Mechanical Design Solutions for Wind Resistant Microphone Ports

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DIVISION OF PRODUCT DEVELOPMENT | DEPARTMENT OF DESIGN SCIENCES | FACULTY OF ENGINEERING LTH | LUND UNIVERSITY

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MASTER THESIS

1666

Mechanical Design Solutions for Wind Resistant Microphone Ports

A product development project investigating important factors of microphone ports for increased speech intelligibility when exposed to wind.

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Abstract

This project's objective was to gather knowledge of ways to mechanically increase speech intelligibility and decrease wind noise through the design of microphone ports. The project focused on ports that would be applied in outdoor intercom products.

The project used experimental testing through the development method Robust Design to investigate different parameters that could be changed in a microphone port. This was done to further understand how changes of the parameters could give the microphone the best chances of producing high speech clarity when challenged by wind. A total of 18 port designs were tested through the human-centered method of speech-in-noise testing to evaluate the generated speech intelligibility of the ports. The designs were tested in several different noise setups to evaluate their ability to yield good speech clarity regardless of the mounting of the product or changes in wind direction.

The iterative development process, conducted in two cycles, was able to conclude that conically shaped ports with a length of 20 mm produced the highest voice clarity in a varying and challenging wind environment. The ports could be positioned both facing forward and downward under the condition that a forward-facing port would need a mesh or foam windscreen added in the port for desirable performance. The project was also able to conclude that the phenomenon of destructive interference could have a significant impact on the performance of a microphone and should always be considered in the placement of a port.

Keywords: Microphone port, wind noise, Robust Design, speech-in-noise testing, noise reduction, mechanical engineering

Sammanfattning

Målet med detta projekt var att samla kunskap om sätt att mekaniskt öka talförståelse och minska vindbrus genom designen av en mikrofonport. Projektet fokuserade på portar applicerade på snabbtelefonprodukter i utomhusmiljö.

I projektet utfördes experimentell testning genom produktutvecklingsmetoden Robust Design för att undersöka olika parametrar som kunde förändras i en mikrofonport. Detta gjordes för att vidare förstå hur ändringar av parametrarna kunde ge mikrofonen de bästa förutsättningarna till att producera hög taltydlighet under påverkan av vind. Totalt 18 portutformningar testades genom den människocentrerade testmetoden tal-i-brus för att utvärdera portarnas genererade talförståelse. Portutformningarna testades i flera olika brusuppställningar för att kunna utvärdera deras förmåga att frambringa god taltydlighet oavsett montering av produkten eller vindriktningsändringar.

Den iterativa utvecklingsprocessen, utförd i två cykler, kunde slutligen konstatera att en koniskt formad port med längden 20 mm frambringade den högsta taltydligheten i en varierande och utmanande vindmiljö. Mikrofonportarna kunde positioneras riktade både framåt och nedåt under villkoret att en framåtriktad port skulle behöva ett nät eller puffskydd för att prestera önskvärt. Projektet kunde också dra slutsatsen att fenomenet destruktiv störning kan ha en betydande inverkan på mikrofonens förmåga och bör alltid beaktas vid placeringen av portar.

Nyckelord: Mikrofonport, vindbrus, Robust Design, tal-i-brus-test, brusreduktion, maskinteknik

Acknowledgments

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Firstly, we would like to thank our supervisor at the company Henrik Liberg for always giving his support, time and technical knowledge to the project. The subject of acoustics was new to us and the contributions by Henrik was vital to accomplish the project.

We would like to thank our supervisor and examiner at Lund University, Elin Olander and Giorgos Nikoleris. A special thank you to Elin for giving us your valuable guidance within academic writing and the methodology of conducting tests throughout the project.

Finally, we would like to thank all the people participating in our tests making it possible to visualize our results.

Lund, June 2021

Erik Hagman and Hedvig Sannar

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List of Acronyms and Abbreviations

dB	Decibel
dBSPL	Decibel Sound Pressure Level
DOE	Design of Experiment
DSP	Digital Signal Processing
FDM	Fused Deposition Modeling
Hz	Hertz
MEMS	Microelectromechanical System
Mic	Microphone
SIN	Speech-in-noise
SNR	Signal-to-noise Ratio

1 Introduction

An introductory chapter presenting the product segment, purpose, objective, and scope of the thesis project, as well as time plan and report disposition.

1.1 Product Segment

This master thesis was conducted in cooperation with a company which will not be disclosed in this report, it will hereafter only be referred to as “the company”. A subdivision of this company oversees the development of network intercoms, digital door station devices. The purpose of these products is to gatekeep entrances and to only let people with permission go through doors and gates. These devices are in most cases equipped with cameras, speakers and microphones as means of communication. If someone without direct access wants to be let through, voice communication is available through network connection to the one in charge of allowing that person to enter. These intercom devices are fitted both indoors and outdoors.

1.2 Purpose

The purpose of the project was to enhance the company’s network intercom’s microphone capabilities for outdoor use. Outdoor wind creates noise that is picked up by the microphone when the product is in use. The mission was to further develop the mechanics surrounding the microphone inlet, the port design, to enable it to remain functional in stronger wind conditions, than the current solutions at the time could manage.

1.3 Objectives

The objective of this thesis project was to investigate changes in the mechanical design of the port that could improve the audio output of a microphone within an intercom product, located in windy conditions. Through the mechanical design factors, the aim was to identify and find optimal design solutions for the construction of microphone ports. The optimal design would mitigate the effects of wind noise in the products with microphones. Information about how to improve microphone port design should be collected and facilitate the development of new products' audio capabilities. This would hopefully lead to the company producing better performing future solutions with voice communication. For the product customer it would mean reduced risk of miscommunications and consequently increased security.

1.4 Delimitations

This project was conducted with a mechanical approach. This means that no development was to be made into digital or electrical solutions to the problem at hand.

The investigation of wind noise was made through audio recordings in an anechoic chamber to ensure repeatability and as measurement systems required power supply and stable conditions, instead of outdoors. Because of this reason, the test environment did not fully correspond to the intended habitat of the products.

The project was based on reducing wind noise in intercoms. These devices have a general geometry that forms the base of the proposed solutions.

The testing was conducted with a microphone made for scientific studies instead of a microphone usually fitted inside an intercom product, in order to gather more reliable data.

The material of developed prototypes that were tested did not correspond to the material of intercoms of the company.

1.5 Time Plan

The project proceeded during the spring of 2021 within a period of 20 weeks starting in January. During the initial week of the project the workload was divided into different segments and activities to create an organized and even workflow. A Gantt chart was created to visualize this workflow. During the progress of the project the activities real time consumption did not always match the estimated values, a copy of the time plan was created showing the real time spent on each activity. The biggest difference was that the development became an iterative process which led to several steps being conducted twice during different periods. Through the iterative process, an elaborated result was given. Gantt charts can be found in Appendix A. Both authors shared the workload of the project equally.

1.6 Disposition

The project focused on product development, and this report will explain the complete process from start to end. In the second chapter called “Research”, all theoretical background information is presented which was necessary for understanding the basis of the project for the authors. Fundamental theory of microphones and its relation to wind is presented. It does also include research made through conversations with employees of the company accustomed to the problem that was investigated. Chapter three, “Methodology” explains the methodologies that have been used to conduct the scope of the project. Two main methods will be described, one for the product development process that is called Robust Design and one method for testing that is called Speech-in-Noise testing. The second became a major part of the projects data gathering. A third method was applied called Continuous Sweep and is also described in Chapter three. Chapter four “Test Development” and five “Product Development” describes the process of developing an audio test and the development of microphone ports through investigative experiments. Chapter six “Proposed Guidelines and Designs” unveils and describes the final prototyped port that the development process resulted in as well as the design guidelines they were built from. Further on in Chapter seven, “Discussion”, the project and development process are reviewed with recommendations for microphone design and for further investigations in the field. In the last Chapter “Conclusions”, final remarks are drawn about the result of the project.

2 Research

This chapter presents the projects initial research into the problem area. It includes essential theory, current noise reduction solutions and conducted interviews.

2.1 Sound

Sound is mechanical disturbances that propagates through an elastic material medium. The disturbances are causing an alteration in pressure or displacement of particles of the material which can be detected by a person or an instrument. The disturbances are waves which travel in concentric spheres. The sound waves expand at a fixed velocity which has been found to be approximately 343 meters per second at 20 degrees Celsius, commonly called *the speed of sound*. The speed does however depend on altitude and the conditions of the atmosphere. Sound waves are produced by vibrations from a source for example a tuning fork or the human vocal cords (Berg, 2020; Western Electric Co, 1969).

The rate of the vibration corresponds to the frequency of the sound. Frequency is the number of wavelengths passing per second and is measured in hertz (Hz). A high rate of vibration will create a high tone while a low rate will create a low tone. Further on the amplitude of a sound vibration referrers to the volume of the sound. A visual representation of a sound vibration can be seen in Figure 2.1. Sound that is audible for the human ear has a frequency range between roughly 20 Hz and 20 kHz. Frequencies below 20 Hz are referred to as infrasound and higher than 20 kHz as ultrasound (Western Electric Co, 1969). The frequency range of the human speech is 125 – 8000 Hz (Ecophon, n.d.).

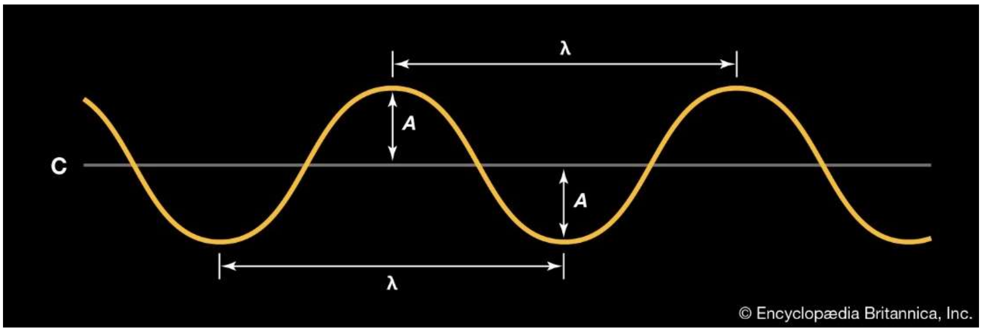


Figure 2.1 Graphic representation of a sound wave showing amplitude (A) and wavelength (λ) (Berg, 2020).

The mechanism of the human ear can respond to both small and large pressure waves as they are nonlinear. Due to this mechanism the ear works more efficient when responding to soundwaves with smaller amplitudes than those with larger. Because of this nonlinearity of the ear sensing pressure waves, there is a nonlinear scale to describe the intensity of soundwaves, the decibel scale (dB). Sound is therefore normally measured in dB. Decibel is a logarithmic scale and an increase of 10 dB approximately double the loudness of a sound (Berg, 2020). The unit of sound pressure level in acoustic measurements is commonly dBSPL, which is the measured pressure relative to 20 micro Pascals (Interacoustics, 2016).

The frequency of a sound and its wavelength are correlated. The equation being:

$$Wavelength = \frac{Speed\ of\ sound}{Sound\ frequency}$$

A low frequency sound has a long wavelength, by reference 20 Hz sound has a wavelength of 17 meters, which is the distance the wave can travel before a new wave start. For a high frequency sound of 1000 Hz the wavelength is only 3,4 cm. The length of a wave makes a difference in how the sound can be managed (Pyzdek, n.d). Soundwaves that are bigger than an obstacle in its path can bend around it, but if the obstacle is bigger than the wave the sound will be reflected or absorbed by the obstacle as it is illustrated in Figure 2.2.

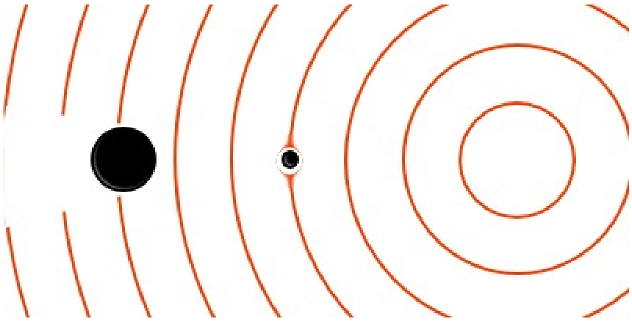


Figure 2.2 Illustration of soundwaves and how they behave against obstacles of different sizes (Pyzdek, n.d).

2.1.1 Frequency range and response

The frequency range of a microphone is defined as the interval between its upper limiting frequency and its lower limiting frequency. In other words, the range of frequencies that the microphone can record. The frequency range can also be referred as bandwidth (GRAS Sound & Vibration, 2020).

The frequency response of a microphone is how it responds to different frequencies. When determining the signature of the sound of a microphone the frequency response is the most important factor. It is presented as a response curve with the frequency [Hz] on the x-axis and relative response [dB] on the y-axis. The curve should be a smooth line. If it has a lot of peaks and valleys the audio from the mic would risk not being perceived as natural (Shure, 2017). An example curve is shown in Figure 2.3, which is smooth until after approximately 6 kHz where the audio may differ. The microphone port affects the frequency response of the microphone and therefore it is important to investigate the curve when developing different design solutions.

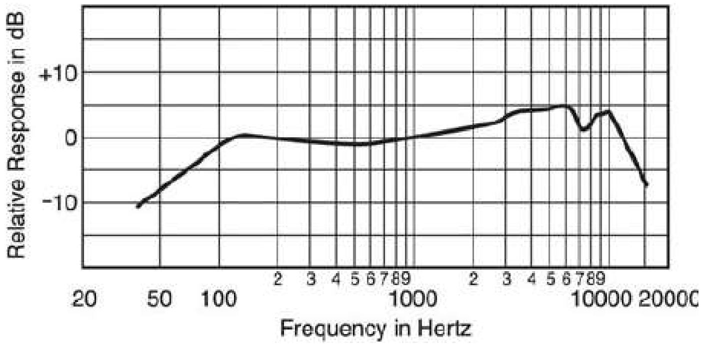


Figure 2.3 A frequency response curve (Bojinov et al, 2014).

2.1.2 Resonance

Resonance is the phenomenon when the amplitude increases due to a periodically applied force with an equal frequency as the natural frequency of the system that it acts on (Halliday et al, 2003).

The Helmholtz resonance describes how air flows traveling into a cavity can create resonant sounds. What frequency the resonance occurs at depends on the cavity's volume, length and diameter. Where the resonance occurs is detected through a frequency response test as the first peak value (Morcelli & Widder, 2014).

If a microphone is located within a cavity in resonance, the sound causing the resonance will be much stronger than any other surrounding sound source. This phenomenon can be used in a positive way in certain instances but can also create trouble in others. This is due to a roll-off in sensitivity that occurs above the resonance frequency, as can be seen in Figure 2.3. When designing microphone ports, the resonance frequency needs to be considered to reduce its impact. Optimal design makes the resonance occur outside of the microphone’s frequency range. This is often done by having a very high resonance frequency. A reason for this is that a microphones ability to receive sounds of frequencies above its resonance peak is lowered. Research into optimal acoustic path shapes has been conducted in analytic software which concludes, among other things, that an inward bend on a microphone port will significantly move the resonance peak into lower frequencies (Morcelli & Widder, 2014).

2.1.3 Interference

With sound being waves of pressure it is subjected to wave interference. It means that waves of sounds coming from different sources will constructively or destructively interfere with each other. If two sources emit sound of the same frequency and doing so in the same phase towards a specific point, the amplitude of the waves will combine and increase in height. This is explained as constructive interference and results in an increased volume of the emitted sound. The opposite would happen if the waves were out of phase, this is referred to as destructive interference and instead reduces the volume of the sound (Berg, 2020).

2.2 Microphones

Microphones are electroacoustic devices which converts acoustic energy into electric energy. There are two purposes of microphones. The first is to convert sounds into acoustic signals that are transmitted and processed and thereafter reproduced. The second purpose is to be used as a measurement instrument by converting acoustic signals into electric currents that are processed and displayed graphicly (Beranek & Mellow, 2019).

Most microphones fulfill its purpose by containing a diaphragm which vibrates by air and is connected to a part that can create or allow a small electron flow. Three major parts that exist in every microphone are:

- Diaphragm – The diaphragm starts to vibrate when the sound wave hits it.
- Transducer – The transducer converts the mechanical vibrations of the diaphragm into an electric signal.
- Casing – The casing provides as mechanical support and protects the diaphragm and transducer. It can also help to control the microphone’s directional response (Owsinski, 2005).

There are a large variety of microphones which have been developed depending on various factors such as shape, size, fidelity of reproduction, high electrical output, cost, durability, and climate changes. There are several different types of microphones that functions in different ways. However, pressure microphones which are the most popular and the one primarily used in the company´s products, was therefore also the microphone used in this project.

Applications of the pressure microphone are acoustic measurement systems and to pick up music and speech in broadcast studios, public-address installations, and hearing aids. There are two types of pressure microphones: electromagnetic and electrostatic (Beranek & Mellow, 2019). The electrostatic type called condenser microphone was used in this project.

The condenser microphone, also known as electrostatic microphone or capacitor microphone, consists of two electrically charged plates. One plate act as a diaphragm and the other is fixed, called a backplate. The pair form a condenser with a positively and negatively electrode and a space of air between. When the sound wave hits the diaphragm the space of air changes and consequently the voltage potential as well, an electrical signal is created. The voltage potential needs to be amplified to be usable therefore a power supply is needed, see Figure 2.4, (Owsinski, 2005).

