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**EXPERIMENTAL AEROACOUSTIC STUDY OF NOISE REDUCTION
DEVICES FOR UAVs**



UNIVERSIDADE FEDERAL DE UBERLÂNDIA
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Bachelor thesis submitted to the Undergraduate's
Course of Aeronautical Engineering of
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Aeronautical Engineering.

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To my Dad

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I would like to thank my father Wellington for all the support and encouragement in every aspect of my life and especially throughout this journey.

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ABSTRACT

The present study focuses on the effects of noise reduction devices for unmanned aerial vehicles, motivated by the sudden growth in the number of consumer and commercial drones, which could lead to an increase in noise pollution, especially in major cities. Initially, a summary of possible solutions to noise reduction is presented in the literature review section, then, the 3D printing and manufacturing process is explained for each device built. Thereafter, two duct and four propeller configurations are tested and analyzed through the signal acquisition of the noise frequency spectrum, which demonstrates that ducts amplify the noise signature in a range of high frequencies, while certain propeller configurations manage to reduce over 0.5 dBA for most of the frequency spectrum and up to 4 dBA at certain frequencies. Finally, results and conclusions are discussed in the final chapters, comparing the effectiveness of each device to the unshrouded standard propeller.

KEYWORDS: *Noise Reduction, Aeroacoustics, UAV, Drone.*

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RESUMO

O presente estudo é focado nos efeitos de dispositivos de redução de ruído para veículos aéreos não tripulados, motivado pelo súbito crescimento no número de drones recreativos e comerciais, que poderiam levar a um aumento da poluição sonora, especialmente em grandes cidades. Inicialmente, um resumo de possíveis soluções para redução de ruído é apresentado na seção de revisão de literatura, então, o processo de fabricação e impressão 3D é explicado para cada dispositivo construído. Em seguida, duas configurações de duto e quatro configurações de hélices são testadas e analisadas através da aquisição de sinal do espectro de frequência do ruído. O qual demonstra que dutos amplificam a assinatura acústica em uma faixa de frequências altas, enquanto que certas configurações de hélice conseguem reduzir acima de 0.5 dBA para maior parte do espectro de frequência e até 4 dBA em determinadas frequências. Por fim, resultados e conclusões são discutidos nos capítulos finais, comparando a eficiência de cada dispositivo com a hélice padrão sem duto.

PALAVRAS CHAVE: Redução de ruído, Aeroacústica, VANT, Drone

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LIST OF ABBREVIATIONS AND ACRONYMS

UAV - Unmanned Aerial Vehicle

FAA - Federal Aviation Administration

EASA - European Aviation Safety Agency

NASA - National Aeronautics and Space Administration

ANC - Active Noise Control

dB - Decibel

dBA - A-weighting Decibel

RPM - Revolutions per minute

ESC - Electronic speed controller

ABS - Acrylonitrile Butadiene Styrene

SPL - Sound Pressure Level

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Chapter I

1. INTRODUCTION

1.1 Background

The beginning of the history of unmanned aerial vehicles (UAVs) or drones as they are popularly called, dates back to 1783, when the Montgolfier brothers using fire, bags of silk, paper and linen, attempted a new experiment, by placing a flame on the bottom of a bag and causing it to rise [1], thus creating balloons as we know them today.

Decades later, in 1849, non-crewed balloons with twenty-three feet in diameter and loaded with explosives were launched during the battle between the republic of Venice and Austria [2], proving the concept of unmanned aerial vehicles as military weapons.

Admittedly, in the following years after the notorious flight of the Wright Brothers, experiments were made to design motorized aerial vehicles that could take off vertically. In fact, in 1907, Jacques and Louis Breguet achieved such a feat, when their quadrotor took off 2 feet off the ground for about a minute [3], thus initiating the era of quadrotors.

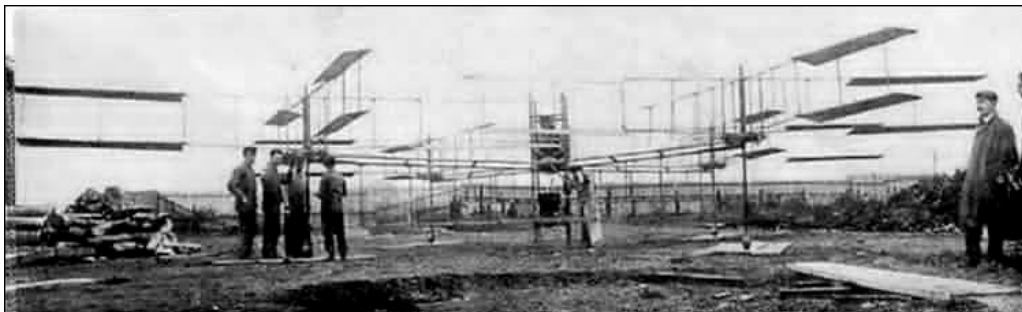


Figure 1 - The Quadrotor of the Breguet Brothers¹.

Since then, humankind has advanced conceptually and technologically in the aviation industry, and the hard work applied by scientists in the past, allowed us to develop new technologies such as UAVs, whose advent proved its importance in the

¹ Source: <https://alchetron.com/Breguet-Richet-Gyroplane#->

aviation industry, especially in battlefields, for reconnaissance, surveillance and target identification.

Additionally, as technology progressed, new cost-effective components for UAVs became available to the public, instead of just the military, which explains the sudden growth in popularity of drones as consumer products, especially quadcopters.

1.2 Application

Several companies such as Amazon, UPS and Dominos are already testing delivery systems based on drones, which provide low-cost deliveries, improved efficiency and logistics enhancement.



Figure 2 - Drone Delivery System².

Besides delivery, UAVs may also be used in civil security. As a matter of fact, England and the United States are already developing this technology for surveillance purposes. England is using it for search and rescue of missing people and traffic monitoring, while the US is working towards monitoring their borders using drones with infrared cameras and facial recognition capabilities [4].

Wildlife observation is another interesting use of UAVs. Hence, researchers from Duke University use it to monitor, count and analyze elephants' migration. However, they are concerned about how drone noise makes them agitated, albeit they believe it is because their sound resembles bees, which elephants do not like, therefore, new UAV configurations are being considered so they do not disturb these animals in their habitat [5].

² Left Figure. Amazon. Source: <https://www.asme.org/engineering-topics/articles/robotics/developing-delivery-drones>.

Center Figure. UPS. Source: <http://www.dailymail.co.uk/sciencetech/article-4245826/UPS-tests-drone-deliveries-Florida-eye-cost-cuts.html>.

Right Figure. Dominos. Source: <https://www.electricvehiclesresearch.com/articles/9885/dominos-pizza-delivery-drone>

Moreover, drones became very popular in videography, especially on wedding shoots, movie recordings and concerts, though, videographers seek quieter drones that do not disturb wedding ceremonies, allowing audio recordings without noise interference.

Furthermore, the amount of consumer drone shipments are projected to double by 2021, according to a Business Insider's article [6], and new drone applications are developed each year and many more are expected to come, therefore, it is fair to say that aerial vehicles will play an important role in society, improving logistics while deploying low-cost solutions.

1.3 Noise

In addition, it is worth noting that the advent of such aerial vehicles has brought with it, new challenges for society because of their growing presence in sky. In fact, the possible effects of the noise generated by UAVs have called the FAA and EASA's attention, since there are already several restrictions regarding noise levels emitted by general and commercial aircraft, and they plan get stricter over the years.

Noise is considered an unpleasant and unwanted sound and there is a natural concern on the quality life of citizens regarding noise disturbance, due to the increase in the number of UAVs operating over populated areas, which could cause discomfort to city residents.

In regard to this matter, a NASA study indicated that some people find sounds that seem to linger and high-pitched noise, which is a sound characteristic of most drones currently in operation, more annoying than low-pitched and brief noises [7].

Moreover, noise pollution can have adverse effects on human health, for instance, physical symptoms and psychological effects such as sleep disorders, cardiovascular problems and hypertension have been related to aviation noises [8].

Hence, the increase in the number of drones may lead to an exacerbation of noise pollution, which points to the necessity of investigating possible solutions to mitigate the noise generated by UAVs, which is the main objective of this research paper.

Chapter II

2. LITERATURE REVIEW

This chapter presents a brief review of research papers and articles regarding acoustic control of UAVs, demonstrating the current technologies under development as well as different approaches towards noise reduction.

2.1 Sound Characteristics

First, there are certain aspects of sound that need to be further discussed to better understand how the human ear perceives sound. Therefore, the sound is defined as fluctuations in pressure that travel in the form of sound waves, which are interpreted by the brain through the auditory system. The rate in which these fluctuations occur is known as frequency, given in cycles per second or Hertz [9], and the frequency range audible to the human ear lies between 20Hz-20kHz.

Another important characteristic of sound is the sound intensity, which is measured in decibel (dB), because its scale demonstrates a correlation with the human hearing [9], ranging from total silence (0 dB) to the beginning of hearing loss (140 dB), as it can be demonstrate in figure 3.

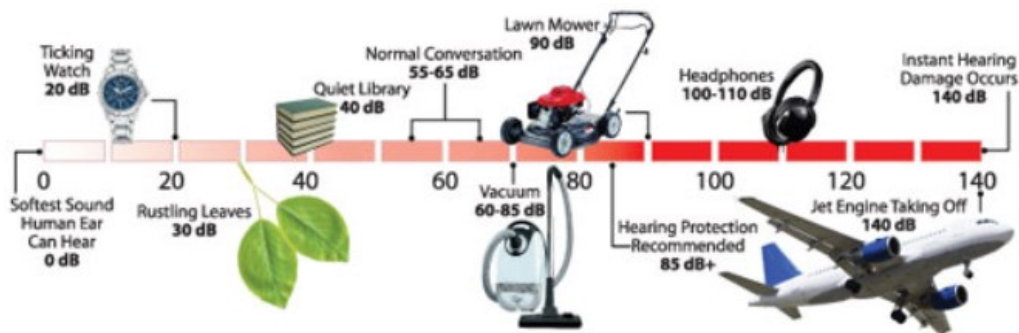


Figure 3 - Sound Intensity Scale ³.

However, the sound perception of the human hearing is not linear, and the way it is perceived by the ear changes for different frequencies. Thus, to adjust the sound intensity (dB) to represent the exact sound as interpreted by the ear, it is necessary to

³ Source: <https://www.homershams.co.nz/Articles/Sound.html>

consider weights for each frequency, such weights are represented on the A-Weighting curve on (Figure 4), which demonstrates how the human ear is less sensitive for low frequencies and more sensitive around 1000-8000 Hz, where the sound is slightly amplified. Also, it becomes less sensitive again for high frequencies [10], meaning that a sound emitted at a 100 Hz would be attenuated around 20 dB by the auditory system and amplified around 3 dB at 5000Hz.

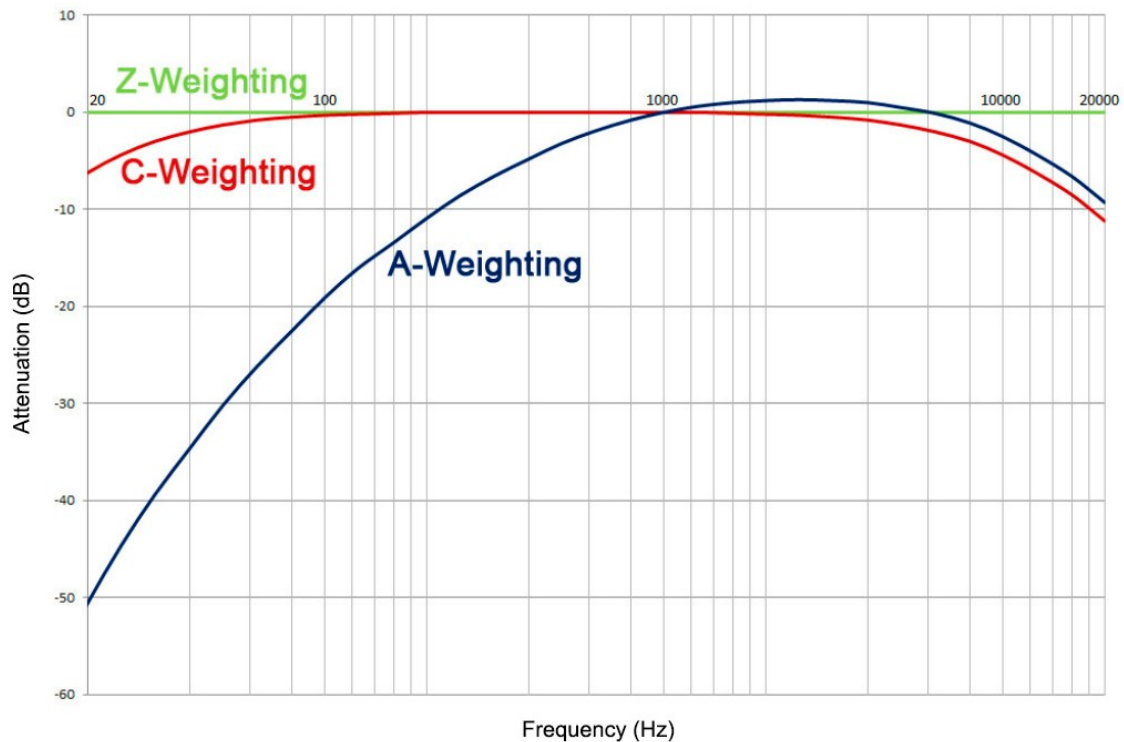


Figure 4 – ‘A’ Frequency Weighting⁴.

