (8 Gb of memory ram) could not handle and save the data using Matlab. A super machine or another programme language maybe solve this point. The choice used was to process the data in the program Thermal Pro. It took several days in the office.

After that, other binary files were generated. A studied about the data structure was done and a new routine written. The Thermal Pro software save the data in a specifically sequence of eight statistical parameters: mean velocity, normal stress (variance), standard

deviation, turbulence intensity, third moment about the mean, skewness coefficient, fourth moment about the mean and flatness coefficient.

Generating the first point results, it was realized that the mean velocity was completely wrong. The expected values to Mach 0.25 (around 80 m/s) was around three and four times bigger. Checking along the other points, it was found that the calibration curve used is incorrect. Since this curve is not linear and is specific to each sensor, the results cannot be used, unless a new and correct calibration would use again in the program. Even the statistical results, the fluctuations values are not true using this manufacturer calibration curve.