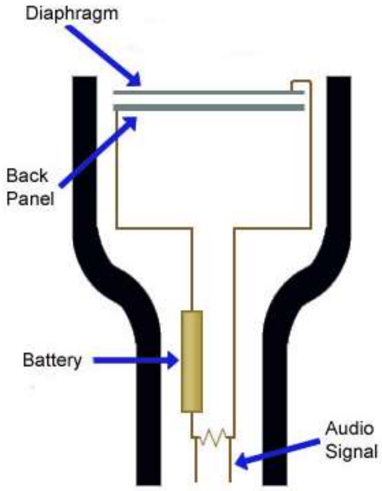


Figure 2.4 Construction of a condenser microphone (ProSoundWeb, 2010)

Microphones used in a lot of modern technical devices are one of two types of condenser microphones called electret microphones and microelectromechanical system (MEMS) microphones. These two types are used in almost all of the company’s products. In the electret microphone the diaphragm exists as a permanently polarized electret material. In this way it is not necessary with a polarizing power supply and the microphones can be made very small and inexpensively (Owsinski, 2005).

2.2.1 Microphone Port

A microphone port, also known as the acoustic channel of the mic, is the opening to the mic in a product as seen in Figure 2.5. It can be described as the channel where air and acoustical waves travel through to reach the microphone that is located further in. The construction of a good microphone port maximizes the performance of the mic by reducing turbulence of air surrounding the product. The acoustic properties of the port are determined by its length, diameter and shape. (Infineon Technologies AG, 2018)

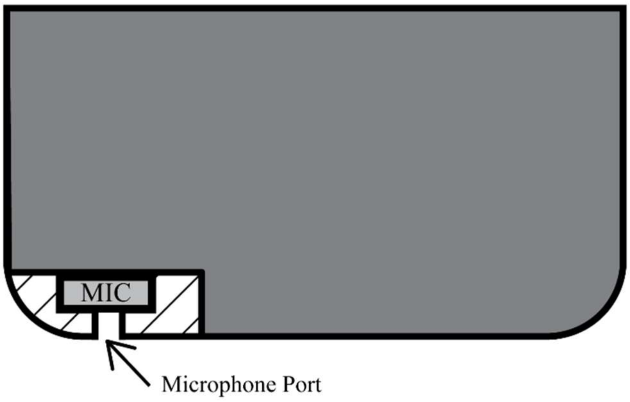


Figure 2.5 A cropped cross-section of an intercom showing the microphone port, the opening to the mic in a product.

2.3 Wind Noise

2.3.1 Wind Turbulence

Wind is the movement of air in relation to the surface of Earth (Britannica, 2012). It occurs by spatial differences in atmospheric pressure which normally exists due to temperature changes from solar heating and surface radiation. Wind noise is a consequence of wind turbulence. There are two types of turbulence: convective and mechanical (Walker & Hedlin, 2010).

Convective turbulence is driven by thermal fluctuations in the atmosphere. The biggest demonstration of this turbulence is clouds in the troposphere. Mechanical turbulence is described as the interaction of wind and the Earth's surface layer. It is created when wind collides with objects or topography. Mechanical turbulence is of a smaller scale than its convective counterpart. The turbulent air creates low frequency noise.

According to Morgan and Raspet's (1992) investigation on the wind's low frequency sound generation, the dominant factors of wind noise in microphones outdoors are the turbulent air's velocity and pressure fluctuations. However, in a low-turbulent scenario the noise mainly comes from the microphone's body, deflecting the winds kinetic energy and converting it into pressure energy. Both types of wind noise generate infrasound as well as audible low frequency sound.

2.3.2 Reynold's Number

Reynold's number is a dimensionless number used to investigate fluids and determine whether they are in laminar or turbulent flow. A low Reynold's number correlates to a more laminar flow and a higher to a more turbulent flow (Rehm et al, 2008). Reports suggests that a correlation can be made between an air flow's Reynold's number and noise reduction by a foam windscreen. A higher Reynold's number decreases the wind noise reduction effect by a windscreen. Foam windscreens are further presented in Chapter 2.4.1. The report explains that testing the noise reduction can be done in both high and low Reynold's number flow environments. This is possible because the results from the low flow can be translated into more turbulent flow situations. The noise reduction will concern the same frequency broadband but the amount of dB that can be reduced will be lower in more turbulent air flows (Zheng & Tan, 2002).

2.4 Current Solutions to Reduce Wind Noise in Microphones

There are currently a couple of solutions that mechanically reduce the noise generated by wind reaching the microphone. Elimination of all wind noise is very hard to achieve if acoustic energy shall be able to reach the microphone.

All current solutions try to mitigate wind in different ways, but there is no way to reduce it to zero without reducing all sounds.

2.4.1 Foam Windscreen

A windscreen is a common accessory to reduce wind induced noise in microphones. When shielded by a windscreen the microphone is covered by a porous material. The material reduces non-acoustic pressure fluctuations and transforms the wind's kinetic energy into thermal energy within the material. Windscreens are most effective when they can surround the microphone in cylindrical or spherical shapes and larger windscreen diameter correlates with higher effectiveness in reducing wind induced noise (Zhao et al, 2017). Through the use of windscreens the wind velocity becomes lower and the flow less turbulent which results in less stress put on the microphone (Zhao et al, 2020). Figure 2.6 shows an example of an ordinary foam windscreen. In addition, some windscreens are made of fur instead of porous materials where the effects on noise are quite similar, since they reduce winds energy in the same way (Woolf & Prudden, 2000). These windscreens are commonly called "deadcats" or "windjammers". A concern with a foam windscreen is that the plastic foam material handles long expose to ultraviolet light poorly. After a while it will become brittle and its lifespan is projected to one year of continuous outdoor use (Schomer et al, 1990). The possible benefits of windscreens are however interesting enough to investigate.

Figure 2.6 Foam Windscreen

2.4.2 Basket Windshield

Basket windshields are normally made of a wire mesh that encloses the microphone. A common basket windshield is presented in Figure 2.7. The mesh is acoustically transparent which lets sounds travel effortlessly to the microphone. Its way of mitigating wind noise is the creation of turbulence when the wind hits the mesh. This turbulence slows the kinetic energy of the wind and reduces the fluctuations inside the basket. The windshield is effective of reducing noise when there is a distance between the mesh, which creates turbulence, and the mic that wants to operate in a calm environment (Hill, 2006). The sound is in this way less affected by the wind. Perforated plates are another example of wind reduction solution that uses the same technique.

Figure 2.7 Example of basket windshield (Adorama, n.d.)

2.4.3 Placement

The placement of the microphone in a product is important to minimize wind noise. In a study performed for Nokia Mobile Phones at the University of Salford, different placements of the microphones were tested on different sizes of objects, in combination with different wind directions and wind speeds. The size of the object could stand in comparison of what would be tested in this project. The tests were conducted in a wind tunnel with the object being connected to a cylinder fixed to the ceiling. Five sizes of a wooden model were used to investigate the relationship between wind noise and the dimensions of the object. The models were placed in eight orientations according to the wind direction, the angles tested were: 0º, 45º, 90º, 135º, 180º, 225º, 270º and 315º. Five of the directions can be seen in Figure 2.8. Seven microphone placements on the objects were analyzed where number 1-3 are placed on the center line of the front side, number 4-5 along an edge and number 6-7 facing downwards from the object as shown in Figure 2.8 (Bradley et al, 2003).

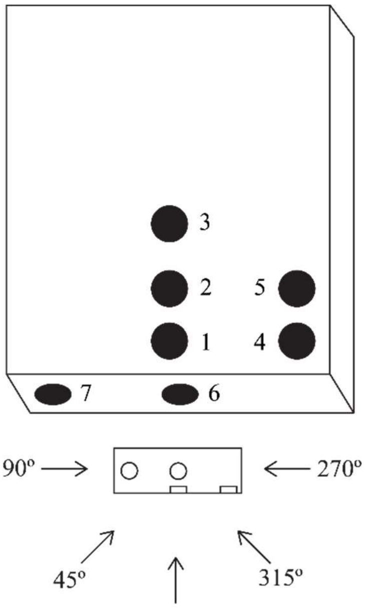


Figure 2.8 Placement and wind direction in noise study.

The result of the study showed, regardless of the size of the object, that the placement of the microphone at location 7, on the base and edge of the object, gave best result and was most suitable for minimizing wind noise. A general result about the size of the object was that a bigger object generates more wind noise. How the increase in size affected different position in different direction varied however a lot.

For the best position, 7, minimal noise occurred in the angle of 90º, and maximum noise occurred in the angle of 315º. Furthermore, it was evident that the distance to the side edges is more important than the distance to the bottom edge. Location 7, placed close to the side edge, produced 10 to 20 dB lower low frequency noise levels than location 6, placed in the center. In terms of wind speed, it was found that higher wind speed increases wind noise.

Regarding positions on the front side, it was harder for Bradley et al (2003) to draw conclusions, but the belief was that noise was reduced in relation to distance away from the center.

2.4.4 Digital Signal Processing (DSP)

There are currently many microphone signal processing techniques that enhance the desired sounds to be heard above the environmental noise as wind noise. This chapter will discuss the main ways wind noise can be reduced on a non-mechanical level. Implemented software has the possibility to process and manipulate recorded audio to optimize the functionality of a microphone. Common techniques are filtering the sound or using multiple microphones (Beckmann, 2016). It is however the performance of the mechanical design that puts boundaries on how effectively software can process any audio input. The better mechanical design, the more headroom for sound improvement by algorithms.

Filtering the sound is a versatile way of rejecting the unwanted noise. When reducing wind noise, a high-pass filter might be used to reduce the low frequencies where the wind noise mostly operates. Another efficient way for canceling noise is using multiple microphones. If the position of the desired source in relation to the microphone is known, multiple microphones can create a pickup pattern of the directions to isolate the source from the unwanted wind noise. Sounds that are arriving from a specific direction will be amplified and other sounds will be attenuated (Beckmann, 2016).

This project was not investigating nor developing any software solutions, it was rather trying to develop a mechanical solution that could work in synergy with existing software programs. A mechanical design of a port on an intercom should therefore be able to be duplicated on the product and have some distance between the ports.

Some software filtering of audio was nonetheless used within the project, however not for noise reduction purposes. Two filters in specific were used:

1. Gain flattening filter: Filter that can be used to flatten out unequal signal intensities (Iridian, n.d.). When speakers are placed in an acoustic space, interactions occur between different speakers and between the speaker and the space. The interactions cause changes in the frequency response at the listener position, with the reason of that the listener will perceive the sound from the speaker in different ways depending on its position and reflective surfaces (floor, walls, ceiling etc.) (Biamp, 2020). To reduce this problem, gain flattening filter is applied to the device to flatten the output frequency response. This filter was used when conducting continuous sweeps, described in Chapters 3.3
2. A-weighting filter: Filter that has been developed to describe how the human ear perceives the sound, by applying it when doing acoustic sound level measurements. A-weighing filters are as an example commonly used when measuring traffic noise (Swedish Transport Administration, 2020). The filter is most often used for graphical purposes to visualize how people perceive sound frequencies. This filter was applied in noise tests presented in Chapter 6.3.2.

2.5 Further Research within the Company

Interviews were conducted at the start of the project with two people at the company. Both had important insights on the project at hand and provided valuable information. A port design document previously created by the company was also reviewed.

2.5.1 Alexander, 8th of February

Alexander works as the product owner of intercom devices at the company. As stated in the purpose of this thesis, and strengthen by Alexander, there have been possibilities of improvements identified regarding sound recordings from door stations used outdoors in particularly windy conditions. Intercoms commonly affected by strong winds were usually located in large harbors and ports. Figure 2.9 a-c shows an example of such a place in a port in a northern European harbor. Most intercoms were mounted on walls, but at some extent also mounted on pillars as seen in the pictures.

Figure 2.9 a-c, Intercom devices mounted in the windy conditions of a European harbor.

2.5.2 Magnus, 21st of February

Magnus works at another department at the company as an electronics engineer. He was during 2019 working with reducing the wind noise in microphones in a different outdoor product.

His team investigated some mechanical parameters of a port that could influence the sound. The shape of the microphone port was a conical frustum and different diameters of the top and bottom surfaces were tested. The results of the different designs were relatively similar and the conical shape was discovered as successful. Porous materials to put in front of the mic was discovered to distort the sound too much and could also be destroyed by UV light, and therefore not used. Different meshes in front of the microphone did although give a good result. Two sintered metallic meshes with different patterns pressed together was put approximately 1 cm from the MEMS mic and was agreed upon as the best choice. This solution is now a part of the product.

Magnus explained that the further away the metallic mesh is from the mic the better the result in terms of wind noise. This is because sound is created when the mesh interacts with the wind. With bigger distance to the mic the local noise becomes more distant and less affecting.

2.5.3 Company Microphone Port Design Guidelines

As a start-off point for the further development of wind resistant ports the company had an existing manual for microphone port design. The guidelines were mostly focused on ports for indoor products but also gave advise on designing for outdoor environments and wind. The main points the guidelines focused on were:

- The port diameter should be above 1 mm, but the effects of making it bigger than that would be negligible.
- The length of the port was recommended to be less than 4 mm, the shorter the better.
- A conical shape was recommended to mitigate resonance.
- Sharp edges should be avoided and replaced with chamfers or rounds.

To design towards outdoor conditions further guidelines included:

- Using a mesh will create turbulence that calms the air. When using a mesh, the microphone should be placed at least a radius of the diameter of the port away from the mesh.

The reference to this document will remain undisclosed in agreement with the company.

2.6 Research Takeaways

Subjects discovered that were deemed important for the further development in the project are listed below. The points will cover, in short, the different elements that would need consideration when developing a well-functioning microphone port for an outdoor intercom.

- Regarding sound it was deemed important to design a port that functions well in the whole audible spectrum and most importantly in the spectrum of speech for an intercom product. Both resonance and interference could influence a ports functionality and needs to be watched out for during a development.

- Wind noise is creating the most noise in low audible frequencies. It is the intensity of the wind and the amount of turbulence it produces that decides how much wind noise that is created. To mitigate wind noise the most optimal way is to create a calm environment for the microphone to operate. This is what a good microphone port needs to succeed in.

- The most common way of mechanically reduce wind noise today is by using foam windscreens or a basket windshields. This calms the air by creating turbulence at a safe distance from the microphone, while remaining acoustically transparent. The positioning of the port could also significantly affect the noise in a microphone, and it was suggested that an optimal position of the port was on the bottom side and close to a side edge.

- Through research within the company, design guidelines were brought forth that could form a basis for the project’s development process. The intercoms mounting position was perceived as to possibly influence noise levels and would be investigated further.

3 Methodology

A chapter describing the methodology used as a framework for the product development process, as well as two methods selected for wind noise testing.

3.1 Robust Design

To investigate how to design microphone ports in products to mitigate wind noise, the methodology of “Robust Design”, as it is written in Ulrich and Eppinger’s book “Product Design and Development”, was used as the project’s framework (Ulrich & Eppinger, 2012).

The Robust Design method originates in the practice of *design of experiments* (DOE). DOE is a cornerstone in applied statistics and a method of creating experiments that holds significant statistical value. Genichi Taguchi applied DOE within product development and product quality in the 1960s. He called the method Robust Design, and it became common practice in big engineering firms in the United States in the 1990s. It is a seven-step method, see Figure 3.1, to improve a design in relation to a chosen problem. The method means to find parameters in a design that can be controlled and changed to mitigate the effects of certain noise factors that are identified to be causing problems. The investigation is made by designing, conducting, and analyzing results of experiments to determine ideal parameter performance (Ulrich & Eppinger, 2012).

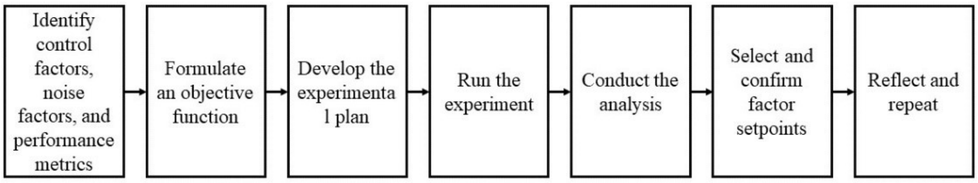


Figure 3.1 The seven steps of the Robust Design process.

3.1.1 Identify Control Factors, Noise Factors and Performance Metrics.

The first step of the Robust Design process was set to identify the control factors and noise factors that could change the performance of the microphone port.

C*ontrol factors* are design variables that can be controlled and changed on the product to find an optimal setpoint, and in this project, to enhance the sound of the speech when it is windy. The chosen design variables of the microphone port originated from the background theory and investigative interviews. The factors were chosen since they were mentioned in wind reduction principles, but without clear data of how much they could impact the speech intelligibility of a microphone.

Noise factors are variables that cannot be controlled during manufacturing and operation of the microphone port. The goal was to design a port that worked well regardless of the values of these factors. The choice of factors is detailed in the product development chapter of the report.

Performance metrics are the product specifications of interest in the product development. In this project scores on a speech intelligibility scale were the main investigated parameter. How clearly a spoken message is understood. However, the developed microphone port performance was also analyzed through frequency response curves created with Continuous Sweep, described in Chapter 3.3.

3.1.2 Formulate an Objective Function

The objective function is a transformation of the performance metrics to a measurable scale of performance. The microphone port designs were to be tested in speech intelligibility. This was to be done in a test that gave the designs a speech-in-noise (SIN) score. How clearly a spoken sentence is understood when challenged by wind noise. The scale of performance would range from a high SIN score which would translate to a good speech intelligibility, to a low SIN score that would translate to bad speech intelligibility.