To better illustrate the attenuation and amplification of the previous graph, one can observe the human hearing domain represented on Figure 5, which demonstrates the correlation between frequency and sound level, exemplifying how the threshold of hearing varies for different frequencies [11]. Thus, allowing a person to hear frequencies between 3000Hz to 5000Hz better than other frequencies. For instance, a sound level of 10 dB at 5000Hz would be clearly audible to an individual whilst the same sound level at 50Hz would be totally inaudible.

⁴ Source - Adapted from: <https://www.atp-instrumentation.co.uk/blog/frequency-weightings-explained/>

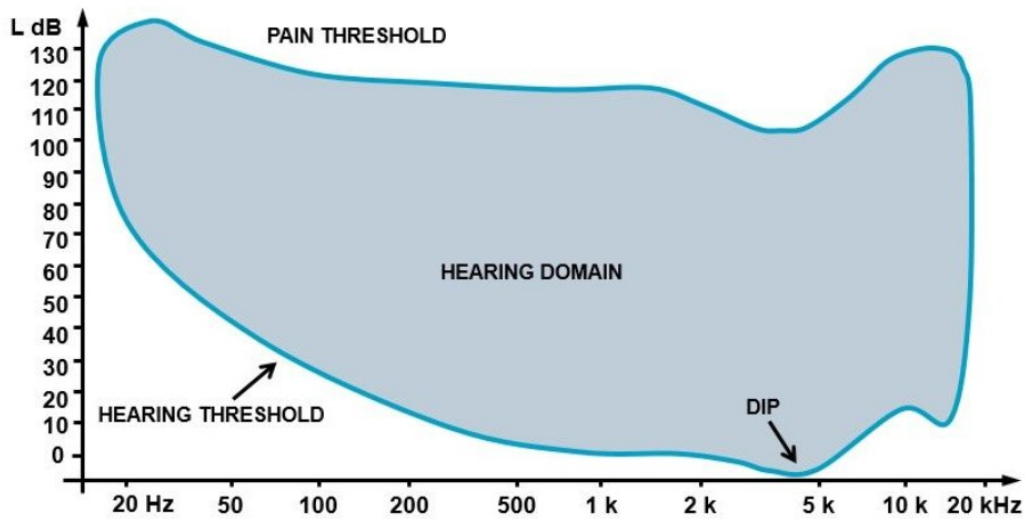


Figure 5 - Human Hearing Domain⁵.

In addition, the loudness parameter which is measured in units of phon or sone needs to be discussed since the dBA scale does not represent exactly how loud a sound is, or how intense it feels [11].

The unit phon represents the equal loudness of a pure 1000Hz tone (Figure 6) meaning that at 1kHz on 40 phon curve indicates precisely 40 dB.

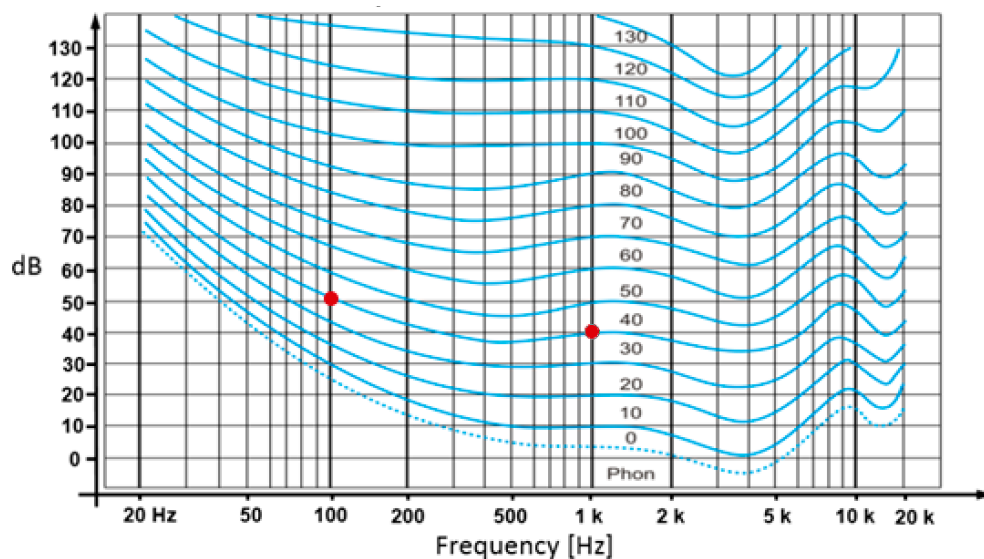


Figure 6 - Equal Loudness Curve for Sinusoidal Tones⁶.

Therefore, by observing the 40 phon curve, it can be noted that a sound being emitted at 100 Hz and 51 dB will feel just as loud as a sound being emitted at 1000Hz

⁵ Source: <https://community.plm.automation.siemens.com/t5/Testing-Knowledge-Base/Sound-Quality-Metrics-Loudness-and-Sones/ta-p/423283>.

⁶ Source: <https://community.plm.automation.siemens.com/t5/Testing-Knowledge-Base/Sound-Quality-Metrics-Loudness-and-Sones/ta-p/423283>. (Points added for exemplification)

and 40 dB, demonstrating that the perception of sound relies on more than one acoustic characteristic.

Likewise, the sone is also a unit of loudness, however, it is mostly used to describe sounds, because its scale is directly proportional to loudness, while the phon is not. Thus, to calculate sone from phon the following equation can be used:

$$Sone = 2^{(Phon-40)/10} \quad (1)$$

The use of the sone scale can better indicate how loud a sound really is and how it changes, because according to the rule of thumb [11], a 10 dB increase is needed to double the perceived loudness of sound, however, it is not an accurate rule because it does not work for all frequencies. Therefore, the sone is the only scale that ideally represents the loudness of a sound because of its linear scale, so 4 sones would sound twice as loud as 2 sones.

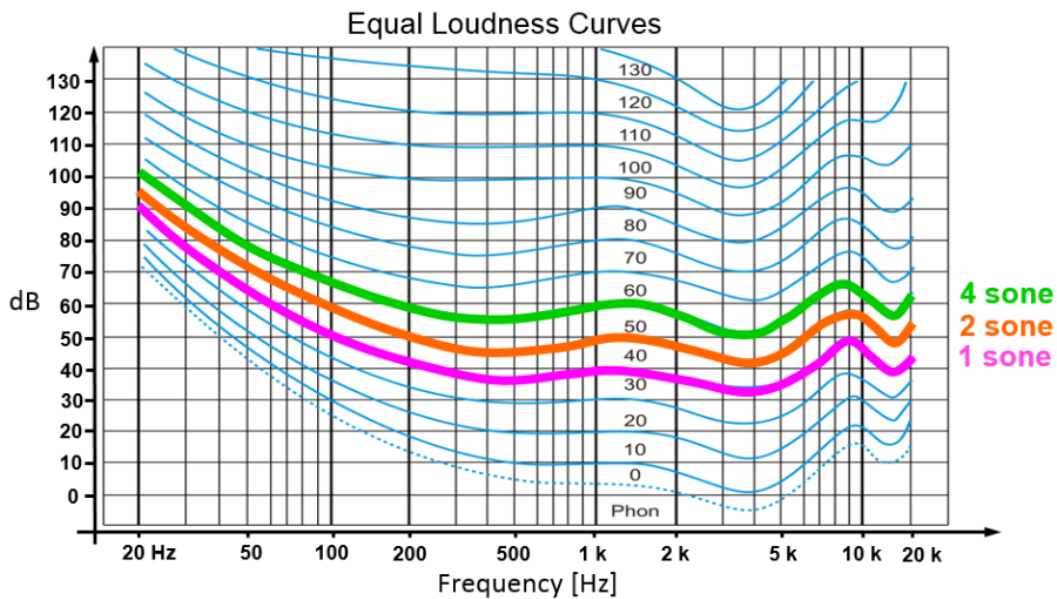


Figure 7 - Equal Loudness Curves⁷.

In summary, a small reduction in dB or dBA could represent a more abrupt reduction of loudness for a determined frequency, for instance, a reduction of .6 dB or 2.2 dBA (Figure 8) caused a reduction of 28.5 sones, meaning that a drop of 95.9 to 95.3 dB would cause a loudness reduction of about 33 per cent.

⁷ Source: <https://community.plm.automation.siemens.com/t5/Testing-Knowledge-Base/Sound-Quality-Metrics-Loudness-and-Sones/ta-p/423283>.

	A	B
Decibel	95.9	95.3
dB(A)	95.4	93.2
Sone	86.6	58.1

Figure 8 - Loudness Comparison Table⁸.

As a result, it is important to not only analyze the overall sound pressure level of a noise, but also consider how the frequencies correlate to the human hearing and how other acoustic parameters such as loudness have an impact on noise perception.

2.2 Noise Reduction Mechanisms

This section will further discuss the possible solutions for noise reduction, approaching passive, adaptive and active control systems designed to reduce noise in a variety of applications.

2.2.1 Propeller

In 1995, Nasa investigated noise reduction technologies in aircraft propellers, analyzing not only the concept of noise attenuation, but also the cost and manufacturability process [12]. Concluding that the most effective approaches to noise reduction would be elliptical tip blade planforms, reduced propeller diameter, and an increased number of blades, considering the weight added to the system and the performance characteristics of each parameter altered.

It also explains that a reduction in propeller RPM is a useful noise reduction mechanism and that some aircraft use oversized engines to operate them at a lower RPMs to attenuate the overall noise, although it highlights that such configuration could cause and increase in fuel consumption and weight.

Also, the report mentions the effects of adding proplets, which present structures similar to winglets on a wing, altering the pressure distribution on the tip of the blades to reduce induced drag. However, it points out that the by the time of that study, only a few

⁸ Source: <https://community.plm.automation.siemens.com/t5/Testing-Knowledge-Base/Sound-Quality-Metrics-Loudness-and-Sones/ta-p/423283>

applications of propellers were known to exist and that further evaluation of their results would be necessary.

In 2008, a reduction in broadband noise was proposed through the modification of a propeller's surface. First, several experimental tests were conducted in static condition and on wind tunnels to better analyze the noise reduction mechanism, next, a trip was applied at the leading edge of the propeller to possibly eliminate the laminar separation bubble, because researchers believed that this technique could reduce the noise source generated on the laminar boundary layer due to the laminar separation without affecting the blade's performance [13].

Consequently, the leading-edge trip proved to work effectively since it managed to reduce 6-7 dBA of the broadband noise, however, there would not be a noise reduction when the tripper height surpassed the boundary layer thickness, occurring in an increase in broadband noise in some tests.

Next, in 2016, another acoustic study regarding UAV's propellers was carried out. When researchers from Iowa State University analyzed the acoustic and aerodynamic effects at a low Reynolds number of saw-tooth serrated trailing edge on the baseline of propellers, which resulted in a broadband noise reduction in high frequency without any detriments to aerodynamics [14].

Later that year, researchers in Australia studied the noise generated by the airfoil tip vortex formation, which pointed out the significance of flow-induced noise in aircraft wings and in blades. Thus, inside an anechoic wind tunnel, acoustic measurements were made on an airfoil with a flat ended tip for different flow speeds and angles of attack, next, sound maps were generated, allowing a better analysis of the noise generation mechanism on the airfoil tip [15].

Also, the study indicated that the low and high frequency tip noise is a result of the vorticity scattering on the trailing edge of the tip section, in addition, the results demonstrated that the noise generated by the vortex formation had a stronger dependence on the Mach number than on the angle of attack variation, although both contributed to the noise level increase.

Finally, although, this research paper discusses the noise reduction techniques in aircraft propellers, the same concepts can be applied to attenuate the noise in UAVs.

2.2.3 Duct

Researches have been studying the effects of ducts on aircraft for decades, and extensive investigation of shrouded rotors demonstrated aerodynamic improvements such as increased thrust and power consumption reduction [16]. Besides aerodynamic performance, the duct configuration could provide noise attenuation which is the focus of this study and potentially protection against blade injury.

Thereby, geometric duct parameters indicate a strong influence on the noise generation mechanism, for instance, the tip clearance [16], which is the distance between the propeller tip and the duct inner wall, affects the vortices generated at the blade tip and may attenuate the induced drag noise through a physical wall, blocking the high-pressure airflow on the lower camber from moving upwards to the low-pressure area, thus reducing the vortices generated at the blade tip and consequently the vortex induced noise.

In 2016, researchers conducted experiments with ducts to analyze the noise generated by a multi-rotor and provide a technology capable of mitigating this problem. They concluded that the main source of noise is due to the high-speed rotating blades [17], then, they investigated the effects of engine rotor ducts regarding their acoustic absorption capabilities. The analysis involved two ducts, a non-perforated and a micro-perforated wall configuration, both fabricated with 3D printing technology.

As expected, they confirmed an increase of noise with higher propeller RPM, however, adding a duct did not meet the researchers' expectations regarding noise attenuation, although it presented some acoustic benefits. In the conclusion chapter, they suggested an analysis of the interaction between the duct and the propeller and an evaluation of the acoustic characteristics of the whole duct structure.