To receive a SIN score the port designs needed to be SIN tested, what this is and how the testing was conducted is described in Chapters 3.2 and 4.

An illustrated overview can be seen in Figure 3.2.

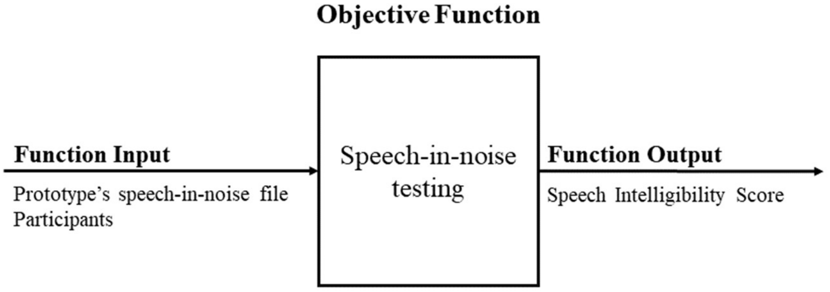


Figure 3.2 Objective function.

3.1.3 Develop the Experimental Plan

The goal of the SIN testing was to identify how different factors within microphone port design affect the intelligibility of speech, when it was windy outside.

The test study was done through two test cycles. A first test study was conducted with the objective of finding good single parameter designs from a wide field of control factors. After a review of the test results a second test study would initiate to investigate combinations of control factors and new parameter settings that reflected the findings made from the first test cycle. The test setup and method would stay the same throughout the first and second test cycle apart from the differentiating microphone port design that were to be investigated.

The choice of number of designs, which means what to be tested, and what the test setup would consist of would be decided by the experimental plan, which is an informative matrix. An example of how an experimental plan can look like can be seen in Figure 3.3. It depicts, from the left, eight prototypes (1-8) consisting of two different level settings of 7 control factors (A-G). From the right, three noise factors (Na-Nc) create four different noise setups through combinations of the levels of each noise factor. The “X” represents a chosen test to conduct, of a chosen prototype in a chosen test setup.

								1	1	2	2	Na
								1	2	1	2	Nb
	A	B	C	D	E	F	G	1	2	2	1	Nc
1	1	1	1	1	1	1	1	✖				
2	1	1	1	2	2	2	2					
3	1	2	2	1	1	2	2		✖			
4	1	2	2	2	2	1	1					
5	2	1	2	1	2	1	2					
6	2	1	2	2	1	2	1			✖		
7	2	2	1	1	2	2	1					
8	2	2	1	2	1	1	2					

Figure 3.3 Example of an experimental plan with seven control factors (A-G) and three noise factors (Na-Nc) at two levels each.

Two experimental plans were created in this project, one for each test cycle. These experimental plans are detailed and explained in Chapter 5.

3.1.4 Run the Experiment

Running the experiment meant recording the SIN files according to a constructed experimental plan, as well as performing SIN tests including the files with test participants. The SIN tests created the performance data of the port designs that could be analyzed and evaluated. The process of developing the tests and executing them is described in Chapter 4.

3.1.5 Conduct the Analysis

After running the SIN tests where test participants had listened to recorded SIN files and answered to questions about their speech intelligibility, the test data could be collected. The answers were to be assessed and complied according to rules described in Chapter 4.8 to result in a mean performance score for each port design that could be compared the other designs that were tested. With each design being given a score, a ranking of robustness between the designs could be made. An analysis of how much effect each control factor that was tested had on the resulting SIN score could also be conducted. The analysis of tested designs is found in Chapters 5.1.3 and 5.2.3.

3.1.6 Select Factor Setpoints

When the results were fully analyzed and scored, the factor setpoints could be established. Factor setpoints means deciding the best level of each tested control factor in order to create an as robust design as possible.

Some factors could however be contradicting others and their relation to each other could be unknown. Since this was a considered possibility from the start of the project, a second test cycle was planned. By performing a second test cycle good combinations of control factors could be found, to get more information about advantageous designed microphone ports for speech intelligibility. The factor setpoint charts for both test cycles are found in Chapter 5.

3.1.7 Reflect and Repeat

After the first test cycle was completed and fully analyzed the second one began. The second cycle aimed to build upon the results of the first one to further investigate interesting control factors, to include new factors and to find good factor combinations. By doing two cycles the testing conducted in the project would be more efficient and focused.

The method of SIN testing and evaluation stayed the same during both cycles. Only test factors and experimental plans to execute were changed.

3.2 SIN Testing

SIN testing is a method for evaluating the ability of hearing in noise for both adults and children. It is mostly used for patients who are having hearing difficulties, as an assessment tool of hearing loss. There are a lot of different SIN tests available, for adults, sentence- and word-level tests are used. Sentences are played at different levels of signal-to-noise ratios (SNR). Starting with a high ratio that is lowered in intervals, making the signal increasingly harder to comprehend by the patient (Portnuff, C. & Bell, B, 2019). The signal is commonly a female voice speaking, as it has been discovered to be significantly more difficult to discriminate than a male voice (Kilic & Ogüt, 2004), and the noise is usually background babble from a group of people.

The SIN testing method that was implemented in this project is based on the work made by Picheny et al (1985) with its resulting nonsensical sentences. They created a framework for test sentences based on uncoherent and phonetically balanced words with a defined length and structure to be used for speech intelligibility purposes. The sentences are grammatically correct but without sense, for example:

“Her mail wheels your fork.” They include three to four key words that are to be understood and written down by a test subject. Its original purpose was to recognize difficulties in speech intelligibility in clear vs. conversational speech for hearing impaired. However, the test method has through time been implemented regarding other noise factors. Jackson et al. (2014) used the test method with the purpose of speech recognizability in microphones challenged by different levels of wind noise and wind gustiness. Thus, there was a lot of relevance using SIN tests in this project and the aim was to further develop the test method for wind noise tests.

3.3 Continuous Sweep

As an addition to the SIN testing method the frequency response from the port designs was measured to analyze the acoustical phenomenom of the performance. This was accomplished with the product APx526 Audio Analyzer by AP which is a software-controlled analyzer. It includes a method called Continuous Sweep that is a patented implementation of impulse response measurements using log-swept sines. (Dickason, 2020)

A brief broadband stimulus sine-signal is played through a speaker towards the prototype with a microphone. The stimulus consists of a log-swept sine that moves continuously across a specified range of frequencies. The performance of the microphone is acquired by the analyzer and is mathematically processed to provide several results, as for example the frequency response that was used in this project. (Audio Precision, 2012)

By measuring the frequency response, the resonance frequencies can be detected. As mentioned in Chapter 2.1.2 a high frequency of the resonance peak is to prefer and therefore important when developing an advantageous microphone port design. The sweep test could also detect if any designs were better than others in recording certain frequencies. A well-designed port would record most frequencies within the spectrum of speech at a higher dB than a less performing port.

4 Test Development

This chapter describes the development of a test method for speech intelligibility testing in combination with wind noise.

4.1 Speech Files

To conduct the SIN tests the speech files had to be created. Firstly, several nonsensical sentences by Picheny et al (1985) were synthesized by a digital voice software through www.hearling.com. The sentences were spoken by a female voice in English with American accent. The used sentences can be found in Appendix D.

4.2 Prototypes

A frame of a generic intercom was designed in CAD software, seen in Figure 4.1. The model was thereafter realized by a 3D-printer. It represents a generic shape of an intercom. In the frame different prototypes of the microphone port could be placed and tested. The port prototypes were produced through CAD software and 3D-printing as well. These prototypes were designed with all the different factors that were agreed upon to test in Chapter 5. The placement of the mic, and consequently the microphone port, was set to the base and side edge of the rectangular frame, as Bradley et al (2003) found it to be the most wind noise resistant.

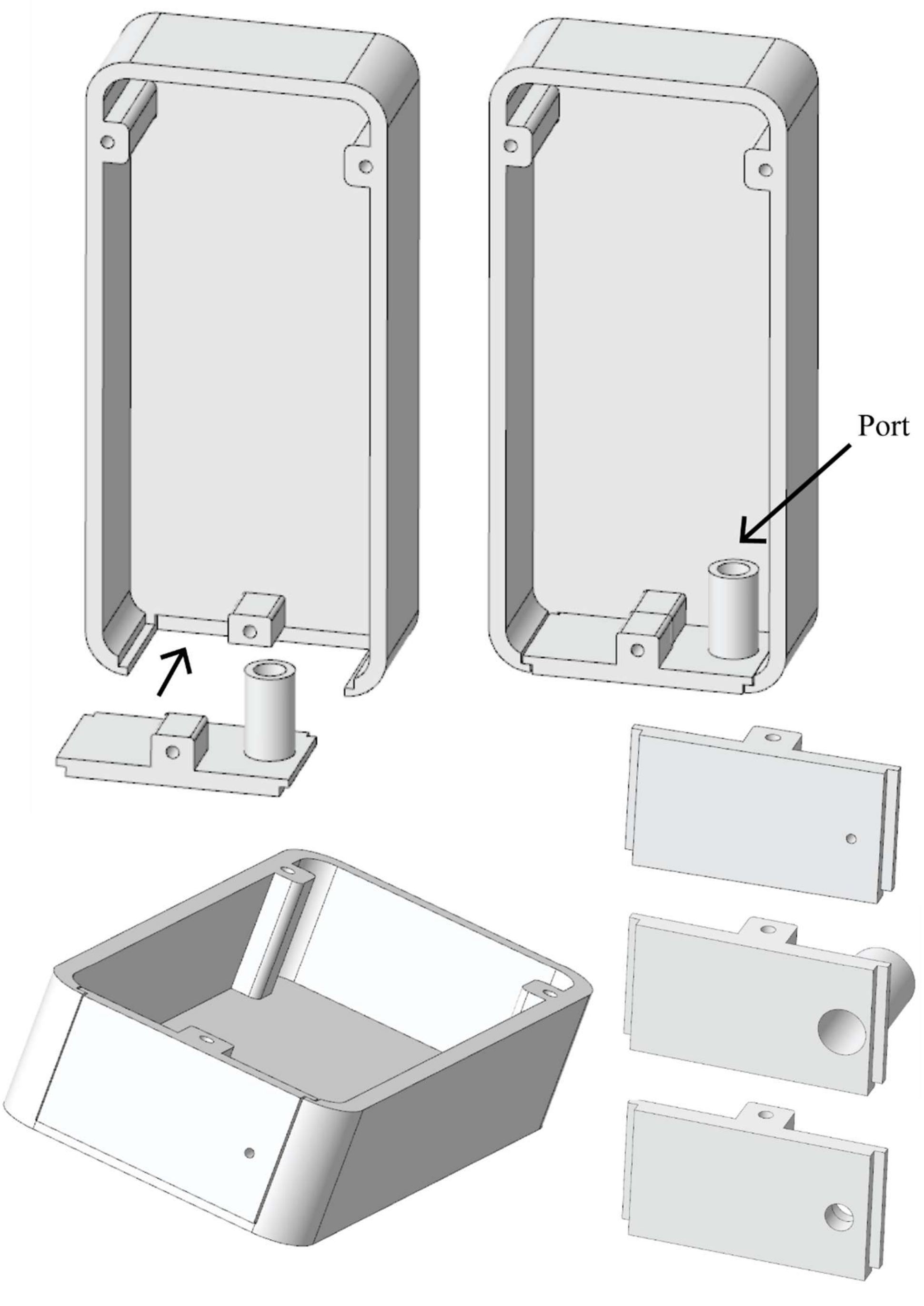


Figure 4.1 Prototyped intercom with the possibility of changing the port part and examples of the port part.

The 3D-printers differed between the two test cycles due to the one used first were taken out of operation between the cycles. The printer used for the first cycle was a Fused Deposition Modeling (FDM) printer. This printer uses thermoplastic filament which is heated to a viscous liquid that is ejected through a moving nozzle and added layer by layer. In terms of resulting prototypes, it means that the surface gets somewhat of a roughness in one direction, with every layer being 0,2 mm thick. The layers can be seen going in a horizontal direction in the part on the left in Figure 4.2. For the second cycle the prototypes were instead produced through a MultiJet printer. In this printing method, layers of UV curable liquid plastic are added on top of a workpiece and then through UV-light is melted together. This creates a prototype that is more homogenous and therefore also has a smoother surface finish. This can be seen in the part on the right in Figure 4.2. Through the lens of this project the MultiJet, with its better surface quality, was believed to be the more optimal choice. The belief was that it would generate less friction for the wind to interact with and thus generate less wind noise. It was however more brittle and needed to be handled with more care through testing.

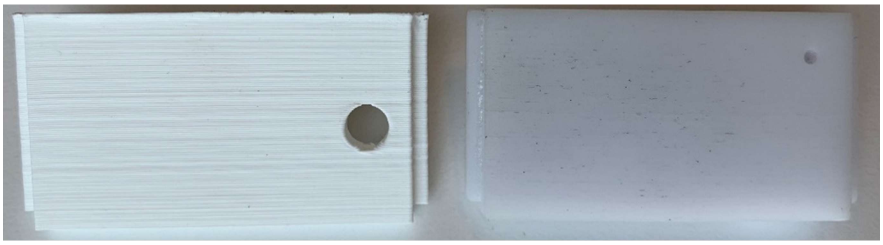


Figure 4.2 Quality of different 3D-prints.

In some investigated ports a metallic mesh and a part of a wind screen were applied. The metallic mesh was in the same material as used by the engineer Magnus, discussed about in Chapter 2.5.2. A shape in the size of the outer diameter of the port was cut out from the material called “Rostfrei 1.4401 St. St. Type 316” from PACO and applied on the outer rim of the port. When applying a windscreen to a port a piece was cut out from a windscreen called “WS1” from SAMSOM, to fill up the whole volume of the port. The placement of mesh and wind screen can be seen in Figure 4.3.

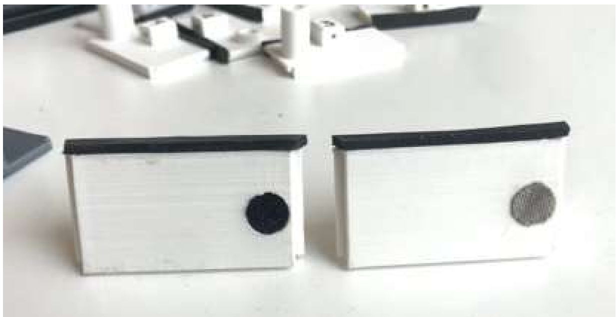


Figure 4.3 Placement of wind screen and metallic mesh in ports.

4.3 Production of Audio Files

The production of the audio files used for the test was made in an anechoic chamber to reduce unwanted background noise, see the environment in Figure 4.4. The prototypes were mounted in an IEC 268-5 standard test baffle to simulate wall mounting or on a wooden pillar. The synthesized speech files were broadcasted through a GRAS 44AA Mouth Simulator towards the prototype, fitted with a microphone in a detailed test setup. The mouth was placed on a horizontal distance of 30 cm with an angle of 60 degrees and a relative vertical distance of 7 cm above the microphone port. The height of the mouth was initially higher to represent the length of a human, but as the function of the microphone was limited, it was required to lower the mouth to the same level as the prototype. The speech signal level was set to -1,7 dBPa, when measured on a point located on axis and 25 mm in front of the mouth speaker, accordingly to the Standard ETSI ES 202 739 V1.4.1 (ETSI, 2015).

Figure 4.4 Audio recording setup. 1. is the mouth speaker, 2. is the prototype fitted with a microphone and 3. is the air flow generator.

Meanwhile the speech files were playing, an air flow generator was generating air through a nozzle straight towards the microphone port at a horizontal distance of 50 cm and in the same vertical level. This created the wind noise that the port designs were desired to mitigate. The wind speed was measured using an anemometer in the line of wind at 10 cm in front of the prototype and the speed was adjusted on the generator between each test setup. The setup is detailed in Figure 4.5.

The back of the prototype was open and in the baffle behind there was a hole to be able to place the microphone into the prototype. The mic was sealed against air flow by reusable adhesive, see the placement in Figure 4.6. Recordings of the combined sound of the speech and the wind noise was created by the measurement microphone GRAS 46BD. It is a condenser microphone with a frequency range of 4 Hz to 70 kHz. Its big frequency range makes it capable to record a significant amount of low frequency wind noise and was chosen for that reason. The audio files were saved as 24-bit WAV files. Further information of the test setup material can be found in Appendix B.

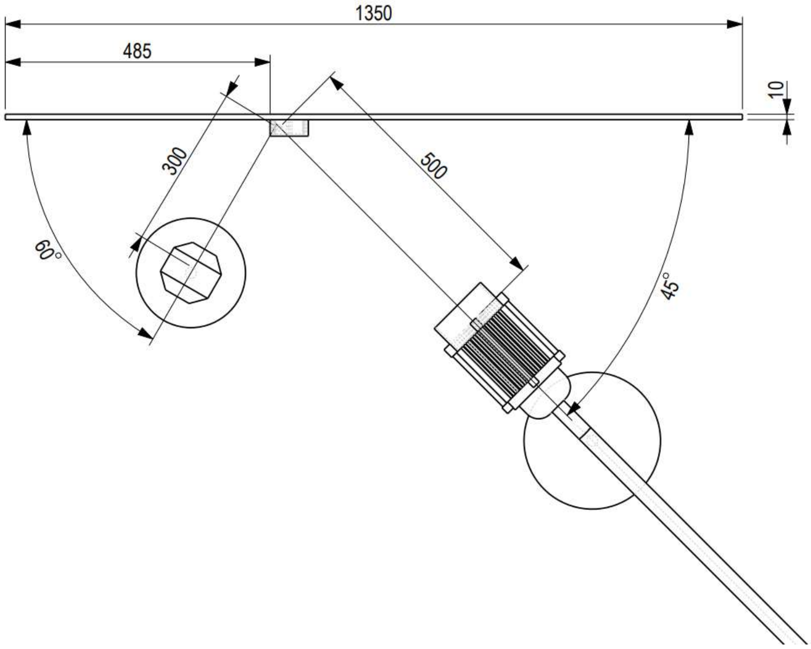


Figure 4.5 Details of the test setup.

Figure 4.6 The placement of the measurement mic on the back of the prototype.

4.4 Reliability

To increase the reliability of the SIN tests two random and different nonsensical sentences were recorded two times by each prototype with specific noise setup. This resulted in four files for each test setup.

The recorded audio files were transferred into Google Forms to be used for the test sessions. Each form included a test description, two practice SIN-files and further on all the SIN-files that were to be listened to. The order of the audio files in the form were randomized for each test participant. Also, of the four files created for each test setup one was randomly picked for each form. The order was mixed to mitigate the sequence of the audio files effecting the judgement of the participant. Using two sentences per setup was done to validate the results and minimize the risk of a particular sentence being more difficult than another. Recording every sentence two times mitigated the variance in wind recording. The wind noise is organic and hard to control so this technique allowed the noise to vary in a natural fashion but still receive reliable test results (Ulrich & Eppinger, 2012).

4.5 Performing the Test

To perform the test people were participating. One participant at the time was welcome to participate in the test and fill in their individual form. Through the form, the test participants were able to listen to the SIN-files and were requested to do two tasks per file. The first task was to listen to the SIN file once and write down the perceived sentence, for the purpose of comprehending the right keywords. Secondly, the test participant was to rate the speech clarity on a scale of 0-10 of the played audio files. For the latter task, the participant could listen to the audio file several times. The two first SIN files in every test were practice files to make the test participant comfortable with the format of the test and the answers to these were not included in the result. When a participant had completed all tasks, they were required to confirm if they had a good understanding of English and of not having any hearing disabilities.

4.6 Test Environment

The participants performed the SIN test in a quiet and closed off room at the company office. The equipment the participants used was a laptop connected with the audio interface Zoom U-44 and headphones Shure SRH940. The participants were instructed to sit by the computer and follow the instructions on the opened Google form to complete the test. The instructions can be seen in Appendix C.

4.7 Participants

10 people participated in the SIN test and were all employees at the company. The participants had to be regarding themself as proficient in English, however not native in the language, and not have any known hearing disabilities. In the second test cycle only people who earlier had participated in a SIN test or pilot were picked to test.

4.8 Result Evaluation

With the data from the SIN tests the speech intelligibility of each prototype could be analyzed. The forms filled out by the participants gave two results. Firstly, a result of how many key words the test participant heard from each sentence. The instructions for assessing the answers were implemented accordingly to the assessment used by Jackson et al. (2014):

- If a single phoneme of a word was omitted or misidentified words, it was marked as incorrect. However, the incorrect addition or omission of suffixes such as “s,” “ed,” and “d” were not considered sufficient to count as an incorrectly identified word.
- Typos and misspellings were accepted as correctly identified words if the attempt was clear and unambiguous.
- Homophones of the target word (e.g., there, their, they are) were also accepted as correctly identified.

The second result was a subjective opinion, a score between 0-10 of how clear the participant thought the listened to sentence was.

The combination of the perceived keywords and the rating of the clarity for each audio file was further on to be put into a total average score. The word score would be calculated as the percentage of keywords correctly answered times ten, a score of 5 would equal 50% correctly answered keywords. The rating of the clarity was kept to a value of 0-10. The worst combined score, the minimum value, could therefore be (0+0)/2=0 and the best combined score, the maximum value, (10+10)/2=10. This led to a middle score of (5+5)/2=5.

Through these different results each prototype that was tested had the possibility to be rated against another prototype. In this way it could be analyzed how big effect each tested factor had on speech intelligibility. Each prototype was also rated against all other prototypes which gave a result on the best functioning design.

4.9 Pilot Testing

To secure that the resulting data from the SIN tests was meaningful a pilot test was conducted by four participants. The pilot tests examined three different wind speeds (3, 3.5 and 4 m/s) on three different microphone ports developed in cycle one. Each test setup was paired with one individual speech sentence. This resulted in nine unique audio files to be listened to by the test participants. The reason for the pilot test was to find improvements for the actual SIN test and to find out what wind speed yielded a desirable average signal to noise ratio and difficulty. The chosen test wind speeds equaled a light breeze but amounted to a high amount of noise in the microphone.

Initially, one test participant did the pilot test, where concerns came up about audio playback volume and a desire for more clarification in the introductory test instructions. These concerns were examined, and changes of the test were made to make it easier to understand and the playback volume was increased. When the changes had been made three more people performed the test, from where test data was collected.

An analysis of the test data was done to determine what wind speed gave the most desired SNR ratio. In this case the medium combined score of 5 was desired. The resulting data was given as shown in Table 4.1. The score of 3 m/s and 3.5 m/s both became very close to the desired value. However, it became clear that four-keyword-sentences were harder to remember because of their length, than three-keyword-sentences. The files recorded with 3 m/s wind included the most four-keyword-sentence speech files. The scores of these files were by that reason presumed to be higher than what the actual results showed. Discussion was made of what an optimal difficulty by wind speed was for the test, and 3.5 m/s was concluded to be within a reasonable difficulty range and the best option for the real SIN test. A second wind speed reference test was done for cycle two with prototypes from that cycle.

Table 4.1 Results from Pilot Test.

Wind Speed	**3 m/s**	**3.5 m/s**	**4 m/s**
Word score	5.32	5.19	2.59
Clarity rating	6	4.11	3.22
Combined score	5.66	4.65	2.91

4.10 Continuous Sweep Tests

The addition to the SIN testing method, Continuous Sweep, was also performed in the anechoic chamber, see Figure 4.7. The equipment used was the prototypes with measurement microphone GRAS 46BD and a speaker called Genelec 8020. The speaker was placed one meter in front of the mounted prototype, see Figure 4.8. A sine-signal was played through the speaker and picked-up by the measure mic. The speaker was filtered to flatten the output response within +/-1 dBSPL. The level of the filter was developed by measurements at 1 m distance in the frequency range of 80 Hz to 20 kHz in the free field conditions of the anechoic chamber. Frequency response curves of the sine-signal recording were created in order to analyze the performance of the ports.

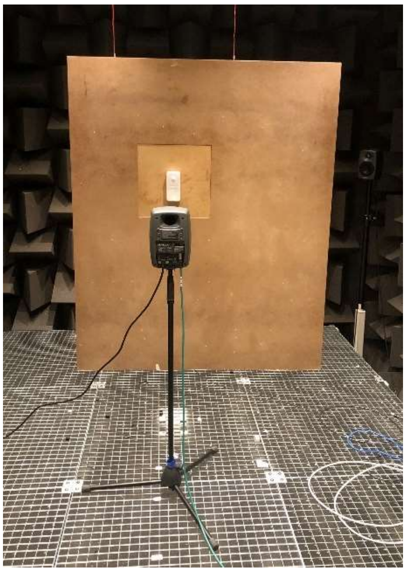


Figure 4.7 Overview of the setup for conducting the Continuous Sweep in the anechoic chamber.

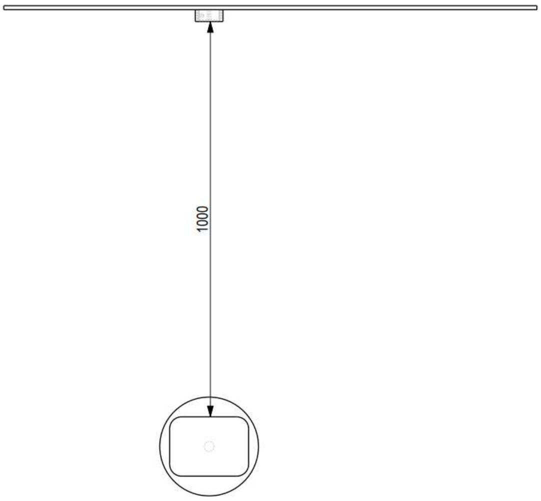


Figure 4.8 Details of the setup from above.

5 Product Development

This chapter of the report focuses on the development of wind noise reducing microphone ports. The development was conducted in two experimental cycles that tested different port designs through the methodology of Robust Design. Each cycle consists of a development section, a result section, and an analysis of the results.

5.1 Cycle One

To get an overview of the first cycle of microphone port development the control factors, noise factors and performance metrics are illustrated in a *parameter diagram* in Figure 5.1 (Ulrich & Eppinger, 2012). This chapter will explain why the factors were chosen and how they were investigated.

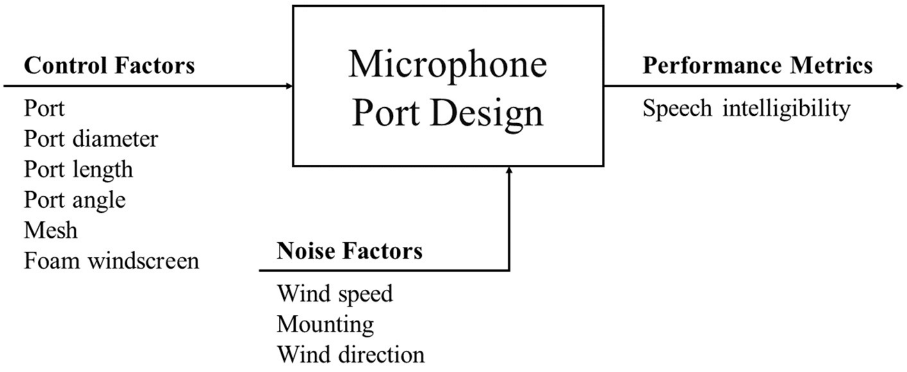


Figure 5.1 Parameter Diagram for the microphone port design cycle one.

5.1.1 Development

Control factors

Following the Robust Design methodology, the start of the product development began with choosing design variables, known as control factors, of the microphone port. The chosen control factors originated from the researched theory and investigative interviews found in Chapter 2 and led to six different factors. The first four are geometrical changes of the port shape, investigating the existing guidelines from the company seen in Chapter 2.5.3. The last two are add-ons to the port, presented in Chapter 2.4, and investigates their functionality in a new setting. There was no clear data of how much any of the factors could impact the speech intelligibility of a microphone located in a port and were therefore chosen to be investigated. The chosen control factors and reasons of choice can be seen Table 5.1.

Table 5.1 Control factors for cycle one.

	Control factors	**Reason of choice**
1	The use of a port	Investigate the benefits of an open-aired port in relation to a not having a port. Not having a port means that the microphone is encapsulated inside of a closed intercom.
2	Port diameter	Investigate how a change in diameter of the port changes the sound. To compare the result to the company’s guidelines.
3	Port length	Understand how the port length, the distance from the product edge to the mic, changes the sound. Comparison to company’s guidelines.
4	Port angle	Investigate how the angle of the port changes the sound as the interviewed, experienced engineer Magnus found a port shaped of a conical frustum successful in his project.
5	Mesh in front of the port	Investigate the effects of basket windshields on mic ports to find out if their use is applicable
6	Foam windscreen in front of the port	Investigate the effects of windscreens on microphone ports to find out if their use is applicable.

The six control factors could be tested through 9 differently designed prototypes of the port, see Table 5.2. The prototypes were built to be able to compare two parameter values of each control factor, this is explained in Table 5.3. For example, to test the effects of the length of a port the results produced by a prototype with a short port length were compared to a prototype with a long port length. Some prototypes were able to be a part of several control factor comparisons.

Table 5.2 Prototype list cycle one.

Prototype	Open Port	Port diameter (mm)	Port length (mm)	Port angle	Mesh	Foam windscreen
1	-	0	0	0	-	-
2	Yes	2	4	0	-	-
3	Yes	2	20	0	-	-
4	Yes	10	20	0	-	-
5	Yes	2	20	22 deg	-	-
6	Yes	10	20	0	Yes	-
7	Yes	2	4	0	Yes	-
8	Yes	10	20	0	-	Yes
9	Yes	2	4	0	-	Yes

Table 5.3 Control factor analysis description.

Control Factor	**Analysis description**	**Prototypes**
Port	Closed port vs open port	P.1 vs P.2
Port diameter	Narrow vs wide port	P.3 vs P.4
Port length	Short vs long port	P.2 vs P.3
Port angle	Cylindrical vs conical port	P.3 vs P.5
Mesh on large port	Large port vs large port with mesh	P.4 vs P.6
Mesh on small port	Small port vs small port with mesh	P.2 vs P.7
Windscreen on large port	Large port vs large port with windscreen	P.4 vs P.8
Windscreen on small port	Small port vs small port with windscreen	P.2 vs P.9

The reasons of choice for the analysis of all the different control factors refers to why the factors were picked in Table 5.1. The analysis of mesh and windscreen were expanded to two different sizes of a port since size was suggested to be an important parameter when using an add-on in the research Chapters 2.4.1 and 2.4.2.

Other possible control factors to test were discarded due to several reasons. Some factors had already been tested in other reports, like the placement of the port. Other factors like density of a foam windscreen were discarded due to lack of knowledge in setting appropriate values to test. The limited time to conclude the scope of the project led to a maximum range of factors that could be selected, the chosen ones were deemed the most essential to test.

Noise factors

Further on, the noise factors were chosen to wind speed, product mounting and wind direction. The selection of noise factors was as well based on the background theory and interviews. The reasons of choice are described in Table 5.4.

Table 5.4 Noise factors for cycle one.

	Noise factors	Reason of choice
1	Wind Speed	Wind speed was through initial testing concluded to be a big factor in the amount of noise in microphones.
2	Mounting	Intercoms that had been identified to be especially affected by wind were mounted on pillars as shown in Figure 2.9 received from the dedicated product owner Alexander. However, most door stations were mounted on walls, according to the company. Therefore, both placements were interesting to investigate and gain knowledge of.
3	Wind Direction	Wind direction played a role in the results of Bradley et al (2003). In this project the maximum noise direction (315°) was compared to a straight facing direction (0°). The different directions were chosen to investigate since wind direction is never fixed and needs to be mitigated through design.

The three noise parameters chosen for the first test cycle resulted in four different noise setups to vary the different factors, as seen in Table 5.5. Important to note is that wind speed was always set to the same value due to keep the numbers of tests at an adequate level. The speed was calibrated to an appropriate difficulty through a pilot test described in Chapter 4.9.

Table 5.5 Noise setups for cycle one.

1	2	3	4	Noise setup
3.5 m/s	3.5 m/s	3.5 m/s	3.5 m/s	Wind speed
Wall	Wall	Pillar	Pillar	Mounting
315	0	315	0	Wind angle

Other interesting noise factors that were not regarded to test were wind turbulence and wind gustiness. The reason for this was lack of possibilities to reproduce and measure these noise factors.

Test setups

The nine prototypes and the four noise setups together resulted in 18 test setups 1.1-5.4, as seen in the DOE matrix in Table 5.6. Tests 1.1-9.1 were mainly focused on comparing all prototypes in a constant wind noise state. The other tests were added to further understand how different noise setups could change the performance of the ports. Extensive investigation was put on the effects of windscreens and mesh in different noise setups, as they are the most common current wind reduction techniques. Tests were also directed towards the conical port shape since the shape was recommended by an engineer at the company, see Chapter 2.5.2.

Table 5.6 DOE matrix for cycle one.

							1	2	3	4	Noise setup
							3.5 m/s	3.5 m/s	3.5 m/s	3.5 m/s	Wind speed
							Wall	Wall	Pillar	Pillar	Mounting
Prototype	Open Port	Port diameter (mm)	Port length (mm)	Port angle	Mesh	Foam windscreen	315	0	315	0	Wind angle
1	-	0	0	0	-	-	1.1				
2	Yes	2	4	0	-	-	2.1		2.3		
3	Yes	2	20	0	-	-	3.1				
4	Yes	10	20	0	-	-	4.1	4.2			
5	Yes	2	20	22 deg	-	-	5.1	5.2	5.3	5.4	
6	Yes	10	20	0	Yes	-	6.1	6.2	6.3		
7	Yes	2	4	0	Yes	-	7.1				
8	Yes	10	20	0	-	Yes	8.1	8.2	8.3		
9	Yes	2	4	0	-	Yes	9.1				

With the 18 test setups a comparative analysis between different tests could be made to identify parametrical differences, see Table 5.7.

Table 5.7 Test analysis description.

Comparison	**Description**
1.1 – 9.1	Comparison of all prototypes in the first noise setup
2.1, 2.3, 4.1, 4.2, 5.1-5.4	Comparison of prototypes without add-ons in varying noise setups
6.1-6.3, 8.1-8.3	Comparison of prototypes with add-ons in varying noise setups

When the test setups had been chosen and motivated, the prototypes were produced and the test material as audio files recorded in the anechoic chamber, as described in Chapters 4.2-4.4. The developed test was further on performed by the test participants, and the results of SIN scores for each test setup were calculated as described in Chapter 4.8.

5.1.2 Test Results

5.1.2.1 SIN Test Results

The average score of each combination of analyzed prototype and noise setup is found and is displayed in Figure 5.2.