2.2.4 Active Control

Active Noise Control dates back to 1933, when Paul Lueg issued a patent for the concept of active noise cancellation [18], and the advent of microelectronics made possible the invention of several devices such as the ANC headphones, commonly used by pilots.

As a result, new applications are developed every day, in fact, researchers in Spain, studied the first use of ANC system for UAVs, motivated by applications that require

quieter drones and by the request of EASA to reduce noise from UAVs in populated areas [19].

It consists of a system involving a microprocessor, microphones and speakers, which reduce the noise through using an algorithm that analyzes the signal acquired by a microphone and emits the same signal characteristics with an inversed phase through a speaker, thus cancelling the original signal.

Therefore, the active control system presents the most adaptable process in noise reduction, however, it presents a more robust system, since it requires optimized algorithms and the need for light microelectronic technology to enable the control system to be embedded into the drone.

Chapter III

3. METHODOLOGY

This chapter specifies the type of research developed, the materials used in the experiments, the manufacturing process and the methods applied in data acquisition.

The experimental investigation of noise reduction is focused in quantitative methods through the analysis of the data acquired in the form of graphs and tables. The techniques applied were developed based on the literature presented on chapter 2, and tests were conducted to determine the effectiveness of each noise control application.

3.1 Experimental Bench

The structure of a quadcopter was fixed on top of a 1-meter-tall metal structure, with a layer of insulation pad between them to protect the drone's circuit board. The drone was placed at height of about 4 times the propeller span to avoid ground effect. Next, a brushless motor was placed on the edge of one of the arms, which was connected to an electronic speed controller (ESC) wired to a circuit board (Figure 9). Then, a radio receiver was connected to the ESC to control the motor's rotation through a remote control.

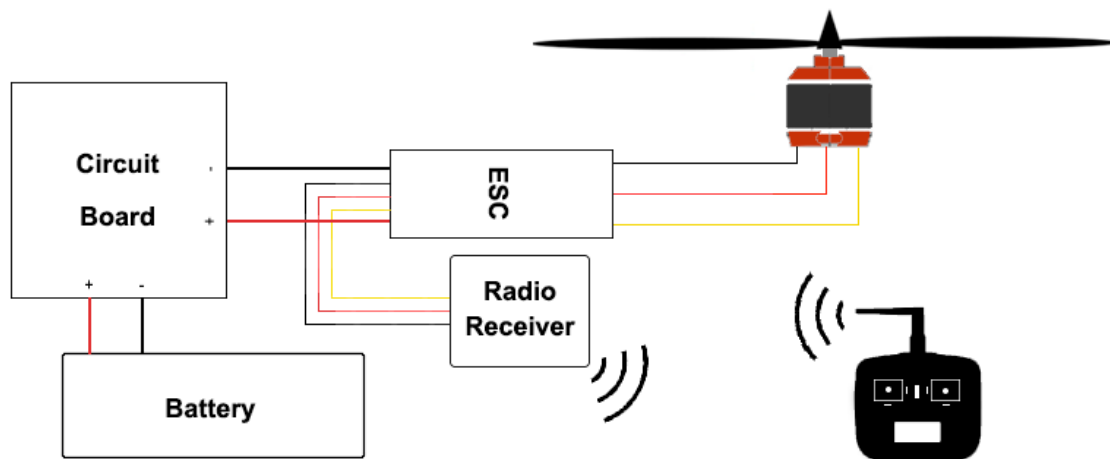


Figure 9 - Drone Wiring Diagram⁹.

⁹ Source: Author.

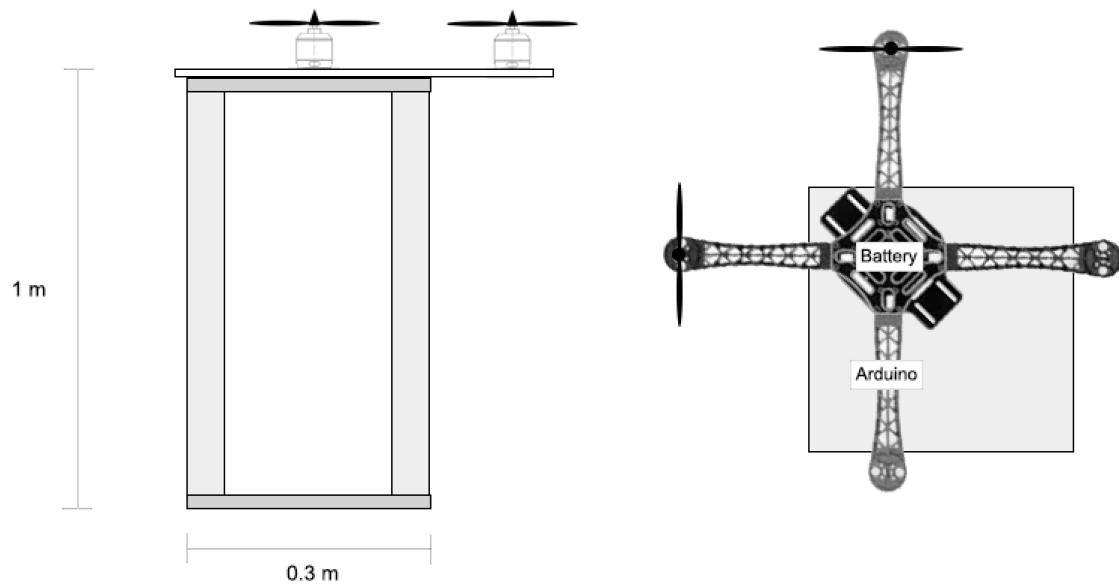


Figure 10 - Experimental Bench¹⁰.

Also, 10x4.5 propellers were attached to each motor and a 5200 (mAh) battery connected to the board to power them. The test bench was designed with the use of consumer products and all the parts involved in the construction are listed below on table 1.

Table 1- Experimental Bench Description.

Part	Specification
Drone Structure	F450 Flamewheel
ESC	Simonk 30A
Brushless Motor	RaceStar 2212 930kv
Propeller 1045	LJI 10x4.5
Battery	Zippy - 5200 mAh - 3S
Receiver	FS-R9B
Radio	Flysky FS-TH9X
Metal Stand	1 x 0.3 x 0.3 [m]

¹⁰ Source: Author.

3.2 Signal Acquisition

This section will explain procedure for acquiring the noise frequency spectrum. Evidently, it is an important process of the research, because the signal acquired must be as reliable as possible, to identify the most accentuated frequencies.

Initially, a microphone (Figure 11) was inserted inside a precision calibrator (Figure 12), which emits a precise sound pressure level of 94 dB at 1000Hz, then, the signal acquired was analyzed to ensure the microphone's reliability.



Figure 11 - PCB Microphone 426E01 ICP¹¹.



Figure 12 - Larson Davis Calibrator Cal 200¹².

Once the microphone was calibrated, the signal was acquired with the aid of an acquisition board (Figure 13) connected to the microphone and a laptop. Subsequently, the data was loaded into the laptop and frequency spectrum graphs plotted, demonstrating the broadband noise spectrum.

¹¹ Source: www.pcb.com

¹² Source: <http://www.larsondavis.com/Support/CalibratorsSupport/CAL200Support.aspx>



Figure 13 – *National Instrument®* NI 9162 USB Carrier / NI 9233 ¹³.

Also, to ensure that the same propeller rotation for each experiment, an Arduino Uno (Figure 14) and an IR sensor were used to determine the motor's RPM. The Arduino was placed on one of the arms of the structure (Figure 10) and the IR sensor attached to the end of arm where the electric motor was placed. A black tape was applied to the rotor with a gap of 10 mm, where a reflective tape was also applied to obtain an accurate RPM reading.

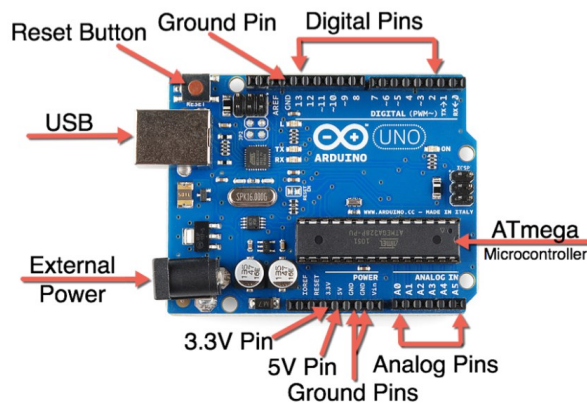


Figure 14 – Arduino Uno®¹⁴ and IR Sensor.

¹³ Source: http://sine.ni.com/nips/cds/pages/image?imagepath=/images/products/us/usb-9162_ni-9234_1.jpg&title=Acceleration%20Data%20Logger&oracleLang=pt

¹⁴ Source: https://wiki.eprolabs.com/index.php?title=Arduino_UNO

3.3 Noise Control Devices

Based on the literature presented on chapter 2, a few devices were designed in the attempt of trying to reduce the noise generated by UAVs and the following paragraphs provide further details regarding each apparatus.

Initially, the duct system was considered, because according to a study carried out in 2008 [16] regarding performance improvements of micro UAVs, rotor shrouding could also influence the noise emitted by drones. Although, it focuses primarily on performance, it provides background information regarding ducts for noise reduction.

Therefore, 2 duct configurations were designed. One considering a flat wall duct (Figure 15), to reduce the blade tip clearance and second one with acoustic material (Figure 16) on the blade tip region to reduce the vortex induced noise.

Both duct walls are 2 mm thick, with a height of 70 mm and a diameter of 252 mm as it can be observed on Appendix A. Such dimensions were designed based within the range of dimensions suggested on the conclusion chapter of the study from the University of Maryland [16].



Figure 15 – Flat Duct Configuration 01¹⁵.

¹⁵ Source: Author



Figure 16 - AM Duct Configuration 02¹⁶.

The ducts were manufactured using fused deposition modeling technology (FDM), also known as 3D printing. Therefore, 3D models were designed in CATIA and then imported into the GTMAX CORE AB printer, once the software was set up, each duct was printed individually, ranging from 8 to 12 hours for a complete print.

Thereafter, an acetone vapor bath was applied on each duct to finish the inside walls of the ducts to ensure an organized flow structure, thus reducing possible vortex generation. Each print remained in a closed container from 1.5 to 2 hours.

Next, three proplets configurations and an elliptical shaped blade were designed to investigate the effects on the noise generation mechanism due to the vortex reduction at the tip of the blade.

The first proplet was designed with a tip bent 18 degrees to the vertical axis (Figure 17) and a height of 7mm, the second proplet was also bent 18 degrees at the tip with a height of 10mm (Figure 18). The third configuration built was a double sided proplet with a total height of 15mm (Figure 19). Lastly, a propeller was designed with an elliptical shape at the tip (Figure 20), taking in consideration the lifting line theory, which demonstrates that the lowest induced drag is achieved at an elliptical distribution.

Every propeller configuration had a diameter of 248 mm, which were modified from the 10x4.5 consumer propeller, therefore ensuring the exact same diameter, even for the duct configuration, thus allowing comparison with standard 248 mm propeller.

¹⁶ Source: Author.



Figure 17 - Proplet 01 ($h=7\text{mm}$)¹⁷.



Figure 18 - 10x4.5 Proplet 02 ($h=10\text{mm}$)¹⁸.



Figure 19 - Double-sided proplet¹⁹.



Figure 20 - Elliptical Tip Blade²⁰.

¹⁷ Source: Author.

¹⁸ Source: Author.

¹⁹ Source: Author.

²⁰ Source: Author.

Admittedly, vibration can be a major source of noise, thus, to ensure the best test environment, all propellers were balanced statically to reduce the vibration on the blades using the prop balancer presented on Figure 21. Initial tests demonstrated the need of a fine prop balance, because a strong vibration was observed on throttle speeds over 50%, however, after final balancing, a stable rotation was observed on the 75% throttle speed.



Figure 21 – Standard 10x4.5 Propeller on Balancer²¹.

3.4 Measurement Procedure

Initially, the motor was measured in combination with the standard 10x4.5 propeller. Subsequently, for each configuration, the following noise signatures were acquired for comparison:

- Duct 01 – Flat
- Duct 02 – Acoustic Material (SONEX® Classic Foam)
- Propeller – Standard 10x4.5 Propeller
- Propeller – Proplet 01 (h=7mm)
- Propeller – Proplet 02 (h=10mm)
- Propeller – Double-Sided Proplet
- Propeller – Elliptical Tip

Thus, 3 different angles were measured (Figure 22), because according to a group of researchers who analyzed the acoustic signature of ducted propellers for small aircraft,

²¹ Source: Author.

the highest noise level occurs at a 45-degree angle for an unshrouded and a shrouded rotor [20].

The same effect was observed by another group of researchers who analyzed the acoustic signature of small multi-rotor unmanned aircraft systems, concluding that the greatest sound radiation comes from about 45 degrees to the horizontal axis as well [21].

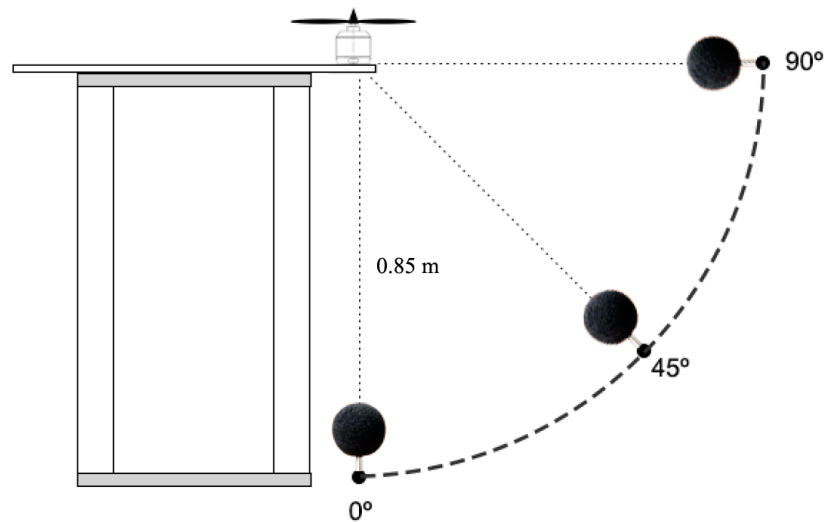


Figure 22 - Measurement Angles²².

Also, measurements were taken inside the laboratory at dawn, acoustic materials placed around the microphone to reduce reverberation. All frequency spectrums were acquired for each angle at 4800 RPMs, equal to 75% throttle speed, monitored by an Arduino Uno to ensure the same rotation throughout the experiment.

²² Source: Author.

Chapter IV

4. RESULTS AND ANALYSIS

This chapter will present the results of all the measurements taken for every configuration mentioned on chapter 3, demonstrating the noise levels and frequencies through the aid of figures and tables. Finally, the results and possible sources of errors will be discussed.

The analysis will be split into two sections, first, demonstrating the results of the duct in comparison to the unshrouded rotor for different angles, and a second one, comparing the noise attenuation of propeller modification to the standard unshrouded 10x4.5 propeller.

4.1 Duct

4.1.1 Flat Duct

The graph on Figure 23 (a) represents the noise frequency spectrum acquired at 0 degrees to the vertical axis of the rotor, demonstrating that the duct was effective on reducing noise frequencies below 280 Hz; however, it can be noted that the sound level pressure is amplified on frequencies above 280 Hz, surpassing 75 dBA.

On Figure 23 (c), at 45 degrees, the duct becomes practically ineffective, even for low frequencies, while still amplifying the sound level at high frequencies, yet, a small reduction can be seen on frequencies below 100 Hz.

The third measurement on Figure 23 (e) at 90 degrees to the vertical axis of the rotor demonstrates noise reductions over 1 dBA for frequencies below 100 Hz, nonetheless, the sound is still amplified for frequencies above 100Hz.

4.1.2 Acoustic Material Duct (AM Duct)

The first measurement right below the rotor Figure 23 (b), also demonstrates an attenuation for low frequencies like the flat duct; however, it can be noted that the AM duct reduces the noise for frequencies below 320 Hz compared to the unshrouded rotor, but it amplifies the overall noise in high frequencies, reaching up to 77 dBA, whilst the flat duct reaches a maximum of 76 dBA at 0 degrees.

The 45-degree spectrum on figure 23 (d), demonstrates a slight attenuation up to the 120Hz frequency, although the same amplification effect as the previous duct can be observed on frequencies above 200Hz. Additionally, the peak highlighted on figure 23 (c) at 316Hz is not visible on the AM duct.

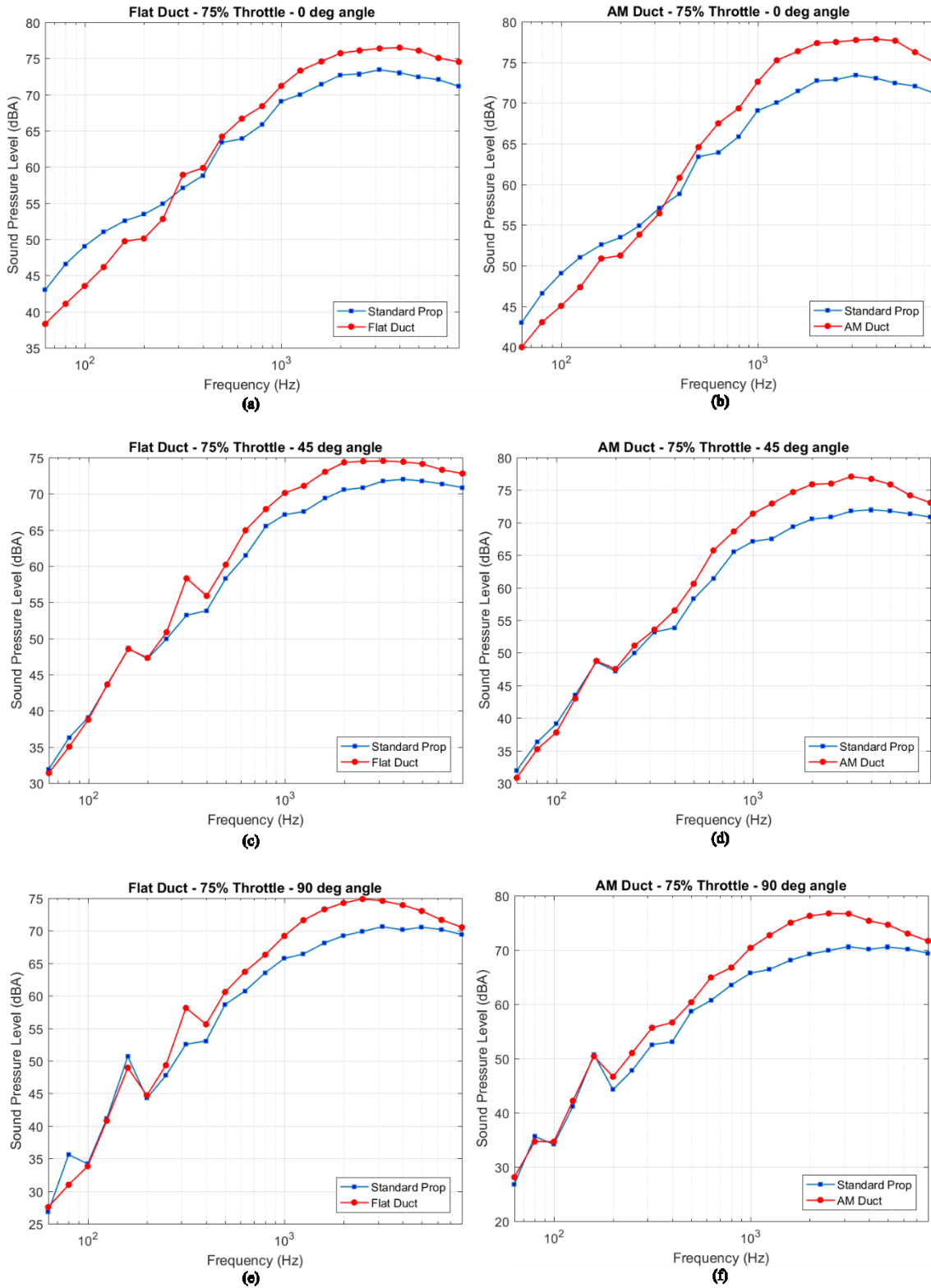
The last frequency spectrum at the 90-degree angle indicated on Figure 23 (e), demonstrates nearly no attenuation, even for low frequencies, causing an amplification of the sound pressure level on frequencies above 160Hz, reaching a peak of 76 dBA at 2500Hz, which is 6 dBA higher than the standard propeller noise for the same frequency.

4.1.3 Duct Considerations

Therefore, although the ducts demonstrated a reasonable attenuation for low frequencies at 0 degrees, the same effect was not observed on other angles, and an increase of 3-6 dBA was indicated on frequencies above 1000Hz for both ducts at every angle.

A possible cause to the increase of SPL at high frequencies can be attributed to a strong rotor-stator interaction [24], yet, another possible cause to this effect could be attributed to the blade tip clearance, which is the distance between the blade and the duct's inner wall, because according to the literature, the tip clearance needs to be reduced as much as possible to attenuate the vortex generation mechanism.

However, such distance was not achieved due to the fact that the wall of the duct was too thin to support the vibration of high propeller speeds, thus, the blades hit the duct at high speeds for 1mm tip clearance. Thereafter, new blades were designed to achieve 75% throttle speed without scratching the inner wall of the ducts.

Figure 23 - Frequency Spectrum Ducts²³²³ Source: Author.

Additionally, a peak can be observed precisely at 160Hz for all three angles measured, which can be observed on the dB scale graphs of Figure 24, whose frequency derives from the blade pass frequency (BPF), calculated through the following equation:

$$\text{BPF} = \frac{4800 \text{ RPM} \times 2 \text{ Blades}}{60} = 160\text{Hz} \quad (2)$$

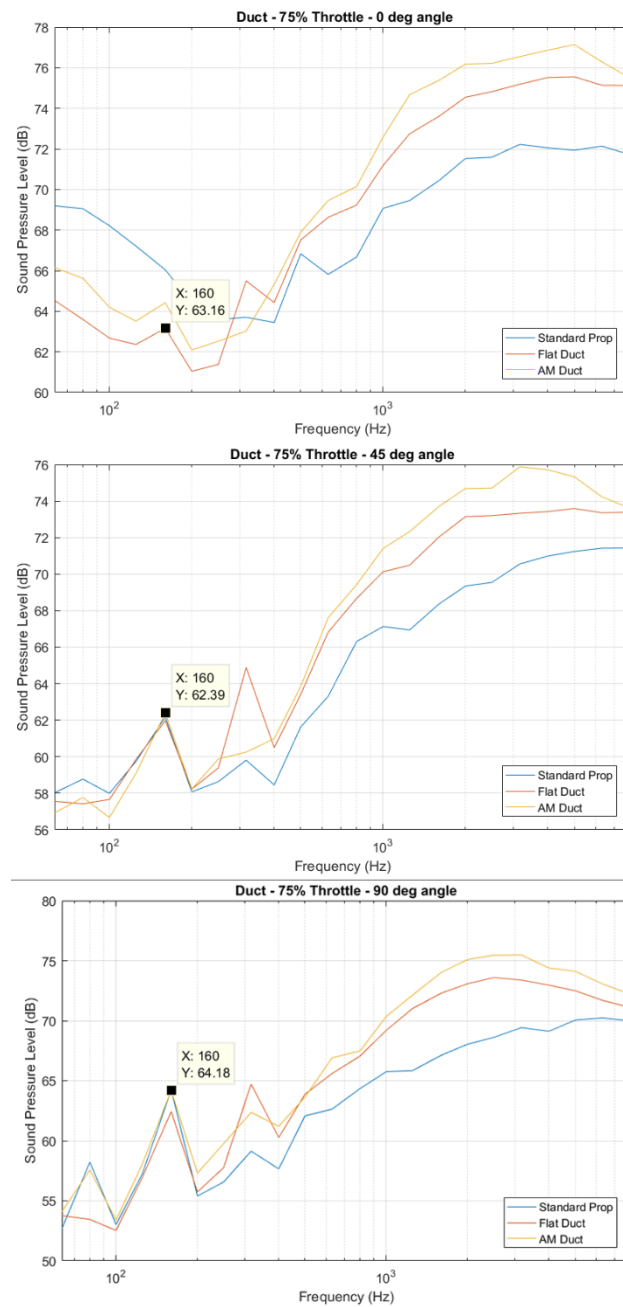


Figure 24 - Sound Pressure Level x Frequency (BPF)²⁴.

²⁴ Source: Author.

4.2 Propeller Configurations

4.2.1 Proplet 01 and 02

The proplet configurations at 0 degrees demonstrated an effective noise reduction for high frequencies, which can be noted on Figure 25 (a) and Figure 25 (b). Although, a slight amplification of the SPL can be noted on the 200Hz-400Hz range, both proplets managed to reduce the overall noise. However, proplet 02 proved to be more effective around 1kHz-5kHz than proplet 01, on the other hand, proplet 01 demonstrated a higher attenuation than proplet 02 on frequencies above 5kHz.

Figure 26 (a) and (b) present the frequency spectrum at the 45-degree angle measurement, demonstrating a 0.5 dBA amplification below 100Hz for both proplets and attenuation on frequencies above 160 Hz, except for proplet 02, which presents a 0.5 dBA amplification above 5kHz.

Ultimately, the 90-degree angle measurement on Figure 27 (c), demonstrated the best results in comparison to the previous angles for both proplets, attenuating almost the entire frequency spectrum, except for proplet 02, which caused the same amplification observed at 45 degrees for frequencies above 5kHz. In addition, both proplets reduced over 3.5 dBA at the blade pass frequency of 160 Hz.

4.2.2 Double-Sided Proplet

The frequency spectrum at 0 degrees indicated on figure 25 (c) shows a 0.5 dBA reduction below 200Hz and a 0.5 dBA amplification around 300 Hz, then it presents a reduction up to the 3kHz frequency, where it starts amplifying the SPL 1.2 dBA up to the 8kHz frequency.

The 45-degree measurement on Figure 26 (c) displays the same noise increase above 3kHz as the previous measurement; however, it presents a noise reduction throughout the entire spectrum, demonstrating the highest reduction of 3.45 dBA at the 800Hz frequency.