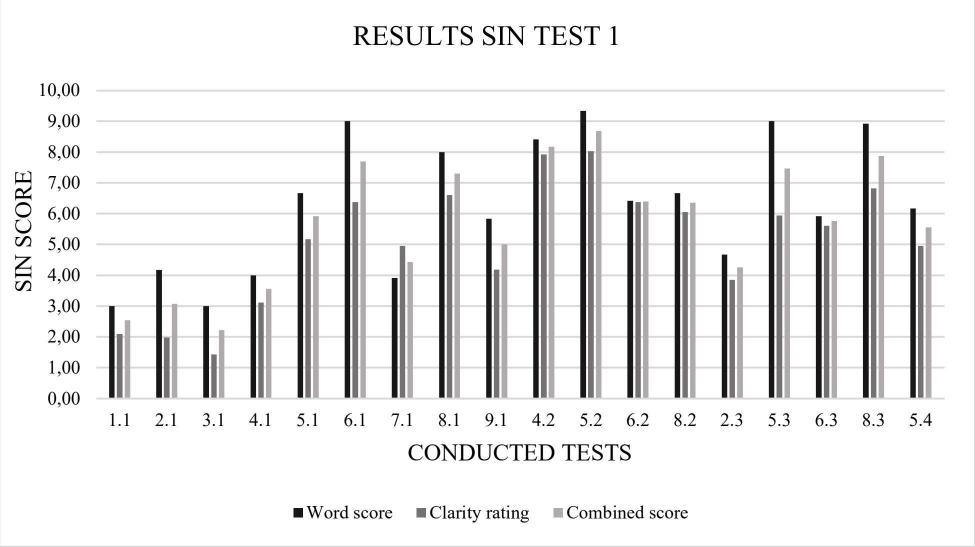


Figure 5.2 Results of SIN test 1

The results show three score bars for each test setup, named with a first number linking it to a prototype and a second to a noise setup. Test 1.1 is therefore referring to prototype: 1 in noise setup: 1. The first bar for each test represents the word score, the average percentage divided by ten of keywords picked up by the test participants. If this bar reached the score of 4 on the y-axis, as for 4.1, it meant that by average 40% of the keywords in the audio file was understood. The second bar for each test setup is the average clarity rating the participants chose for the audio file. If a file received a clarity rating of 5 it meant that within a 0-10 range the average participants believed the clarity of the sentence within the noise to be a subjective value of 5. The scale ranged from 0, equaling no clarity, to 10 being very clear. The third and final bar for each file represents a combined or average score of the first two bars. This score is what represents the official SIN score for the audio file and what was used for comparisons in the analysis.

The reasoning of using an average score of subjective opinion and actual word comprehension was to mitigate possible test errors. If a particular audio file included an unforeseen hard sentence, it might have gotten a bad word score but a higher clarity rating, making the average of the two scores more leveled and better representing the actual speech intelligibility. Vice versa if a sentence was particularly easy.

As seen in Figure 5.2 the word score and clarity rating for an audio file could differ by quite a bit but could also be very equal. A trend that could be seen by a large majority of the files was that the word score was normally higher than the clarity rating.

5.1.2.2 Results of Continuous Sweep

The Continuous Sweep test was performed for each of the nine port prototypes and resulted in the frequency response curves shown in Figure 5.3.

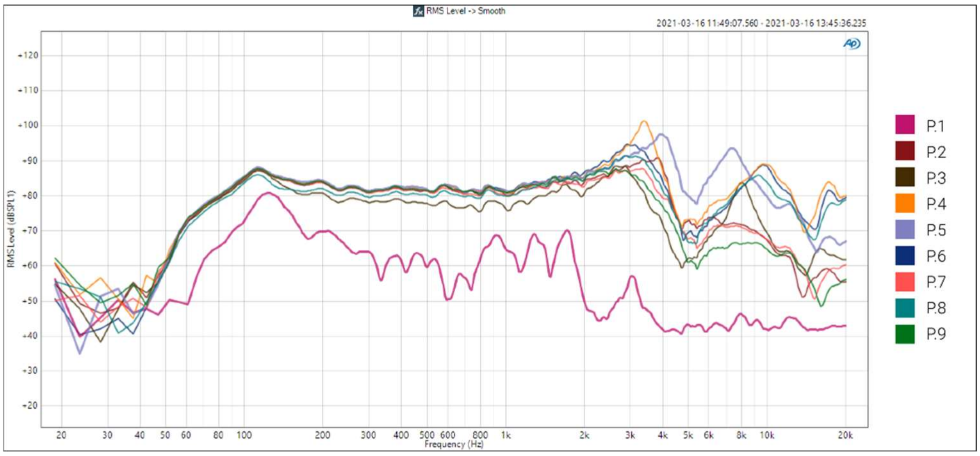


Figure 5.3 Frequency response curves of the nine prototypes.

P.1, being the one without any port and instead a closed construction, had the lowest frequency response, responding significantly worse than any other prototype. The following eight prototypes were all having a peak around 3-4 kHz, dipping at around 5 kHz and to then in most cases bounce up a bit again. P.5, the conical port produced the highest overall response within the speech frequency spectrum.

5.1.3 Analysis

5.1.3.1 Control Factor Effect Analysis

As mentioned in Chapter 5.1.1 the nine prototypes were built to be able to test one or two parameter values of a control factor, this is explained in Figure 5.4. For this comparison all the prototypes were mounted on a wall with a wind angle of 315º (noise setup 1) and the resulting SIN score can be seen in Figure 5.4.

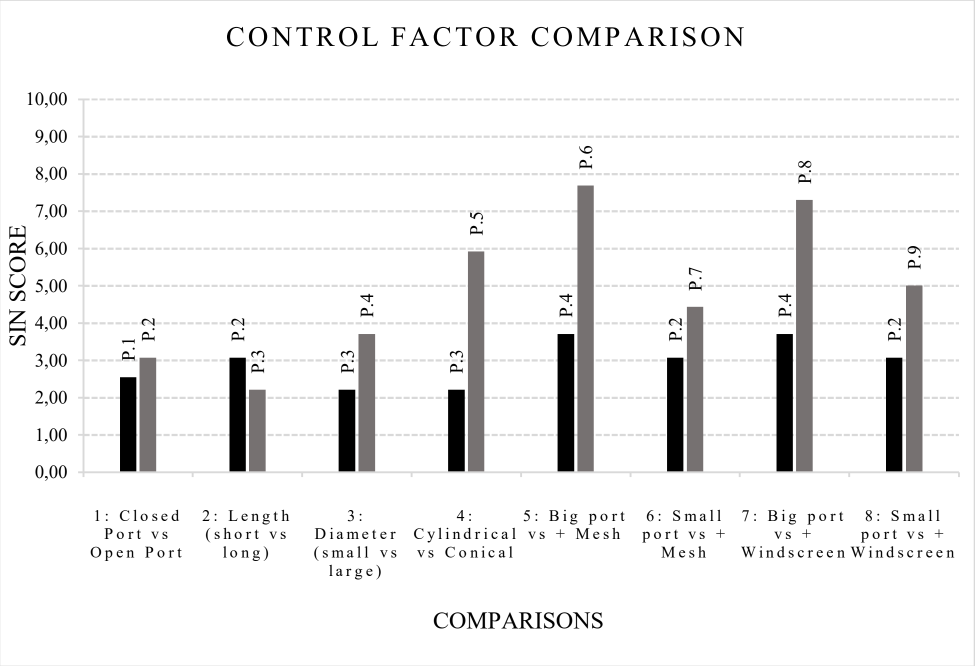


Figure 5.4 Control factor comparison according to Table 5.3, "P.1" means Prototype 1 etc.

The first four comparisons showed the result of SIN scores when changing the geometric shape of the port. Comparison 1 showed that having an open port, as prototype 2, is preferred above not having one at all, as prototype 1. Comparison 2 tested ports with a 2 mm diameter but with a length difference of 4 mm and 20 mm. In this case a smaller length gave a better result. Further on, in comparison 3, ports with a length of 20 mm were compared in terms of the diameter of the port. A diameter of 2 mm was measured against a diameter of 10 mm, where the larger diameter resulted in a higher SIN score. Comparison 4 tested a cylindrical port shape against a conical port shape, and it was shown that the conical shape gave a remarkably better result.

The following comparisons 5-7 tested the port with the add-on of mesh. In comparison 5, prototype 4, which is a port of the cylindrical shape with a diameter of 10 mm and length of 20 mm was tested against prototype 6 with the same shape but with an added mesh placed by the inlet. The mesh yielded a significant improvement. The mesh was also tested in comparison 6 but in a smaller size. Prototype 2 with a cylindrical shape with a diameter of 2 mm and a length of 4 mm was tested against prototype 7 with the same shape but with an added mesh. The use of mesh in a smaller port did also give a better result than when not used.

The use of windscreen was tested as another add-on than mesh in comparisons 7-8. Comparison 7 showed the result between not having a windscreen and having it. Prototype 4, the big port was measured against prototype 8 with the same size but with the added windscreen. The use of windscreen gave a significantly better result than without it. Windscreen was also tested when having a smaller port in comparison 8. Prototype 2 was compared to prototype 9 with the same size but with the added windscreen. The SIN score was clearly better when having a windscreen in a small port as well.

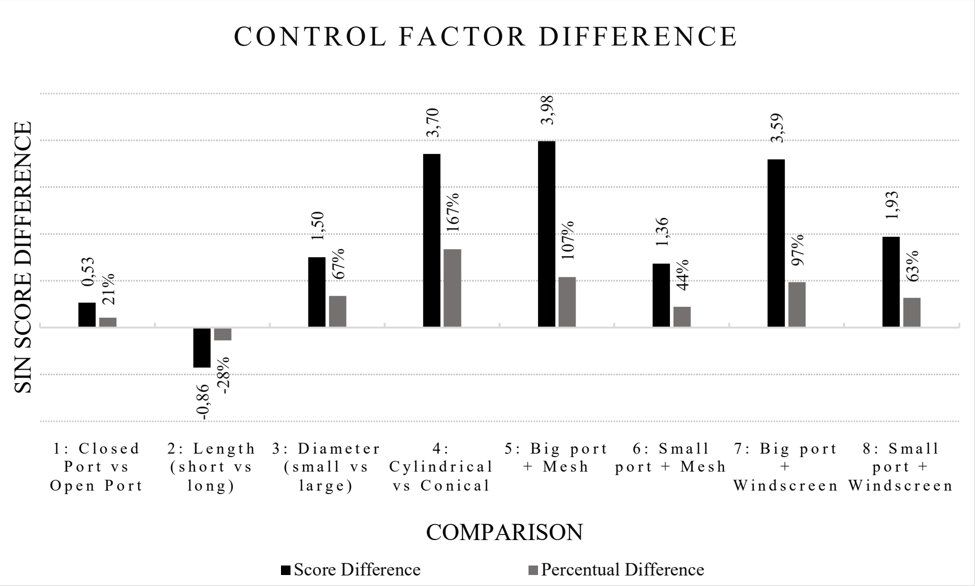


Figure 5.5 The differences in values and percentages of the SIN scores from each comparison in Figure 5.4.

The result in Figure 5.4 was further visualized in Figure 5.5, as the difference in score and percentage of SIN score from each comparison. Biggest percentual differences were in comparisons 4, 5 and 7. To conclude, the port with a conical shape, a large port with mesh and a large port with windscreen were the designs giving the most preferable results in terms of speech intelligibility.

5.1.3.2 Noise Factor Effect Analysis

A noise factor analysis was conducted to review how different ports behaved in different environments. Five prototypes were tested in more than only the first noise setup. Prototypes number 2, 4 and 5 were tested to see the performance of different geometric shapes. Prototypes 6 and 8 were tested to see the performance of ports with add-ons as mesh and windscreen. The results can be seen in Figure 5.6.

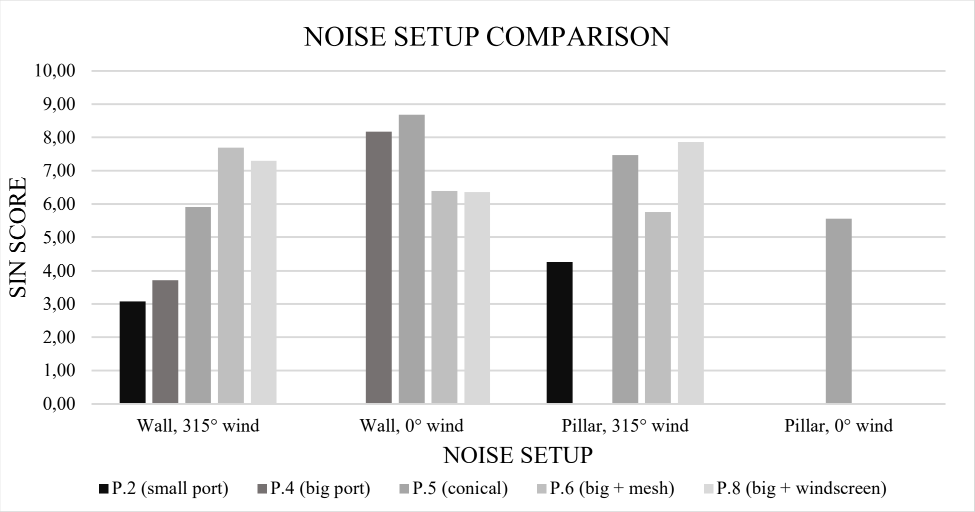


Figure 5.6 Noise setup comparison for cycle one.

When analyzing the performance of the geometric shapes, prototypes 2, 4 and 5 gave different results. Prototype 2 and 4, cylindrical ports in two sizes, gave large score differences when changing the noise setup and were therefore stated as unstable ports. The conical port, prototype 5, performed very well regardless of how it was mounted and facing wind, and was seen as advantageous.

For the ports with an added mesh or windscreen, prototype 6 and 8, the result showed that they were relatively resistant to mounting and wind direction. It can be concluded that adding a mesh or windscreen to a microphone port increases the speech intelligibility when the product is mounted in a windy environment.

Conclusionary, prototypes 5, 6 and 8 did all perform in a desirable way in all the noise setups tested, as seen in Figure 5.7. However, a distinguishing result was that their performance in the different setups did not follow a pattern. For the first noise setup, prototype 6 gave the best result, in the second noise setup prototype 5 was to prefer and lastly in the third setup prototype 8 had the highest performance. The statement of that the wind direction of 315º gives most wind noise (Bradley et al, 2003) and hypothetically the worst SIN score, did not correspond to the result in this test. The reason can partly be because of that Bradley et al (2003) did not do measurements on a wall, on a pillar only. The result did neither show if mounting on a wall or on a pillar is more advantageous.

Prototype 8 performed in the most stable fashion with a difference of 1,51 in different noise setups. Prototype 5 varied the most with a SIN score range of 2,92. Prototype 6 produced a range of 1,93 in SIN score.

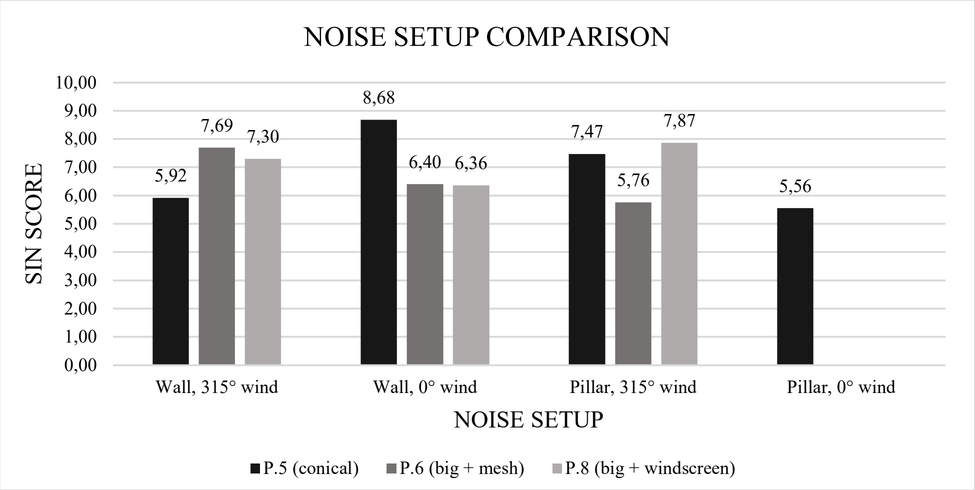


Figure 5.7 Noise setup comparison of the three best prototypes of cycle one.

5.1.3.3 Test Result Analysis

Within Figure 5.8 the spread of the combined score given by each participant is visualized. A line goes from the lowest received score of each file to its highest received score. A circle is also seen on each line which shows the average score given to the corresponding file. As expected, the average score is in most cases close to the middle of the highest and lowest received score. The range of the scores varies a lot between each test setup. Some have a low range, as for example test 6.1 that ranges from 5.97-8.89 in speech intelligibility for different participant. Other tests, as for example 5.1, has a very large range of scores. The different scores for 5.1 ranges from 1.11-9.44 within a scale of 0-10, almost the whole spectrum. It could be said that there is a bigger unity by the participants of the speech intelligibility of some tests more than others.