The 90-degree angle on figure 27 (c) also presents an amplification above 4kHz, albeit, it presents the highest attenuation in comparison to the previous angles, reducing 4.3 dBA at the blade pass frequency of 160Hz and 3.8 dBA at 800Hz.

4.2.3 Elliptical Blade Tip

The elliptical shape at 0 degrees on Figure 25 (c) presented the best results at high frequencies. Although, it presented a 0.5 dBA increase from 125Hz to 400Hz, it managed to reduce nearly 1 dBA for frequencies above 400Hz.

The frequency spectrum on Figure 26 (c) at 45 degrees presents an overall noise reduction, except for an increase of 0.3 dBA at 80Hz. Also, it demonstrates the highest noise attenuation of 2 dBA at 800Hz and 1.5 dBA at 8000Hz. Lastly, Figure 27 (c) presents the frequency spectrum at the 90-degree angle, demonstrating a 1.9 dBA increase at 63Hz, a 3 dBA reduction at 160Hz and an overall reduction at high frequencies.

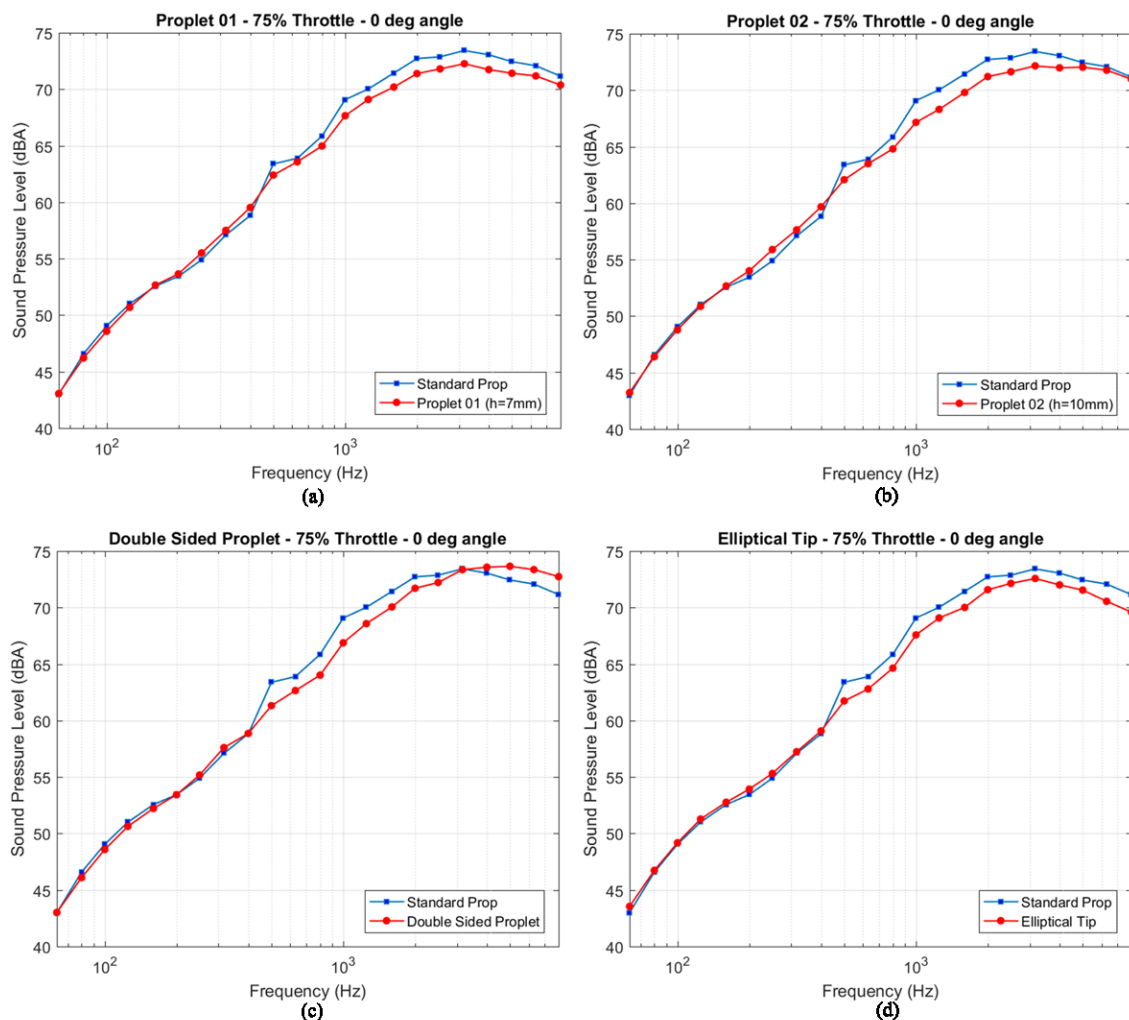


Figure 25 - Propeller Configurations - 0 deg²⁵.

²⁵ Source: Author.

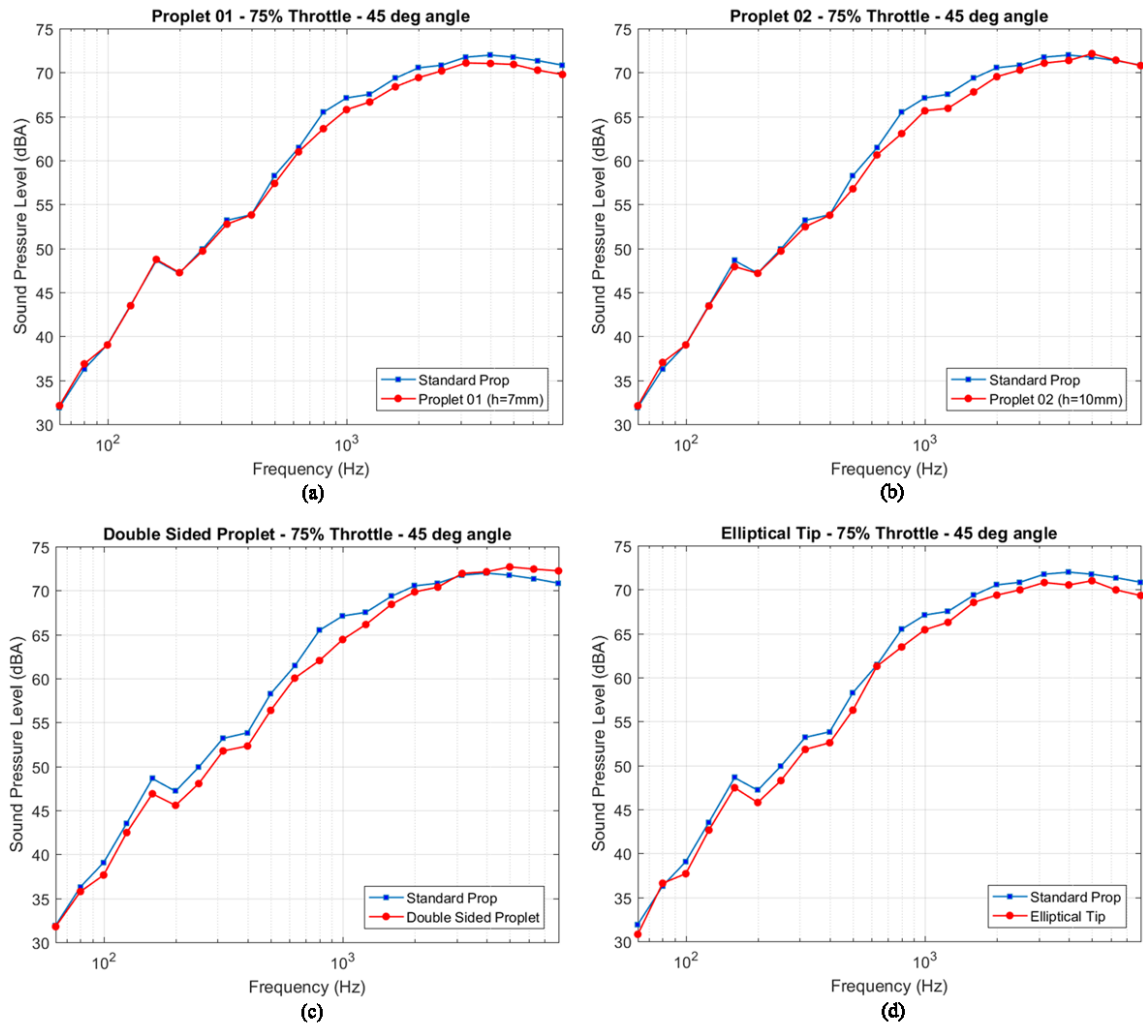


Figure 26 - Propeller Configurations - 45 deg²⁶.

²⁶ Source: Author.

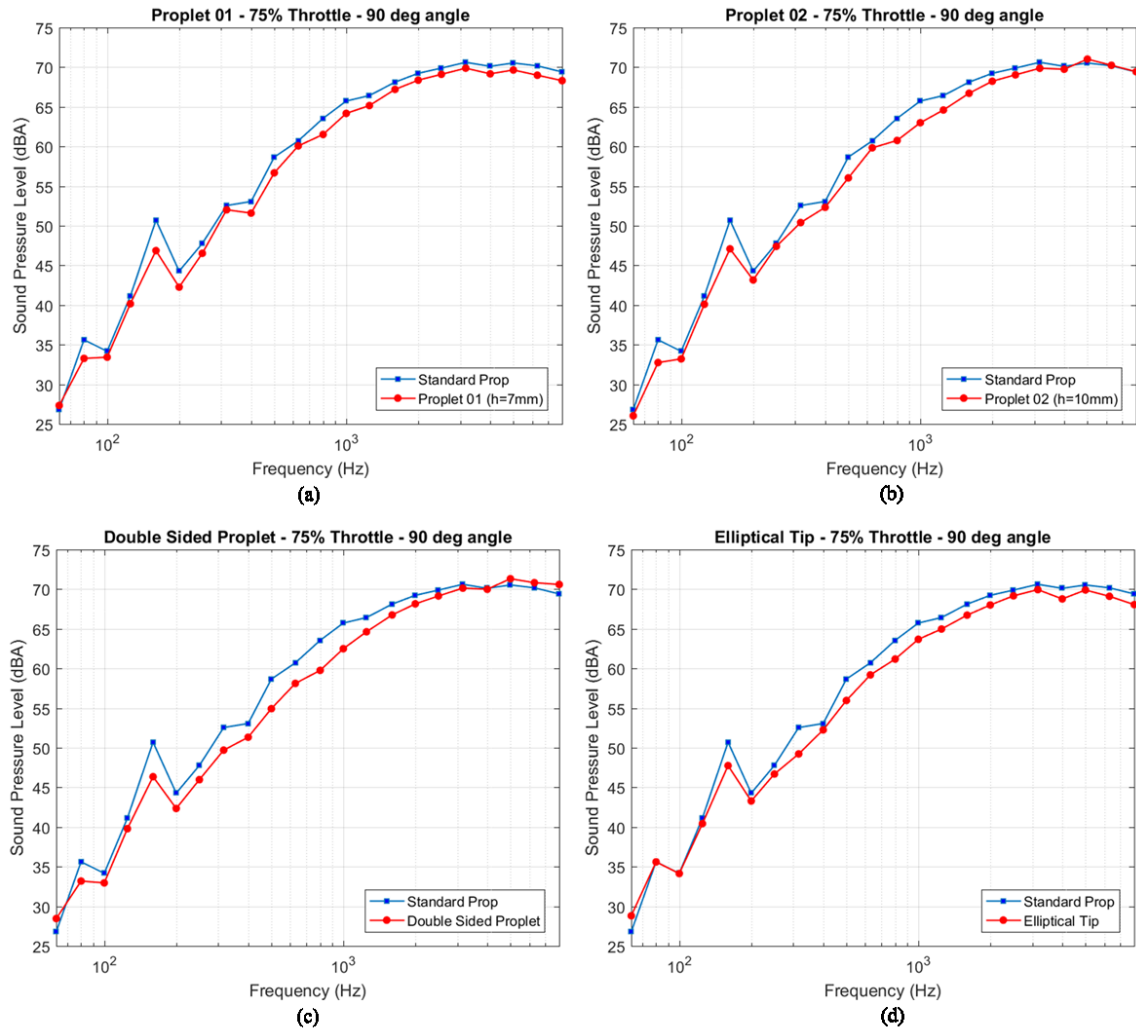


Figure 27 - Propeller Configurations - 90 deg²⁷.

4.2.4 Propeller Considerations

In brief, previous propeller configurations demonstrated a satisfactory noise reduction compared to the standard 10x4.5 propeller, especially at high frequencies, which corroborates the concepts presented on chapter 2, thus reducing the vortex formation at the blade tip, which is responsible for one of the main sources of noise on propellers.

Moreover, among all propellers configurations tested, the elliptical tip blade demonstrated the best noise reduction effect, due to its elliptical shape, which presents the least induced drag, consequently reducing vortex formation.

²⁷ Source: Author.

Furthermore, an increased reduction on the overall noise can be observed at the 90-degree angle in comparison to the 45 and 0-degree angle, effect which is most accentuated at the 160Hz, additionally, it is worth noting that the elliptical blade tip presented the most effective results on frequencies above 4000Hz.