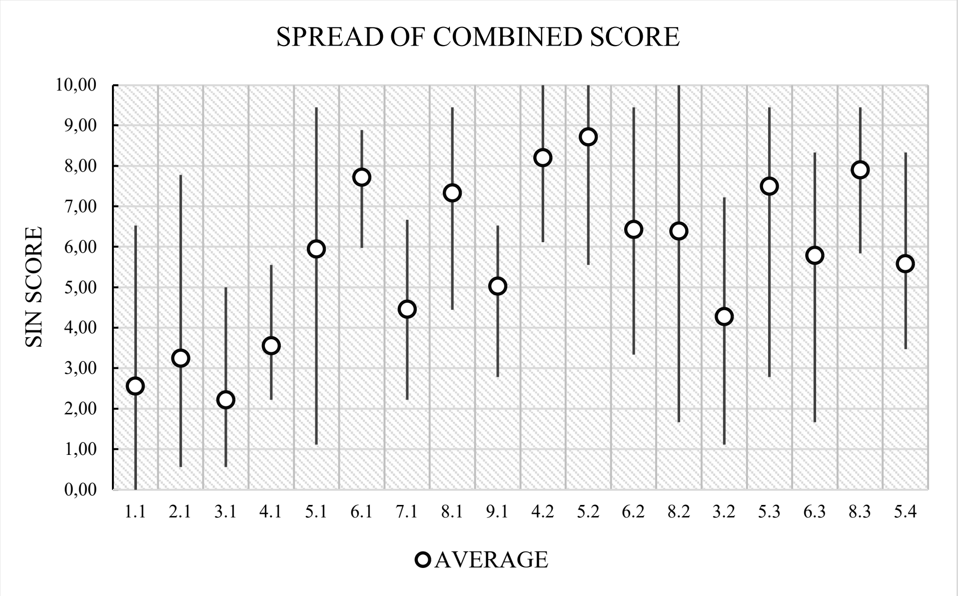


Figure 5.8 Score spread.

Figure 5.9 displays the spread of how the participants scored the prototypes on average. The data is divided into three columns based on the two scores clarity rating and word count, and the resulting combined score. The top of each line represents the maximum average value the participants produced on all the different audio files combined, and the bottom of the line represents the lowest average score a participant produced. The circle on each line represents the average total score given by the average participant. The range of scores was larger in word count than clarity rating and the combined score had the lowest range. The low range of the combined score was expected due to its nature of being a leveling score.

The average combined of 5,72 in SIN ratio was satisfactory and close to the desired middle value of 5.

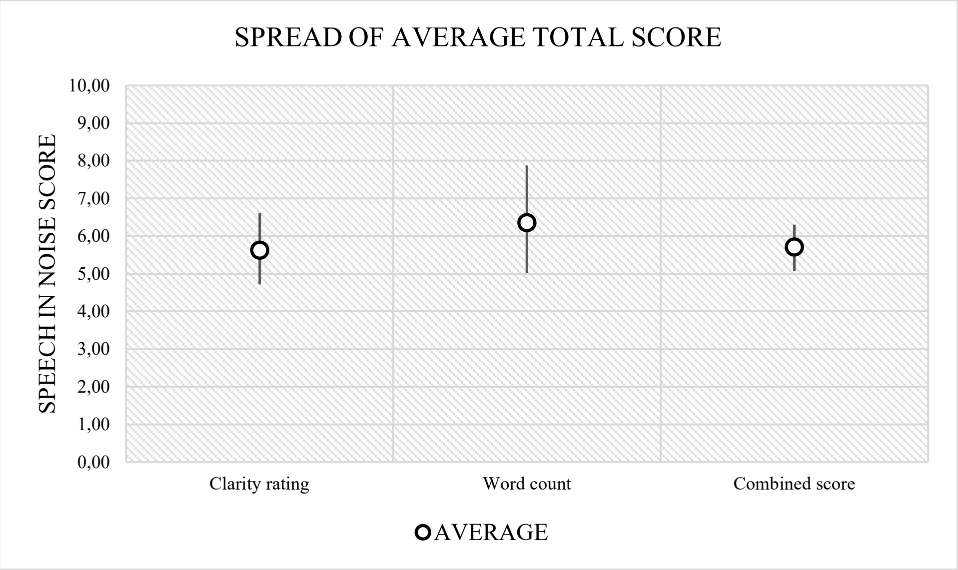


Figure 5.9 Spread of participants' average score.

5.1.3.4 Continuous Sweep Analysis

The frequency responses, given with the Continuous Sweep method, gave interesting results. The resonance peak around 3-4k Hz for prototype 2-9 was very far down in the frequency range and therefore questioned. The prototype was mounted on a wall during the sweeps. The influence of the wall and distance to the mic was investigated through testing to discover if it had any effect. In the new tests the mic was placed in the prototyped generic intercom in the same position as during the SIN tests but through a hole on the bottom so that the top of the mic was parallel to the bottom edge of the intercom, instead of inside a port. This was measured against another port that was identical but with its position being closer to the wall. A change of distance of about 10 mm. The first one being 15 mm from the wall and the second 5 mm from the wall. The new sweep tests revealed a clear improvement in the second prototype, where the resonance dip was moved much further up in the frequency range and outside the range of speech. It became clear that the produced audio files had suffered from destructive interference from the baffle, the simulated wall, reducing audio volume at around 5 kHz.

5.1.4 Reflection

When reflecting on the results there are a few takeaways. First off, many of the designs that were thought to be improving the sound also did, as for example adding a mesh or a windscreen to a port. The SIN score varied a lot between the different prototypes which was very positive, meaning that the tests gave clear and distinct results. The noise factor analysis yielded less clarity and different prototypes behaved very differently when the noise setup changed. No clear pattern could be seen in how wind direction effected the audio files since a change of direction could improve the speech intelligibility, but it could also worsen it for another prototype design. A comparison was made against the results of Bradley et al (2003) where wind noise from different directions had been investigated. The investigation found the noise to be the loudest for simple open aired ports at 315 degrees when placed in a wind tunnel with low turbulence. Those results were replicated on prototype 4 and 5 fitted on a wall in this project but the results did not replicate with prototype 6 or 8 (prototype 4 with mesh or windscreen), in the same noise setup. Neither did it replicate on prototype 5 mounted on a pillar instead of on a wall, where speech intelligibility was worse in straight facing wind. The same inconclusive pattern can be applied towards prototypes being fitted on a wall versus a pillar, some performed better on a wall and some did better on a pillar. A reason for this would need further research and testing. One conclusion that was drawn was however that adding a mesh or a windscreen to a port made the port less affected of change in noise setup.

When reflecting of possible sources of error some topics were agreed upon between the authors to have influenced the results. A main concern was the difference in difficulty of sentences that was unforeseen before the tests. The difficulty of a sentence could depend on a few things. The proficiency in English by the participant or the length of sentences and the difficulty of remembering more words. It was also evident that some letters were harder than others to hear through wind noise. Common mistakes by participants were to mistake “ban” for “van” and “op” for “off”. Letters that is pronounced with a popping sound could be lost in the wind noise. It was assumed that the sentences that included those sounds were harder to recognize than sentences not including popping sounds.

Another source of error was that the lower limit of the range of input volumes, or in audio terms, the dynamic range of the 1/4" measurement microphone was a bit high. This meant that the microphone that recorded the test files generated sound with a very low volume. The recorded audio files therefore had to be amplified with +20 dB to make them appropriate in volume. Consequently, the input noise floor, the sum of all noise sources and unwanted signals, from the microphone wasn't negligible for the recordings. However, it was believed that the noise was not dominating enough to affect the verdict of the files. This was an unforeseen problem that was revealed during production of the SIN-files.

Regarding the Continuous Sweep response produced by the different port it was clear that destructive interference had affected the ports, lowering the volume of certain sounds. It is unclear how big effect it had on the SIN test results. However, the problem was investigated through further Continuous Sweep tests and knowledge in how to design to mitigate the interference was gained.

5.1.5 Factor Setpoints

Through completing the experimental plan, the SIN tests and an analysis of the results, some control factor setpoints were picked as optimal choices. The factor setpoints are listed below:

- Having a port can clearly and significantly increase the audio output in comparison to not having one.
- Only increasing the length of a port did not make the audio better, however the volume of a port may play a positive effect.
- A conical port has significantly better wind noise reduction than a cylindrical port.
- Adding mesh or windscreen to a microphone port can drastically improve wind noise reduction.
- Bigger port is to prefer when applying a mesh or windscreen, the difference can be significant.
- From the Continuous Sweep test and evaluation, it became evident that destructive interference was a problem, however it is easy to mitigate with positioning the port closer towards the reflecting back wall in order to move the interference to higher frequencies.

5.2 Cycle Two

To get an overview of the second cycle of microphone port development the control factors, noise factors and performance metrics are illustrated in a new *parameter diagram* in Figure 5.10.

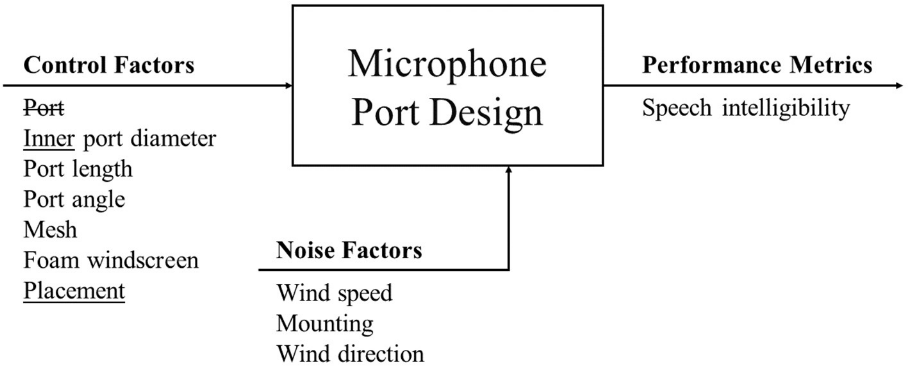
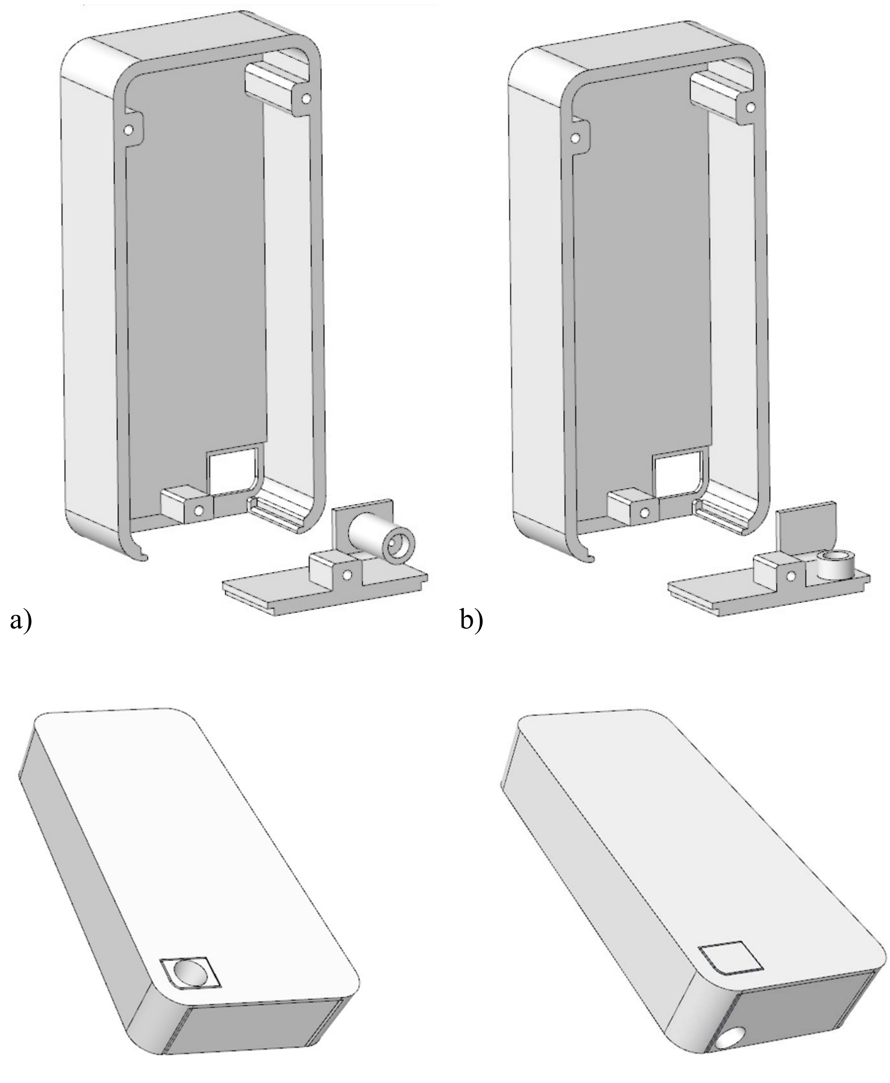


Figure 5.10 Second cycle's parameter diagram.

5.2.1 Development

After reflecting upon the results from the first cycle it became clear that to design a good microphone port it is advantageous to use a conical shape, using a mesh or using a windscreen. Combinations of a conical port with mesh or windscreen needed to be tested to further investigate how these different control factors behaved when operating together.

Another control factor that needed to be investigated was the port placement. Bradley et al (2003) reported that an optimal placement of the port, in regards of wind noise reduction, was on the bottom side of an object and close to the side edge. However, when designing intercom devices with a lot of functions competing for space within a product, compromises must be made. Therefore, an effort was put towards investigating the placement of the port facing forward on the front facing side of the prototyped intercom, close to its position in cycle one in the bottom corner, see Figure 5.11a. By investigating the effects of the placement of a port, the drawbacks and benefits of different locations can be considered when a compromise needs to be made.


a)

b)

Figure 5.11 (a, b) Port placement, front and bottom.

Another change was made for the port placed on the bottom of the prototype. It was moved as close to the wall, when mounted, as possible, see Figure 5.11b. This would minimize the destructive interference of sounds reflecting from the wall, by moving the interference to higher frequencies where they interfere less with speech signals. The destructive interference erupted because sounds of the same frequency collided with each other from opposite directions, lowering their volume, see Chapter 2.1.3. By moving the mic closer to the wall, higher frequencies get affected instead of lower since the distance from the wall stands in relation with the wavelength of sounds that collides.

Lastly, more analysis was put towards a conical shape and more specifically on the effects of changing its volume. To analyze this, the inner port diameter, the small diameter of the conical frustum, was set to a fixed value and the port angle fixed as well. To change the port volume the length of the port was chosen as the changeable factor. The port angle was set to 24° to get the outer diameter to approximately 10 mm. A visualization of how this works can be seen in Figure 5.12

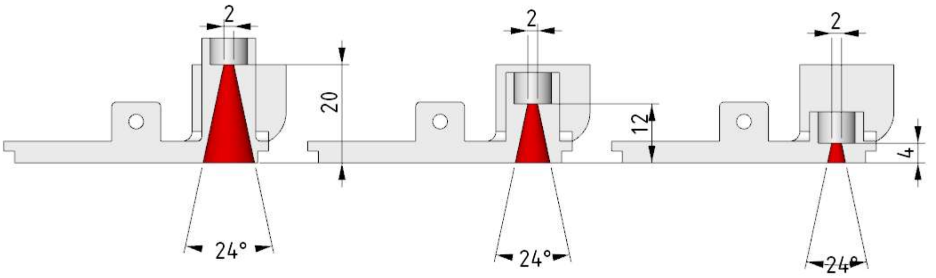


Figure 5.12 Conical port construction.

All the control factors from cycle two can be seen in Table 5.8, coupled with a description.

Table 5.8 Control factors for cycle two.

	Control factors	**Description**
1	Port length	Understand how the port length, the distance from the intercom edge to the mic, in combination with a port angle changes the sound.
2	Inner port diameter	The inner port diameter was fixed to 2 mm for all prototypes.
3	Port angle	The port angle was fixed to 24 degrees for all prototypes.
4	Mesh in front of the port	Investigate the effects of basket windshields in combination with other control factors.
5	Foam windscreen in front of the port	Investigate the effects of windscreens in combination with other control factors.
6	Placement	Investigate the effects of the changing the placement of the microphone.

The six control factors resulted in 10 differently designed prototypes of the port. The prototypes were built to be able to test different values of a control factor, this is explained in Table 5.9.

Table 5.9 Control factor analysis description.

Control Factor	**Analysis description**	**Prototypes**
Port length	Short vs medium vs long port	P.1 vs P.2 vs P.3
Mesh	No mesh vs mesh, placement: bottom No mesh vs mesh, placement: front	P.3 vs P.5 P.4 vs P.6
Foam windscreen	No windscreen vs windscreen, placement: bottom No windscreen vs windscreen, placement: front	P.3 vs P.7 P.4 vs P.8
Mesh and windscreen	No add-on vs mesh and windscreen, medium port No add-on vs mesh and windscreen, long port	P.2 vs P.10 P.3 vs P.9
Placement	Bottom vs Front, No Add-on Bottom vs Front, Mesh Bottom vs Front, Windscreen	P.3 vs P.4 P.5 vs P.6 P.7 vs P.8

Regarding noise factors, the same three factors were chosen as for cycle one: wind speed, mounting and wind direction, see Table 5.10. The second cycle did although limit the numbers of varying noise factors to one. This decision was made since the result of the first cycle yielded too unreliable results in terms of noise factors and few conclusions could be drawn. Since there was a limit of the number of test setups that could be fitted into a SIN test the noise setup variance had to be reduced.

The wind speed was chosen to a fixed velocity in the same way as for cycle one, through pilot testing. The wind speed was increased in relation to the first test cycle since the second cycle investigated better performing designs. When choosing between varying wind direction or mounting, wind direction was deemed more important to test. The reason for this choice was that wind direction variance is constant and needs to be mitigated for any outdoor intercom device. Two different wind directions were chosen to be investigated: 315° and 0°, as for cycle one. The mounting was chosen to wall for all test setups. Most intercoms of the company are mounted on a wall and therefore this mounting was chosen. An analysis of how well the final chosen concept would handle pillar mounting was conducted and can be found in Chapter 6.3

Table 5.10 Noise factors cycle two.

	Noise factors	**Reason of choice**
1	Wind Speed	Wind speed is concluded to be a big factor in the amount of noise in microphones.
2	Mounting on wall	Most intercoms are mounted on walls. Therefore, the tested designs were mounted on a wall.
3	Wind Direction	Wind direction played a role in the results of Bradley et al (2003). Maximum noise direction (315°) is compared to a straight facing direction (0°).

The three noise factors resulted in to two different noise setups. The ten prototypes in combination with the two noise setups led to 20 different test setups 1.1-10.2, see Table 5.11. The factors were tested in the same way as for cycle one. Audio recordings from each prototyped port design and noise setup were produced, as described in Chapter 4.3.

Table 5.11 DOE Matrix for cycle two.

							1	2	Noise setup
							4 m/s	4 m/s	Windspeed
Prototype	Port length (mm)	Inner port diameter	Port angle	Mesh	Foam windscreen	Placement	Wall	Wall	Mounting
							315	0	Wind angle
1	4	2	24 deg	-	-	bottom	1.1	1.2	
2	12	2	24 deg	-	-	bottom	2.1	2.2	
3	20	2	24 deg	-	-	bottom	3.1	3.2	
4	20	2	24 deg	-	-	front	4.1	4.2	
5	20	2	24 deg	Yes	-	bottom	5.1	5.2	
6	20	2	24 deg	Yes	-	front	6.1	6.2	
7	20	2	24 deg	-	Yes	bottom	7.1	7.2	
8	20	2	24 deg	-	Yes	front	8.1	8.2	
9	20	2	24 deg	Yes	Yes	bottom	9.1	9.2	
10	12	2	24 deg	Yes	Yes	bottom	10.1	10.2	

Through the 20 different test setups, including two different wind directions, the wind direction sensitivity of the ports could be measured and compared between them. A noise setup analysis was also planned to further understand what wind direction proved more hazardous, to draw conclusions regarding the port behavior. All ten prototypes were also investigated in a Continuous Sweep test.

5.2.2 Results

5.2.2.1 SIN test results

The average score of each combination of analyzed prototype and noise-setup is found and displayed in Figure 5.13.

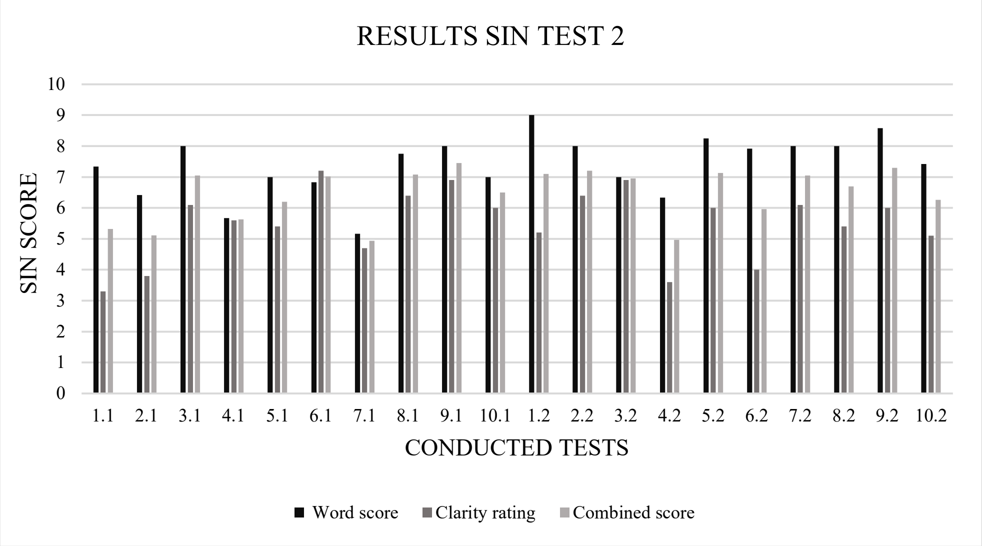


Figure 5.13 Results of SIN test in cycle two.

In the second test cycle ten people participated in the SIN test and listened to and rated 20 audio files from 20 different test setups. 80 files had been recorded, four from each test setup to increase reliability in the results in a manner described in Chapter 4.4. Every participant of the second test cycle had already participated in a pilot or actual SIN test from the first cycle.

The results show, in the same way as in cycle one, three score bars for each of the audio files listened by the participants. Each test is named with a first number linking it to a prototype and a second to a noise setup. Test 1.1 is therefore referring to prototype 1 in noise-setup 1. The first bar for each test represents the average word score, the second referring to its average clarity rating and the last bar to the combined score, being the average of the two first bars. More information about the scores is found under the results of SIN test one in Chapter 5.1.2.1.

As seen in Figure 5.13 the word score was in most cases higher than the clarity rating by a fair margin. The difference was in general larger than in the first cycle where this pattern also was found.

5.2.2.2 Results of Continuous Sweep

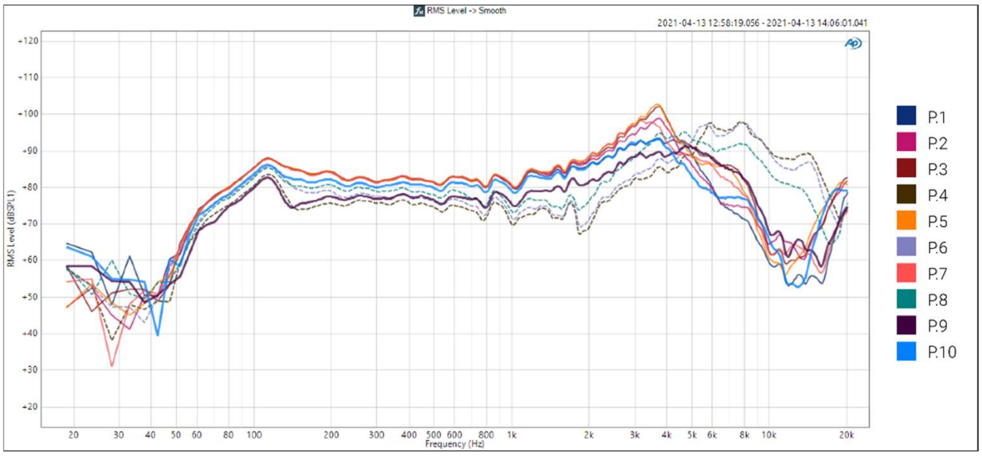


Figure 5.14 Continuous sweep results from cycle two.

The Continuous Sweep results from the second cycle showed an improvement regarding being less effected by destructive interference from reflecting sounds. As seen in Figure 5.14 the dip, previously located at around 5 kHz in the first cycle, can now be seen to be affecting the frequency response at around 10 -14 kHz instead, outside the spectrum of speech. This change is explained by the relocation of the microphone port on the bottom edge to a position closer to the wall. Since most of the microphone ports that were tested had the same shape, they also produced similar results. This meant that adding a mesh or a windscreen to a design did not affect the sweep response in a significant way, (P.3, P.5, P.7). When adding both windscreen and mesh to a port a small decrease in response could be seen (P.9, P.10).

The biggest difference in designs that became evident was moving the port to be facing the front. This resulted in a decrease of destructive interference to a minimal level (P.4, P.6, P.8), illustrated with dashed lines in Figure 5.14. An interesting pattern however was that the ports facing frontwards also produced a significantly lower frequency response within the spectrum of 500 Hz – 4 kHz.

5.2.3 Analysis

The test setups for cycle two included all prototypes being tested in two wind directions. The motivation was that the results could in this way be compiled into one robust score for each prototype, where wind direction change was accounted for. By taking the average score received from each prototype in the two noise setups and combining them, a SIN-score resistant to wind direction could be produced. A robust SIN-score for each prototype can be seen in Figure 5.15.

To further understand how sensitive a designed port was to the change of wind direction a wind direction analysis was conducted. The analysis investigated the difference in SIN-score in absolute percentage between the two noise setups for a prototype. A low percentual change between the two wind directions meant that the port was resistant to wind direction change. The wind direction analysis can be found in Figure 5.16.

It is the belief of the authors that a good and robust port design produces a high robust SIN-score, as well as a low sensitivity to wind direction change. It is motivated by that a port should be able to generate clear voice recordings outdoors regardless of what direction the wind is coming from. Table 5.12 gives a short supplementing description of the prototyped ports to increase clarity of the two Figure 5.15 and Figure 5.16.

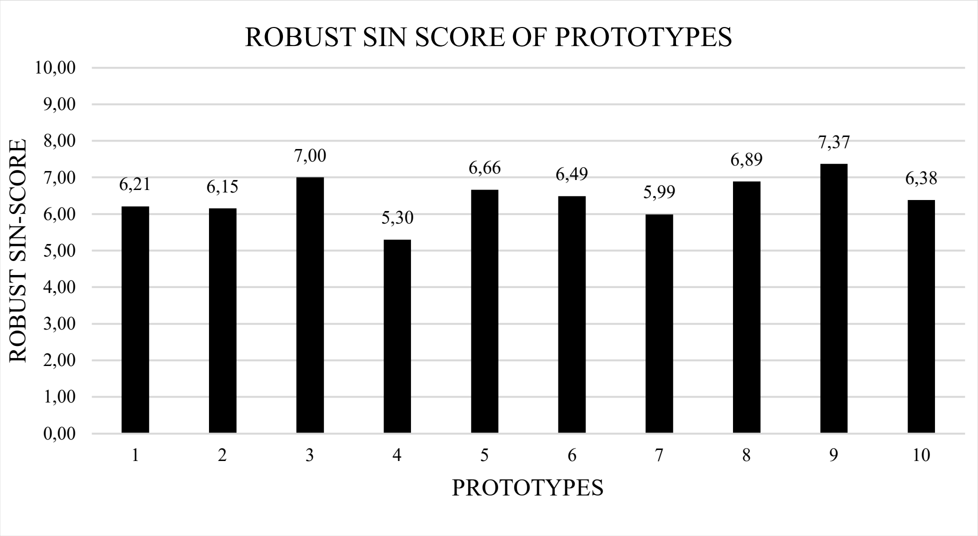


Figure 5.15 Robust SIN score of prototypes.

Table 5.12 Short description of prototypes including length, placement and add-on.

1	2	3	4	5	6	7	8	9	10
Short / Bottom	Medium / Bottom	Long / Bottom	Long / Front	Long / Bottom + Mesh	Long / Front + Mesh	Long / Bottom + Windscreen	Long / Front + Windscreen	Long/ Bottom + Mesh + Windscreen	Medium / Bottom + Mesh + Windscreen

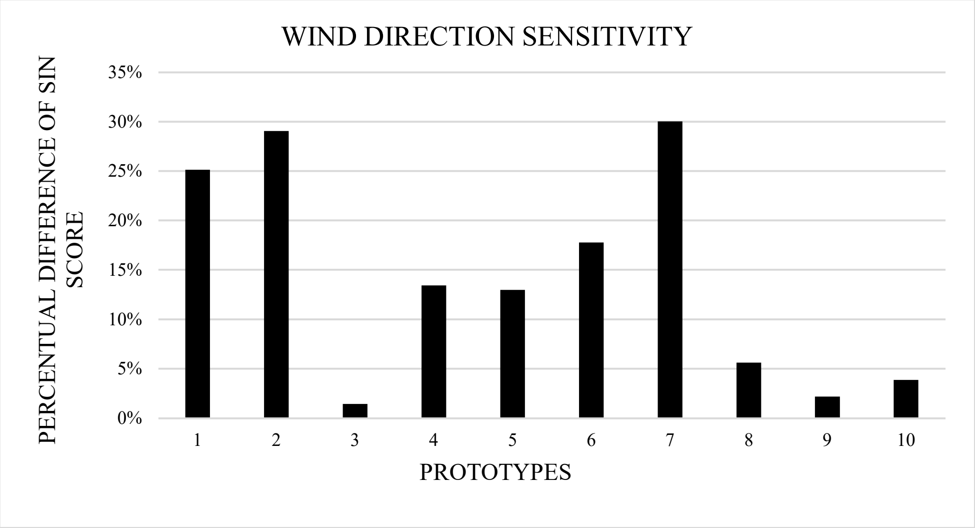


Figure 5.16 Wind direction sensitivity of prototypes.

When looking at the SIN score results of Figure 5.15 it can be concluded that the scores overall are higher and more even than the results of the first cycle. All prototypes received a score higher than the average of 5. The port that produced the best robust SIN score was the large conical port facing downwards with both a mesh and windscreen with a score of 7,37. The worst performing port design was the front-facing port without add-ons with a score of 5,30.

From the wind direction analysis in Figure 5.16 a larger range of scores could be seen. Four prototypes had a very low sensitivity to wind direction change, that being number 3, 8, 9 and 10 with a small percentual difference. Two of these were fitted with both mesh and windscreen. Three other designs were seen to have a very high sensitivity, prototypes number 1, 2 and 7 were all close to 30% in sensitivity. Both two smaller ports without add-ons were highly affected by change of direction.

When looking at the combined results of the two graphs, searching for designs producing high robust SIN score and low sensitivity prototypes 3, 8 and 9 stands out. All of them scoring in the top 3 in SIN score and top 4 in least sensitive.

5.2.3.1 Control Factor Effect Analysis

For the control factor analysis all scores analyzed are the average score received from the two noise setups, the same robust scores that are presented in Figure 5.15. In the following paragraphs an analysis will be conducted on the five investigated control factors that were described in Table 5.9, see Figure 5.17a-e. All port analyzes will also refer to the wind direction analysis in Figure 5.16.

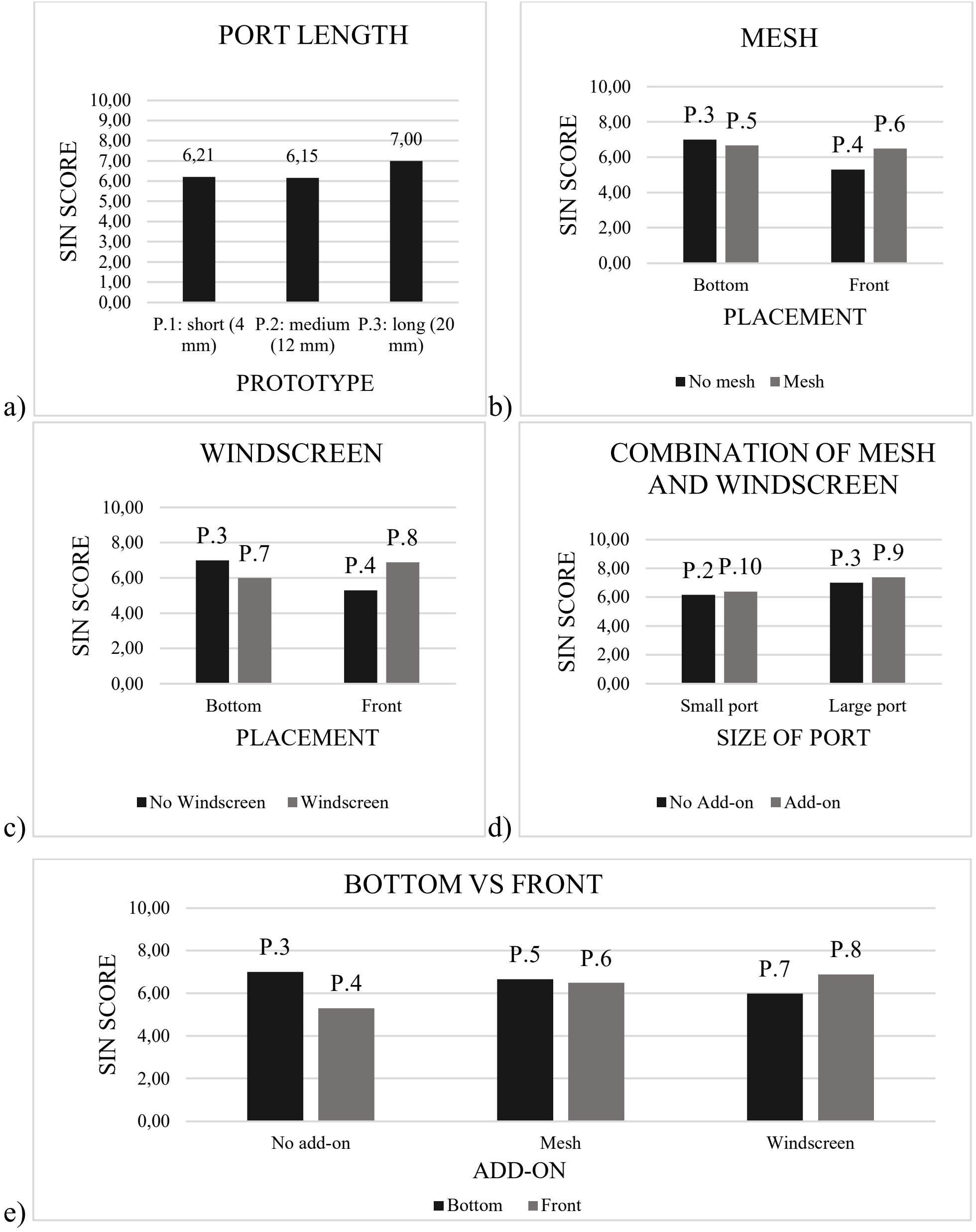


Figure 5.17 a-e. Control factor analyzes cycle two.