4.3 Comparison

The bar graph on Figure 28 presents the total dBA measurements for each device tested, demonstrating that the elliptical tip presents the highest noise attenuation throughout the entire frequency spectrum in comparison the standard 10x4.5 propeller, ensued by proplet 01, which also demonstrated a reasonable noise reduction effect. Also, as expected, the ducts presented the highest noise level compared to the unshrouded rotor.

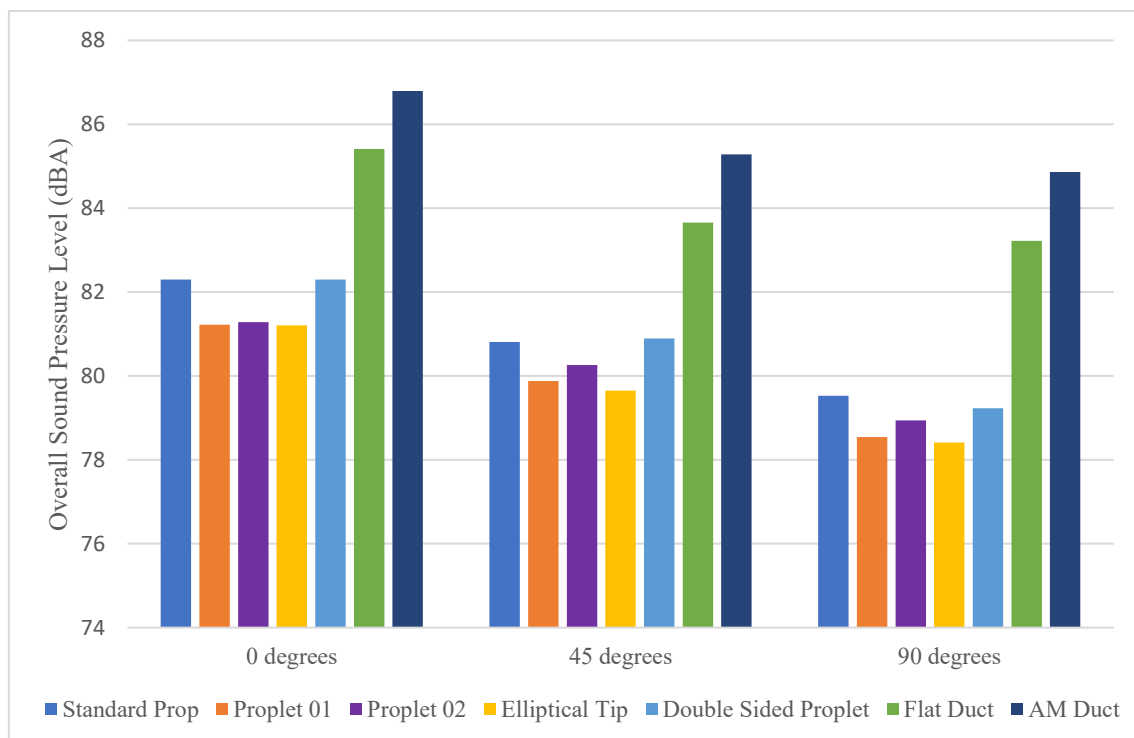


Figure 28 - Overall Sound Pressure Level (dBA).

The attenuation results for the elliptical blade tip can be noted on table 2, which demonstrates that the elliptical shape managed to reduce over 1 dBA at all 3 angles measured.

Table 2 - Attenuation Results for Elliptical Tip Blade.

Angle	Standard Prop	Elliptical Tip	Attenuation (dBA)
0 Deg	82.30	81.21	1.09
45 Deg	80.81	79.65	1.16
90 Deg	79.53	78.41	1.12

Moreover, the loudness parameter can be observed on Figure 29, which compares the subjective perception of sound intensity among all the devices tested previously, demonstrating a higher intensity of auditory sensation by the ducts, which stand out at the center of each angle, and a lower sound intensity perception by the new the propeller configurations in comparison to the standard 10x4.5 propeller.

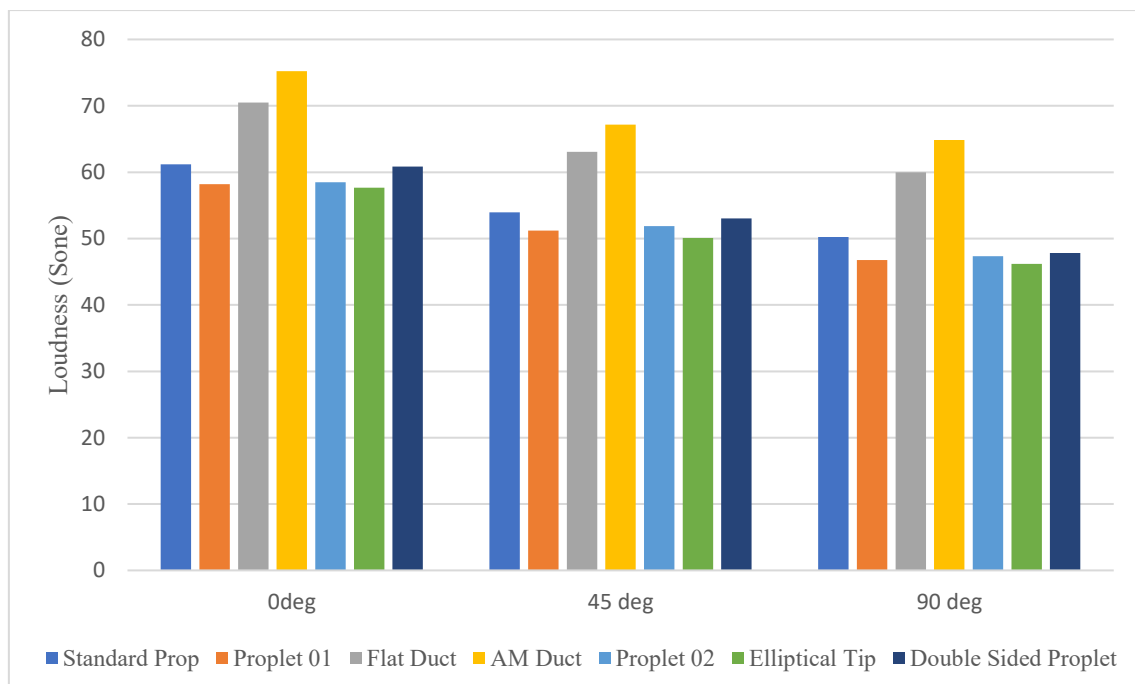


Figure 29 - Loudness Comparison.

5. CONCLUSION

The present study conducts the aeroacoustic experiment of two duct and four propeller configurations, demonstrating the influence of such devices on the overall noise emitted by unmanned aerial vehicles. The duct measurement results demonstrated a possible reduction on the noise frequency spectrum for low frequencies; however, it proved to be completely ineffective for a certain range of frequencies. In fact, sound amplification was observed up to 6dBA at high frequencies, which was attributed to the rotor-stator interaction.

The propeller configurations on the other hand, demonstrated an effective SPL attenuation for almost the entire frequency spectrum, whose results were attributed to the reduction of the vortex formation mechanism, through the alteration of blade tip, which presented the elliptical tip as the most efficient shape to reduce the noise generated by the propellers.

Besides structure vibrations and tip clearance, the infeasibility of conducting experiments inside an anechoic chamber was considered one of the possible sources of error, which could have contributed to the overall noise.

Finally, the use of more robust structures not only could provide more stable configurations, but also allow a smaller tip clearance, thus reducing the vortex induced noise. Also, acoustic and flow simulations could contribute greatly in the prediction of noise propagation to better understand the noise generation mechanism at the blade tips and the propeller-duct interaction.

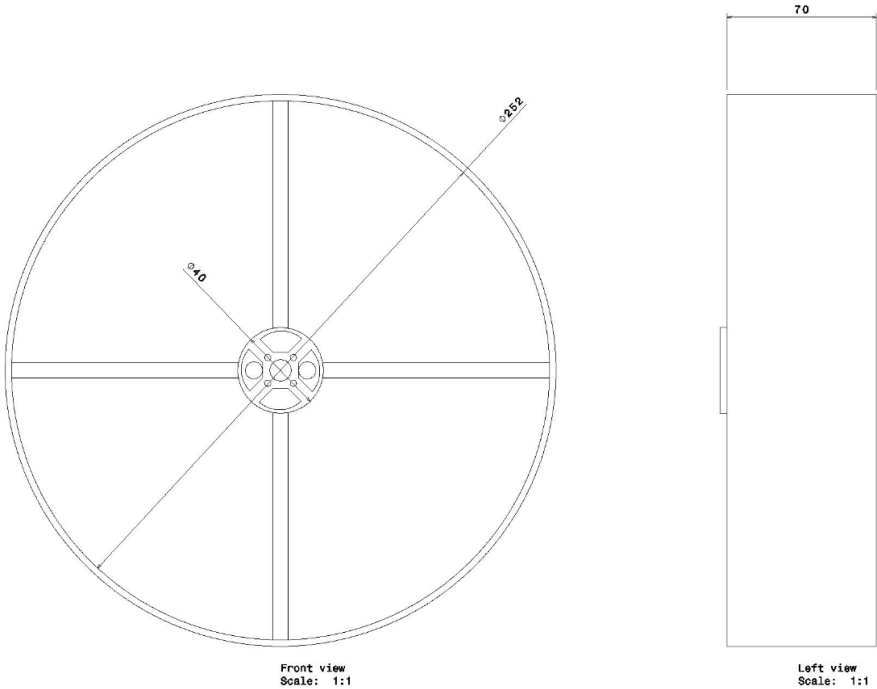
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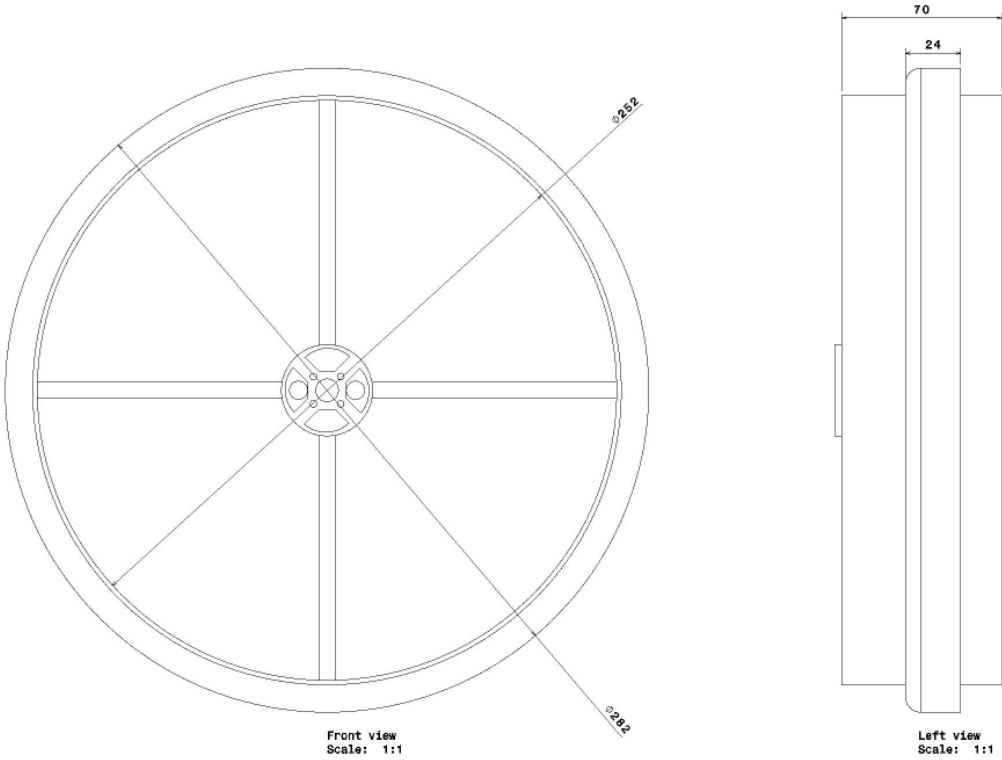
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APPENDIX A

A.1 Flat Duct



A.2 AM Duct



APPENDIX B

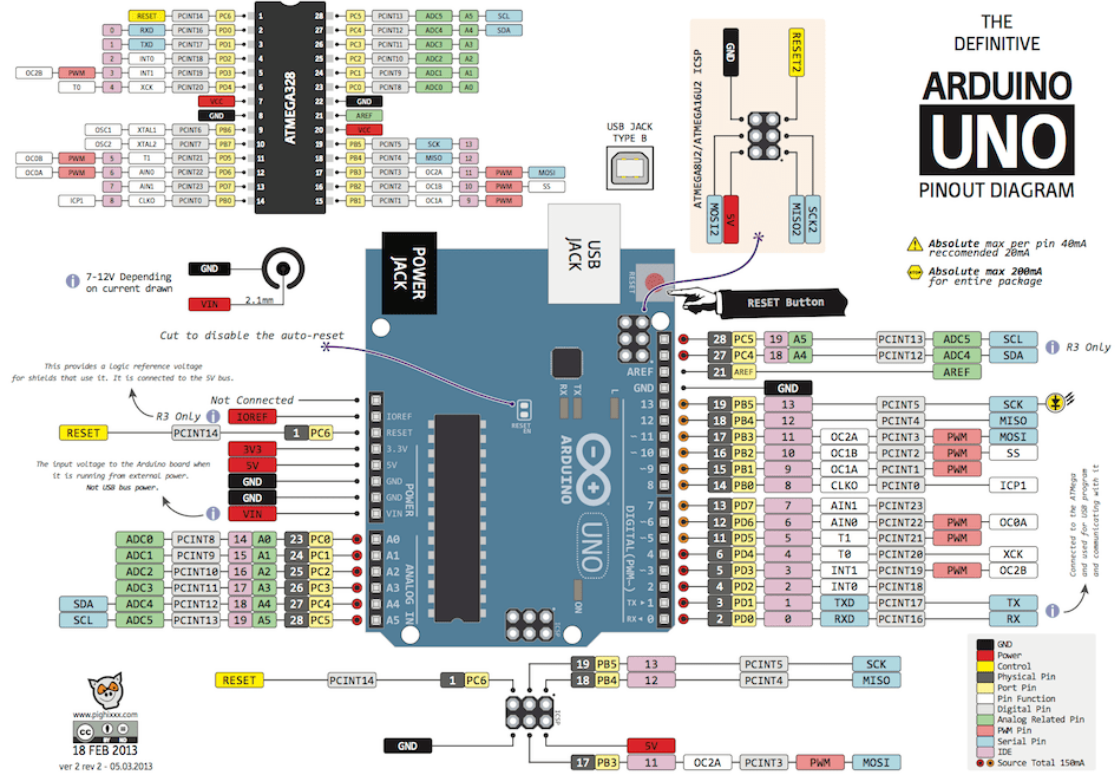
B.1 dBA calculation

```

function [dba,Terc,fc]=Calc_dBA(dB)
f=(0:8191)';
dB1=dB2dBA(f,dB);
x=zeros(16384,1);
x(1)=1;
fc=[63 80 100 125 160 200 250 316 400 500 630 800 1000
1250 1600 2000 2500 3160 4000 5000 6300 7340];
N=length(fc);
Terc=zeros(1,N);
for i=1:N
    [B,A]=butter(3,fc(i)*[1-.115 1+.115]/8192);
    xf=filter(B,A,x);
    XF=fft(xf);
    XF=20*log10(abs(XF(1:8192)));
    Terc(i)=10*log10(sum(10.^((dB1+XF)/10)));
end
fc(N)=8000;
dba=10*log10(sum(10.^(Terc/10)));

```

ANNEX A



ANNEX B

B.1 Microphone and Condenser Specifications

Certificate of Calibration and Conformance

Certificate Number 2007-98560

Instrument Model 426E01, Serial Number 010410, was calibrated on 04OCT2007. The instrument meets factory specifications per Procedure D0001.8204.

New Instrument

Date Calibrated: 04OCT2007

Calibration Standards Used

MANUFACTURER	MODEL	SERIAL NUMBER	INTERVAL	CAL. DUE	TRACEABILITY NO.
Larson Davis	PRA951-L4	0182	12 Months	26FEB2008	2007-90364
Hewlett Packard	34401A	US36015216	12 Months	07MAY2008	298816
Larson Davis	LDSigGn / 2209	0097 / 0118	12 Months	03AUG2008	2007-96249

Reference Standards are traceable to the National Institute of Standards and Technology (NIST)

Calibration Environmental Conditions

Temperature: 25 ° Centigrade

Relative Humidity: 30 %

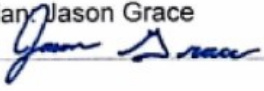
Affirmations

This Certificate attests that this instrument has been calibrated under the stated conditions with Measurement and Test Equipment (M&TE) Standards traceable to the U.S. National Institute of Standards and Technology (NIST). All of the Measurement Standards have been calibrated to their manufacturers' specified accuracy / uncertainty. Evidence of traceability and accuracy is on file at Provo Engineering & Manufacturing Center. An acceptable accuracy ratio between the Standard(s) and the item calibrated has been maintained. This instrument meets or exceeds the manufacturer's published specification unless noted.

This calibration complies with the requirements of ISO 17025 and ANSI Z540. The collective uncertainty of the Measurement Standard used does not exceed 25% of the applicable tolerance for each characteristic calibrated unless otherwise noted.

The results documented in this certificate relate only to the item(s) calibrated or tested. A one year calibration is recommended, however calibration interval assignment and adjustment are the responsibility of the end user. This certificate may not be reproduced, except in full, without the written approval of the issuer.

Technician Jason Grace

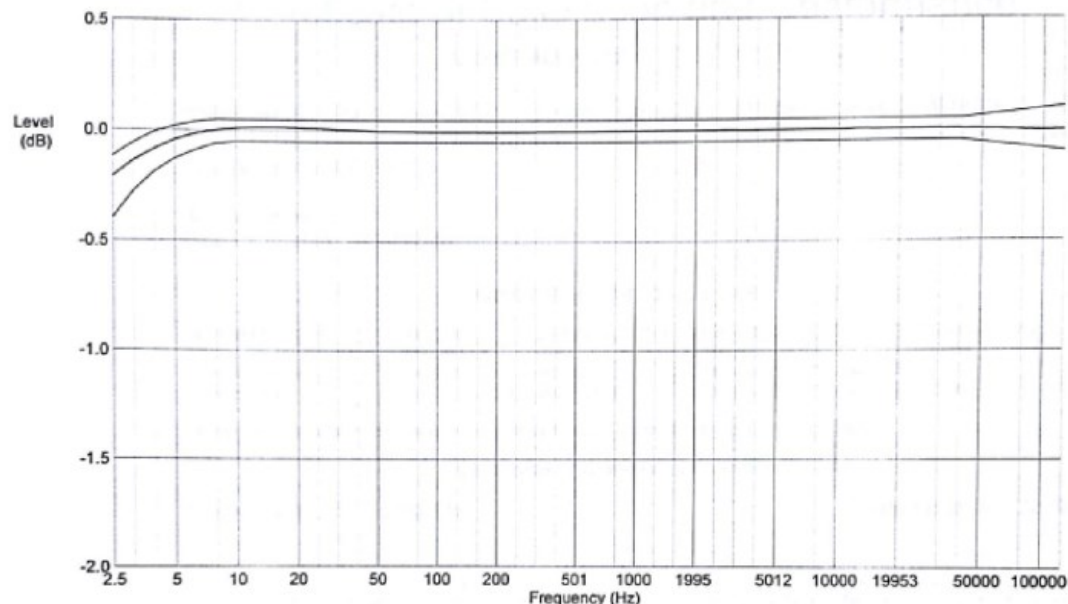
Signed: 

 **PCB PIEZOTRONICS**
A PCB GROUP COMPANY

CORPORATE HEADQUARTERS
3425 Walden Avenue, Depew, New York 14043-2495 USA
Toll Free: 800-828-8840 Fax: 716-684-0987
24-hour SensorLine: 716-684-0001
E-mail: info@pcb.com
Web site: www.pcb.com
ISO 9001:2000 Certified
A21 A Accredited to ISO 17025

Preamplifier Model: 426E01 Serial Number: 010410
Certificate of Electrical Conformance

Frequency response of this model 426E01 preamplifier was tested at a level of 1 Vrms with 18pF microphone capacitance and driving a short cable. Output level at 1kHz is 0.9948 Vrms (-0.045 dBV), uncertainty 0.033 dB. Output is 10.975 V DC, uncertainty 0.001. Results are displayed relative to the level at 1kHz.



Freq (Hz)	Measured (dB)	Uncert (dB)	Tolerance (dB)	Freq (Hz)	Measured (dB)	Uncert (dB)	Tolerance (dB)
2.51	-0.21	0.075	-0.12, -0.40	630.96	0.00	0.016	+0.05, -0.05
3.16	-0.14	0.058	-0.06, -0.28	794.33	0.00	0.016	+0.05, -0.05
3.98	-0.09	0.058	-0.01, -0.19	1000.00	0.00	0.016	+0.05, -0.05
5.01	-0.04	0.036	+0.02, -0.13	1258.90	0.00	0.016	+0.05, -0.05
6.31	-0.02	0.036	+0.04, -0.09	1584.90	0.00	0.016	+0.05, -0.05
7.94	0.00	0.036	+0.05, -0.06	1995.30	0.00	0.016	+0.05, -0.05
10.00	0.01	0.016	+0.05, -0.05	2511.90	0.00	0.016	+0.05, -0.05
12.59	0.02	0.016	+0.05, -0.05	3162.30	0.00	0.016	+0.05, -0.05
15.85	0.02	0.016	+0.05, -0.05	3981.10	0.00	0.016	+0.05, -0.05
19.95	0.02	0.016	+0.05, -0.05	5011.90	0.00	0.016	+0.05, -0.05
25.12	0.01	0.016	+0.05, -0.05	6309.60	0.00	0.016	+0.05, -0.05
31.62	0.01	0.016	+0.05, -0.05	7943.30	0.00	0.016	+0.05, -0.05
39.81	0.00	0.016	+0.05, -0.05	10000.00	0.00	0.016	+0.05, -0.05
50.12	0.00	0.016	+0.05, -0.05	12589.00	0.00	0.016	+0.05, -0.05
63.10	0.00	0.016	+0.05, -0.05	15849.00	0.00	0.016	+0.05, -0.05
79.43	-0.00	0.016	+0.05, -0.05	19953.00	0.00	0.016	+0.05, -0.05
100.00	-0.00	0.016	+0.05, -0.05	25250.00	0.00	0.022	+0.05, -0.05
125.89	-0.00	0.016	+0.05, -0.05	31500.00	0.00	0.022	+0.05, -0.05
158.49	-0.00	0.016	+0.05, -0.05	39750.00	0.00	0.022	+0.05, -0.05
199.53	-0.00	0.016	+0.05, -0.05	50000.00	0.00	0.022	+0.06, -0.06
251.19	-0.00	0.016	+0.05, -0.05	63000.00	-0.00	0.047	+0.07, -0.07
316.23	-0.00	0.016	+0.05, -0.05	79500.00	-0.01	0.047	+0.08, -0.08
398.11	-0.00	0.016	+0.05, -0.05	100000.00	-0.01	0.047	+0.09, -0.09
501.19	-0.00	0.016	+0.05, -0.05	126000.00	-0.01	0.063	+0.10, -0.10

Noise floor data: 1kHz (1/3 Octave) = 0.33 μ V, -9.7 dBuV, uncertainty = 0.47 dB

Flat (20Hz-20kHz) = 2.7 μ V, 8.6 dBuV, uncertainty = 0.47 dB

Awt = 1.4 μ V, 3.0 dBuV, uncertainty = 0.46 dB

Uncertainties are given as expanded uncertainty at ~95% confidence interval ($k = 2$).

Technician: Jason Grace Test Date: 04OCT2007

Model Number 426E01	MICROPHONE PREAMPLIFIER			Revision: E ECN #: 32199
Performance	ENGLISH	SI		OPTIONAL VERSIONS
Nominal Microphone Diameter	1/2"	1/2"		Optional versions have identical specifications and accessories as listed for the standard model except where noted below. More than one option may be used.
Gain	-0.05 dB	-0.05 dB	[1][2]	
Frequency Response(± 0.1 dB)(re 1 kHz)	6.3 to 125,000 Hz	6.3 to 125,000 Hz		
(-3 dB)(re 1 kHz)	<0.9 Hz	<0.9 Hz		
Phase Linearity(<1 °)	32 to 20,000 Hz	32 to 20,000 Hz	[2]	
(-1 to +10 °)	3.2 to 32 Hz	3.2 to 32 Hz	[2]	
Electrical Noise(A-weight)	<2.8 μ V	<2.8 μ V	[2]	
(A-weight)	1.7 μ V	1.7 μ V	[2][1]	
(Flat 20 Hz to 20 kHz)	<5 μ V	<5 μ V	[2]	
(Flat 20 Hz to 20 kHz)	3 μ V	3 μ V	[2][1]	
Distortion(3 V rms input at 1 kHz)	<-70 dB	<-70 dB	[2]	NOTES: [1] Typical. [2] Measured with an 18 pF reference microphone. [3] TEDS Capable Digital Memory and Communication, compliant with IEEE P1451.4 [4] See PCB Declaration of Conformance PS064 for details.
Output Slew Rate	2 V/ μ S	2 V/ μ S	[1]	
TEDS Compliant	Yes	Yes	[3]	
Environmental				
Temperature Range(Operating)	-40 to +176 °F	-40 to +80 °C		
Temperature Response	<0.05 dB	<0.05 dB		
Humidity Range(Non-Condensing)	0 to 95 %RH	0 to 95 %RH		
Humidity Sensitivity	<0.05 dB	<0.05 dB		
Electrical				
Excitation Voltage	20 to 32 VDC	20 to 32 VDC		
Constant Current Excitation	2 to 20 mA	2 to 20 mA		SUPPLIED ACCESSORIES: Model ERC-16 Calibration of microphone preamplifier (1)
Impedance(Input)	20 Gohm	20 Gohm	[1]	
Capacitance(Input)	0.06 pF	0.06 pF	[1]	
Output Bias Voltage	10 to 14 VDC	10 to 14 VDC		
Impedance(Output)	<50 ohm	<50 ohm		
Output Voltage(Maximum)	± 7 Vpk	± 7 Vpk		
Physical				
Housing Material	Stainless Steel	Stainless Steel		
Size (Diameter x Length)	0.5 in x 3.18 in	12.7 mm x 80.7 mm		
Weight	1.35 oz	38 gm		
Electrical Connector	BNC Jack	BNC Jack		Entered: <i>JH</i> Engineer: <i>BM</i> Sales: <i>WDC</i> Approved: <i>EP</i> Spec Number:
Mounting Thread(Microphone to Preamplifier)	0.4606 - 60 UNS	11.7 mm - 60 UNS		Date: <i>1-26-10</i> Date: <i>1-19-10</i> Date: <i>1-27-10</i> Date: <i>1-20-10</i> 29303
 [4] All specifications are at room temperature unless otherwise specified. In the interest of constant product improvement, we reserve the right to change specifications without notice. ICP® is a registered trademark of PCB Group, Inc.				 Phone: 716-684-0001 Fax: 716-685-3886 E-Mail: vibration@pcb.com 3425 Walden Avenue, Depew, NY 14043

57746

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REVISIONS		
REV	DESCRIPTION	DIN
NR	RELEASED TO DRAFTING	42362

Ø.52 [13.2]

MICROPHONE CARTRIDGE

Ø.50 [12.7]

PREAMPLIFIER

Ø.03 [.8]

BNC CONNECTOR (OUTPUT)

426E01

UNLESS OTHERWISE SPECIFIED TOLERANCES ARE:				DRAWN		CHECKED		ENGINEER	
DIMENSIONS IN INCHES		DIMENSIONS IN MILLIMETERS [IN BRACKETS]		JDM	12/20/13	JDM	12/20/13	MIT	12/20/13
DECIMALS XX ±.03 XXX ±.010		DECIMALS X ±0.8 XX ±0.25		TITLE OUTLINE DRAWING 1/2" ICP MICROPHONE SYSTEM					
ANGLES ± 2 DEGREES		ANGLES ± 2 DEGREES							
FILLETS AND RADII .003 - .005		FILLETS AND RADII 0.07 - 0.13		PCB PIEZOTRONICS™ 3425 WALDEN AVE. DEPEW, NY 14043 (716) 684-0001 E-MAIL: sales@pcb.com CODE IDENT. NO. 52681 DWG. NO. 57746 SCALE: 1.5X SHEET 1 OF 1					

eDrawings 15:38 4/29/2015

~ Calibration report ~

Microphone Model: 377B02

Serial Number: 108241

Description: 1/2" Free-Field Microphone

Calibration Data

Open Circuit Sensitivity @ 251.2 Hz: 53.39 mV/Pa
-25.45 dB re 1V/Pa

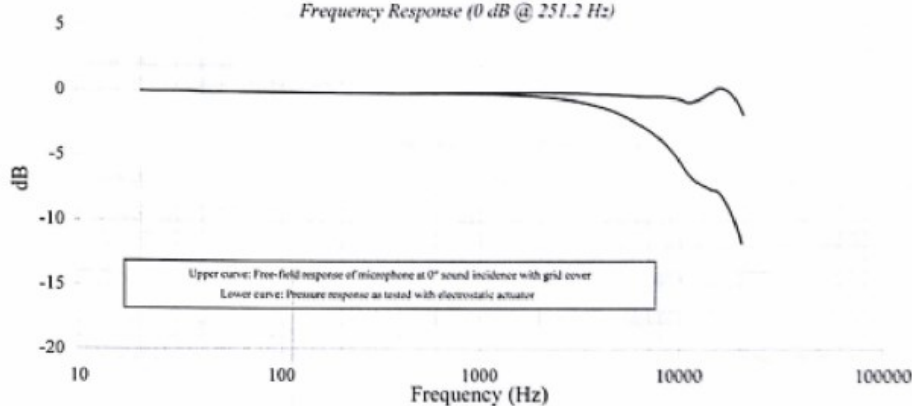
Polarization Voltage, External: 0 V
Capacitance: 11.3 pF

Temperature: 70 °F (21°C)

Ambient Pressure: 987 mbar

Relative Humidity: 34 %

Frequency Response (0 dB @ 251.2 Hz)



Freq (Hz)	Lower (dB)	Upper (dB)	Freq (Hz)	Lower (dB)	Upper (dB)	Freq (Hz)	Lower (dB)	Upper (dB)	Freq (Hz)	Lower (dB)	Upper (dB)
20.0	0.02	0.02	1584.9	-0.20	0.01	6683.4	-2.85	-0.33	-	-	-
25.1	0.03	0.03	1678.8	-0.23	0.00	7079.5	-3.11	-0.33	-	-	-
31.6	0.05	0.05	1778.3	-0.25	0.00	7498.9	-3.41	-0.34	-	-	-
39.8	0.02	0.02	1883.7	-0.27	0.01	7943.3	-3.73	-0.34	-	-	-
50.1	0.03	0.03	1995.3	-0.31	0.00	8414.0	-4.13	-0.40	-	-	-
63.1	0.02	0.02	2113.5	-0.34	0.00	8912.5	-4.55	-0.44	-	-	-
79.4	0.02	0.02	2238.7	-0.38	-0.01	9440.6	-5.03	-0.51	-	-	-
100.0	0.02	0.02	2371.4	-0.42	-0.01	10000.0	-5.60	-0.65	-	-	-
125.9	0.01	0.01	2511.9	-0.47	-0.01	10592.5	-6.20	-0.80	-	-	-
158.5	0.01	0.01	2660.7	-0.53	-0.02	11220.2	-6.63	-0.77	-	-	-
199.5	0.00	0.00	2818.4	-0.59	-0.03	11885.0	-6.95	-0.63	-	-	-
251.2	0.00	0.00	2985.4	-0.65	-0.03	12589.3	-7.20	-0.43	-	-	-
316.2	-0.01	0.00	3162.3	-0.73	-0.05	13335.2	-7.39	-0.20	-	-	-
398.1	-0.02	-0.02	3349.7	-0.81	-0.07	14125.4	-7.60	-0.01	-	-	-
501.2	-0.03	0.01	3548.1	-0.92	-0.10	14962.4	-7.70	0.27	-	-	-
631.0	-0.04	0.00	3758.4	-1.02	-0.12	15848.9	-8.13	0.22	-	-	-
794.3	-0.06	0.03	3981.1	-1.13	-0.13	16788.0	-8.71	0.01	-	-	-
1000.0	-0.09	0.03	4217.0	-1.25	-0.14	17782.8	-9.51	-0.40	-	-	-
1059.3	-0.10	0.03	4466.8	-1.39	-0.16	18836.5	-10.48	-0.97	-	-	-
1122.0	-0.11	0.03	4731.5	-1.54	-0.17	19952.6	-11.74	-1.81	-	-	-
1188.5	-0.12	0.03	5011.9	-1.75	-0.22	-	-	-	-	-	-
1258.9	-0.13	0.03	5308.8	-1.94	-0.24	-	-	-	-	-	-
1333.5	-0.15	0.03	5623.4	-2.14	-0.26	-	-	-	-	-	-
1412.5	-0.16	0.03	5956.6	-2.36	-0.29	-	-	-	-	-	-
1496.2	-0.18	0.02	6309.6	-2.60	-0.31	-	-	-	-	-	-

Technician: Paul Drews P.D. Date: July 7, 2008



PCB PIEZOTRONICS
VIBRATION DIVISION

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TEL: 888-684-0013 FAX: 716-685-3886 www.pcb.com

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Model Number 377B02	PRECISION CONDENSER MICROPHONE				Revision: L ECN #: 47338
Performance	ENGLISH	SI	OPTIONAL VERSIONS		
Nominal Microphone Diameter	1/2"	1/2"	Optional versions have identical specifications and accessories as listed for the standard model except where noted below. More than one option may be used.		
Frequency Response Characteristic(at 0° incidence)	Free-Field	Free-Field			
Open Circuit Sensitivity	50 mV/Pa	50 mV/Pa			
Open Circuit Sensitivity(± 1.5 dB)	-26 dB re 1 V/Pa	-26 dB re 1 V/Pa			
Frequency Range(± 2 dB)	3.15 to 20,000 Hz	3.15 to 20,000 Hz			
Frequency Range(± 1 dB)	5 to 10,000 Hz	5 to 10,000 Hz			
Lower Limiting Frequency(-3 dB)	1.0 to 2.4 Hz	1.0 to 2.4 Hz			
Resonant Frequency(90° Phase Shift)	10.4 kHz	10.4 kHz			
Inherent Noise	15 dB(A) re 20 µPa	15 dB(A) re 20 µPa			
Dynamic Range(3% Distortion Limit)	147 dB re 20 µPa	147 dB re 20 µPa			
Standards Designation(IEC 61094-4)	WS2F	WS2F			
Environmental			NOTES: [1] Typical. [2] Prepolarized [3] re 250 Hz [4] See PCB Declaration of Conformance PS167 for details.		
Temperature Range(Operating)	-40 to +302 °F	-40 to +150 °C			
Temperature Coefficient of Sensitivity(+14 to +122°F (-10 to +50°C))	0.005 dB/°F	0.009 dB/°C			
Static Pressure Coefficient	-0.013 dB/kPa	-0.013 dB/kPa			
Humidity Coefficient of Sensitivity(0 to 100%, non-condensing)	± 0.001 dB/%RH	± 0.001 dB/%RH			
Influence of Axial Vibration(0.1g (1 m/s²))	63 dB re 20 µPa	63 dB re 20 µPa			
Electrical					
Capacitance(Polarized)	12 pF	12 pF			
Polarization Voltage	0 V	0 V			
Physical					
Housing Material	Stainless Alloy	Stainless Alloy	SUPPLIED ACCESSORIES: Model ACS-20 Calibration of Precision Condenser Microphones (1)		
Venting	Rear	Rear			
Mounting Thread(Preamplifier)	0.4606 - 60 UNS	11.7 mm - 60 UNS			
Mounting Thread(Grid)	0.5 - 60 UNS	12.7 mm - 60 UNS			
Size (Diameter x Height)(with grid)	0.52 in x 0.64 in	13.2 mm x 16.2 mm			
Size (Diameter x Height)(without grid)	0.5 in x 0.6 in	12.7 mm x 15.3 mm			
Weight	0.28 oz	7.8 gm			
 [4]			Entered: LK Engineer: MT Sales: MV Approved: MT Spec Number:		
			Date: 10/20/2017 Date: 10/20/2017 Date: 10/20/2017 Date: 10/20/2017 29289		
					
			3425 Walden Avenue, Depew, NY 14043 Phone: 716-684-0001 Fax: 716-684-0987 E-Mail: info@pcb.com		

All specifications are at room temperature unless otherwise specified.
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REVISIONS

REV	DESCRIPTION	DIN
NR	RELEASED TO DRAFTING	

DIAPHRAGM

Ø.52 [13.2]

Ø.64 [16.4]

.36 [9.2]

Ø.50 [12.7]

WITH GRID CAP

Ø.04 [1.0]

BLACK O-RING

.5000-60 UNS [12.7mm-60 UNS] THREADS

Ø.48 [12.1]

Ø.47 [12.0]

.60 [15.3]

.4606-60 UNS [11.7 mm-60 UNS] THREADS

WITHOUT GRID CAP

UNLESS OTHERWISE SPECIFIED TOLERANCES ARE:

DIMENSIONS IN INCHES		DIMENSIONS IN MILLIMETERS [IN BRACKETS]	
DECIMALS	XX ±.03 XXX ±.010	DECIMALS	X ±0.8 XX ±0.25
ANGLES	± 2 DEGREES	ANGLES	± 2 DEGREES
FILLET AND RADII	.003 - .005	FILLET AND RADII	0.07 - 0.13

DRAWN

JDM	9/14/05	CHECKED	ECB	9/14/05	ENGINEER	CCL	9/14/05
TITLE							

OUTLINE DRAWING
1/2" PRE-POLARIZED
MICROPHONES

PCB PIEZOTRONICS™

3425 WALDEN AVE. DEPEW, NY 14043
(716) 684-0001 E-MAIL: sales@pcb.com

CODE IDENT. NO. 52681

DWG. NO. 29288

SCALE: 4X

SHEET 1 OF 1

B.2 NI 9233 Board Specification

Input Characteristics

Number of channels	4 analog input channels
ADC resolution	24 bits
Type of ADC	Delta-Sigma (with analog prefiltering)
Sampling mode	Simultaneous
Internal master timebase (f_M)	
Frequency	12.8 MHz
Accuracy	± 100 ppm max
Data rate range (f_s) using internal master timebase	
Minimum	2.0 kS/s
Maximum	50 kS/s
Data rate range (f_s) using external master timebase	
Minimum	2.0 kS/s
Maximum	51.3 kS/s

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17 NI 9233 Operating Instructions and Specifications

Data rates¹ (f_s)

$$f_s \leq 25.65 \text{ kS/s} \dots\dots\dots \frac{f_M \div 256}{n}, n = 2, 3, \dots, 25$$

$$f_s > 25.65 \text{ kS/s} \dots\dots\dots \frac{f_M \div 128}{n}, n = 2, 3$$

Input coupling

AC

AC cutoff frequency

–3 dB

0.5 Hz typ

–0.1 dB

4.2 Hz max

¹ The data rate must remain within the appropriate data rate range. Refer to the [Understanding NI 9233 Data Rates](#) section for more information.