Figure 5.17a investigates different lengths and volumes of conical ports in three different sizes. The investigated lengths are 4, 12 and 20 mm. All ports had the same angle of 24 degrees and the same inner diameter of 2 mm, making the volume and top to bottom diameter ratio different in all ports. All ports were also placed on the bottom side of the prototype. What can be seen in the figure is that both the short and the medium sized port produced around the same SIN score whereas the large port was performing approximately 13% better than the smaller sizes. From the direction analysis, a large port could also potentially decrease wind direction sensitivity.

Figure 5.17b shows the effects of adding a mesh on a long conical port when it is placed both on the bottom and on the front of the prototype. The results showed a small decrease in SIN score when adding a mesh on a downward-facing port and an increase in score when mesh was added to the front-facing port. Adding a mesh also increased sensitivity to the ports, but not as much as for the fronted port.

Figure 5.17c visualizes adding a foam windscreen on a long conical port when it is placed on the bottom and the front. The analysis shows a decrease in performance when a windscreen is mounted on a downward-facing port but an increase when added on a front-facing port. The same pattern of results could be seen in the wind direction analysis as well.

Figure 5.17d compares ports facing downwards of medium and large size versus the same ports in the same placement but with both mesh and windscreen added. The results showed a small increase in SIN score for both ports when having both add-ons. The direction analysis also showed that having both add-ons yield a low sensitivity to a port. However, the large port without add-ons were also resistant to wind direction changes.

In the last control factor analysis, in Figure 5.17e, the placement of the ports was reviewed. It showed that a long conical port without any add-ons had the best performance on the bottom side of the object. If a mesh was added it provided approximately the same performance if it was placed on the bottom as if it were placed on the front side. Finally, it also showed that if a windscreen was added instead of a mesh the forward-facing port produced the best result. The same pattern of result was found in the wind direction analysis.

5.2.3.2 Noise Factor Effect Analysis

For the second cycle the prototypes were tested in two noise setups. The setups differed only by wind direction and the results of each prototype can be seen in Figure 5.18.

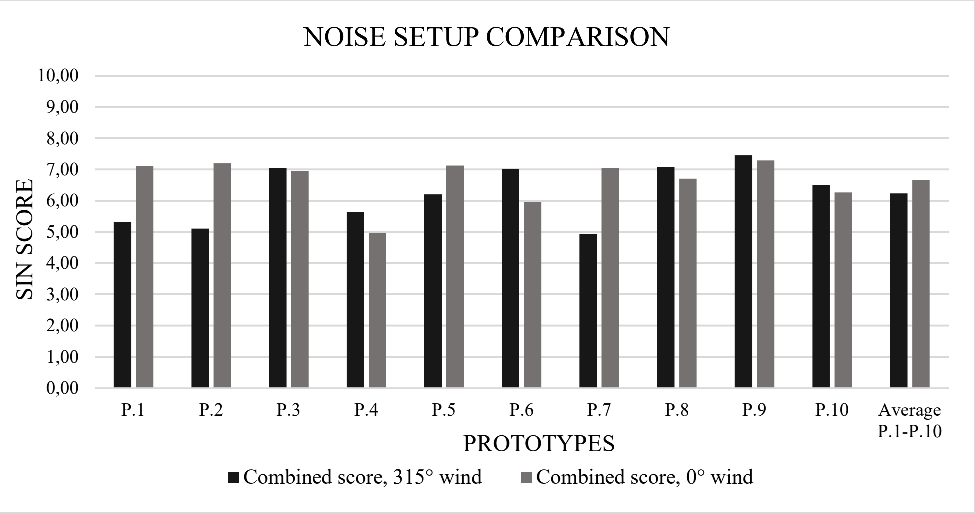


Figure 5.18 Noise setup comparison for cycle two.

For prototypes 1, 2, 5 and 7, all with a downward-facing port, a better result was given when exposed of wind in an angle of 0° than when a wind direction of 315°.

The opposite result was given for prototypes 4, 6 and 8 which performed better in 315° wind direction. The three prototypes had in common that the port was placed on the front of the intercom instead of on the bottom. Prototype 8 did although perform very similarly for both directions.

Prototypes 3, 9 and 10 did all give very similar results in both directions, which is a desired result. Therefore a 20 mm long conical port, a 12 mm long conical port with both mesh and windscreen and a 20 mm long conical port with mesh and windscreen are from the data the ports most resistant to the setup change.

The two bars furthest to the right in Figure 5.18 show the average combined score of all prototypes in each noise setup. The resulting values show that in general wind in a direction of 315º to the port resulted in a lower SIN score for the prototypes than with wind from a 0º direction. This is consistent with the theory of Bradley et al (2003).

5.2.3.3 Test Result Analysis

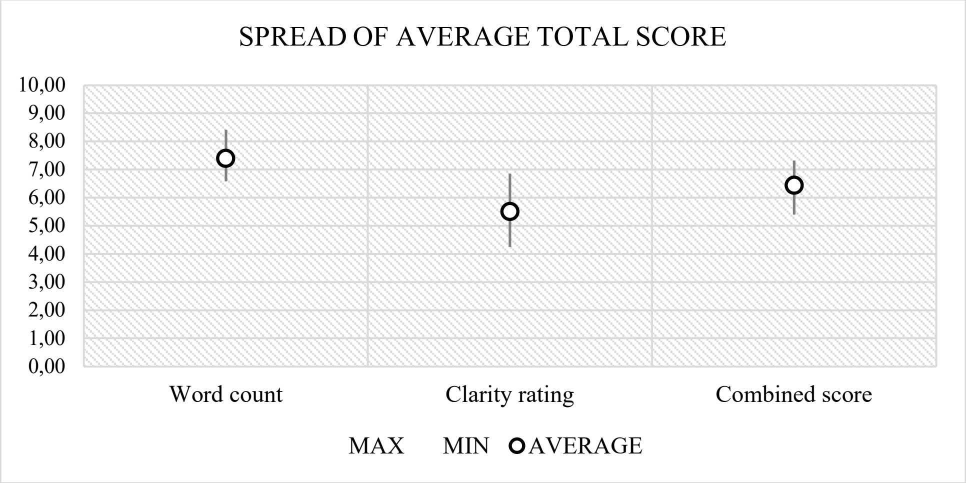


Figure 5.19 Second cycle spread of total score.

When analyzing the spread of scores given by the participants from cycle two, seen in Figure 5.19. the average word score was higher than the general perception of clarity in the audio files. To do a comparison of the result in relation to the first cycle, seen in Figure 5.9, three major differences need to be considered that affected the results in some way:

1. The wind speed was 1 m/s higher creating more wind noise to mitigate.
2. All participants had already conducted a SIN test before and was therefore more experienced.
3. Destructive interference had no impact in the audio files.

There were both things that made the second cycle harder, as increased wind speed, but also easier, as more test experience. The level of difference was not investigated. However, without drawing any concrete conclusions from the analysis, the participants in general got more percentage of keywords correct in the second cycle. When comparing the clarity rating the average scores between the two tests were almost identical.

To summarize, the participants understood more of the sentences correctly in the second test cycle but the clarity rating remained in general very similar between the two cycles.

5.2.4 Reflection

A general reflection of the results from cycle two was that all prototypes gave consistently good results with combined scores over 5. The SIN scores did not vary as much between the prototypes as in the first cycle, but more clear patterns could be discovered for the noise factor analysis and several conclusions could be drawn. An interesting result regarding the SIN scores is that in the second cycle all participants got higher word scores than in the first cycle but did still rate the audio files in the same manner. In this way the participants gave a "better audio file" a worse rating than if it had been included in the first test cycle of files. A reason for this can be that the participants were comparing the audio files against each other and found a new reference of average clarity.

Investigation was put towards the conical shaped port as it gave the best result in the first cycle. The amount of time did though limit the depth of investigation in sizes of the cone. Instead of just changing the length and keeping the inner diameter and port angled fixed, interesting results could have been found if changing the fixed factors in this cycle as well. More studies are needed to be put into which factor of the length, inner port diameter and port angle of the conical port that is most important regarding noise reduction and speech clarity.

A remarkable result was that a port with mesh or windscreen placed on the bottom performed in a less desirable way than without the add-on. When reflecting on the results of using add-ons, it was evident that they had more positive impact when placed on ports that were forward-facing. The combination of mesh and windscreen on a port on the front was not tested but would have been interesting to analyze.

The sources of error that followed through from the first cycle were the difference in difficulty of sentences and that the audio files had to be digitally amplified. No change was done in terms of the size of the mic since changing the microphone was not a possible option due to high costs. The difficulty of sentences remained a possible error since not enough knowledge had been gained in how to reduce it without not allowing for a natural variation of speech. The distortion effect of the digital amplification is deemed to only be of a minor scale.

A positive result was given for the Continuous Sweep test for cycle two. The destructive interference was decreased and showed that better performance was given when the ports on the bottom of the intercom were placed close to the wall. Bottom and front-facing ports provided quite different responses but looking at the results in conjunction with the SIN score it did not seem to have affected the speech clarity.

5.2.5 Factor Setpoints

New control factor setpoints were chosen after completing cycle two of the experiment. The chosen factor setpoints are listed below:

- A length of 20 mm of a conical port increases the performance of the microphone and resistance to wind direction in comparison to a shorter port.
- Using a mesh or windscreen in front of a conical port stabilize the performance of the microphone when it is placed on the front-facing side of the intercom, but not necessarily when placed on the bottom side.
- A port with both mesh and windscreen is very resistant to wind direction change but was not seen to improve the average speech intelligibility.
- Both tested placements of the port have the ability of producing good speech intelligibility. If the port is to be put facing the front it is recommended that any form of wind reduction add-on should be used. However, if it is placed downwards the effect of an add-on is limited.

6 Proposed Guidelines & Designs

This chapter presents design guidelines for wind noise resistant microphone ports. It does also include concept designs, based on the presented guidelines, as well as final noise reduction comparisons of the proposed designs.

6.1 Design Guidelines

From the testing and analysis of the different port designs examined in this project, a simplified design guideline was produced and can be seen in Figure 6.1. The step-by-step chart describes five important factors that should be considered when designing a microphone port for voice applications. Following the guidelines will improve the port for an outdoor environment with a focus on reducing the effects of wind noise. Below a list of motivating factors for each guideline step is presented.

1. A well-designed microphone port generates better audio than a product without an opening to the mic at all. If no port opening exists the mic´s response volume will be lower, and the frequency response distorted.

2. Through the project's background research and experimental testing, it became clear that a conically shaped port produces better audio than a cylindrical port. The conical shape is better in consistently, in different noise setups, provide good noise reduction and speech intelligibility. The cylindrical shape proved to be much more sensitive.

3. From the testing of different sizes of conical ports, the results showed a decreased sensitivity to wind direction change and better speech clarity from a longer conical port.

4-5. Through comparative testing between front- and bottom-facing ports the results showed that an open port produced better sound facing downwards, but if a mesh or/and windscreen were added, both placements could provide good audio quality. A port facing downwards need to take destructive interference into account and be placed close to the back wall. Both bottom and front-facing ports benefit from placements close to the edges of the designed product.

DESIGN GUIDELINES OF MICROPHONE PORTS FOR SPEECH IN WIND NOISE

1. Using a port.
Having a port is almost always better than not having one. Not having a port will decrease general sound quality.

2. Shape of port.
Design the shape of the port to be conical, expanding outwards. It will provide better voice sound quality and wind noise reduction.

3. Size of port.
A longer and more volumous conical port will in most cases produce better noise reduction than a smaller one.

4. Placement of port.
A port can be placed both on the bottom and on the front of the product, but different design rules will apply.

5. Bottom placement.
When a port is facing downwards it is important that it is placed close to the side edge and as close to the product mounting surface as possible. A port facing downwards does not neccesarily need any wind reducing add-ons.

5. Front placement.
When a port is facing forward it is important that it is placed close to the side edges. A port facing forward will need some windreducing add-on to function properly, a metal mesh is recommended.

Figure 6.1 Microphone port design guidelines.

6.2 Final Concept Designs

Two final concept designs were created through following the port design guidelines in Figure 6.1. The designs were picked in conjunction with the company's wishes and were to be further analyzed. The first design followed the guidelines of a bottom facing port and resulted in a 20 mm long conical port without any add-on (P.3 in cycle two). The second was designed for being front-facing and led to a conical port, the same shape as the first concept, and with a metallic mesh as add-on (P.6 in cycle two). The mesh was preferred above using a windscreen by the company because of uncertainties regarding the windscreens lifespan in outdoor use mentioned in Chapter 2.4.1. Both port concepts were placed in a 3D-modelled design of a door station intercom. To be able to measure the concepts against a current solution of the company, a third concept was created containing a port according to today's guidelines of the company, a 4 mm long cylindrical port with the diameter of 1.5 mm. The three prototypes were produced through 3D printing. Pictures of the concepts being mounted on a pillar in a harbor area can be seen in Figure 6.2-Figure 6.6. All three prototypes were constructed with two ports, but only one of them was operational and was tested. Two microphone ports were installed because there are two mics in the intercoms of the company today and to make the appearance of the concepts correspond to reality. Having two microphones increases the functionality of the ports through software, as described in Chapter 2.4.4.

Figure 6.2 & Figure 6.3 Concept one: Conical port facing downwards.

Figure 6.4 & Figure 6.5 Concept two: Conical port with mesh facing frontwards.

Figure 6.6 & Figure 6.7 Concept three: A port following current guidelines of the company. Small cylindrical port facing frontwards.

Current products of the company are secured against particles as dust and liquids through having an acoustic vent in front of the mic. In this way the products are highly IP (international protection) classified. To make the 3D printed concept designs more realistic and comparable to the company's products the same acoustic vent was added, see Figure 6.8.

Figure 6.8 Placement of acoustic vent.

6.3 Final Concept Testing

6.3.1 Impact of Acoustic Vent

Since acoustic vent is necessary in products for long outdoor use it was included in all the forthcoming noise tests. The influence of the acoustic vent was measured to compare the final concepts with earlier results. The measurement was conducted through a Continuous Sweep test which meant playing a sine-signal that is recorded by the microphone and then analyzing the frequency response. In this test the sine-signal was picked up by the measurement microphone placed in the prototypes both with and without presence of an acoustic vent. Frequency response curves were created, found in Appendix E, and showed a large impact of the vent which distinctly lowered the performance of all the ports. The biggest difference was discovered in frequencies between 500-2000 Hz. As human speech has a frequency range between 125-8000 Hz, the vent was shown to lower the volume and hence the speech intelligibility of the microphone. The decreased sound volume would make it harder for the listener to understand which leads to a less functional product even if the sound could be amplified through software.

6.3.2 Noise Factor Tests and Results

Limited amount of time of the project eliminated the possibility of conducting a third cycle of SIN tests for the final concepts. Other methods had to be implemented to measure the performance. The control factors were chosen through the design guidelines. The resistance to the noise factors: wind direction, mounting and wind speed, that were included in the two cycles, remained to be tested for the final concepts. Both two designed concepts, as well as the concept built upon the current guidelines of the company, were tested and evaluated against all the different noise factors to build a holistic picture of their generated wind noise levels.

6.3.2.1 Wind Direction

The resistance to wind direction was investigated through recording the wind noise through each prototype in exposure of 4.5 m/s wind in the five directions: 270°, 315°, 0°, 45° and 90°, see Figure 6.9. The recorded wind noise was then analyzed with the software of APx526. For measuring the wind noise level in a way that described how strong the human ear perceived it, an A-weighting filter was applied to the files. Frequency response curves were created, and each file was analyzed.

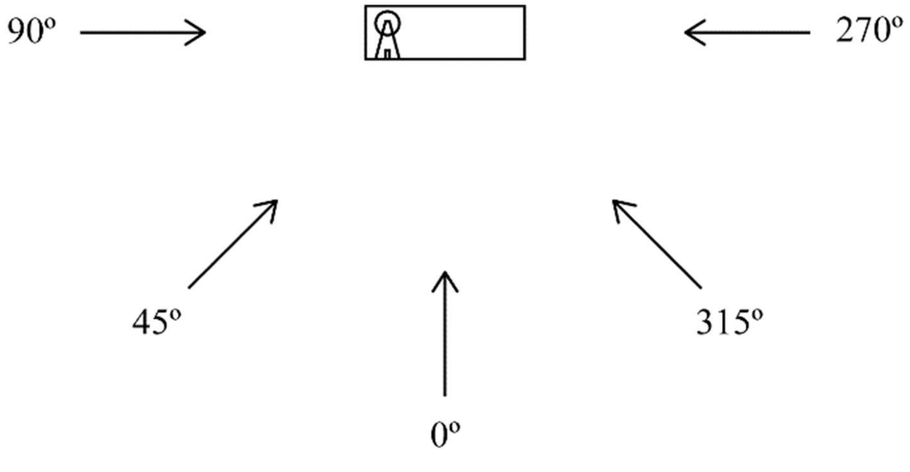


Figure 6.9 Five wind directions to test the prototypes in.

Wind direction analysis of prototype mounted on wall.

In the first test session the three prototypes were mounted on a wall.

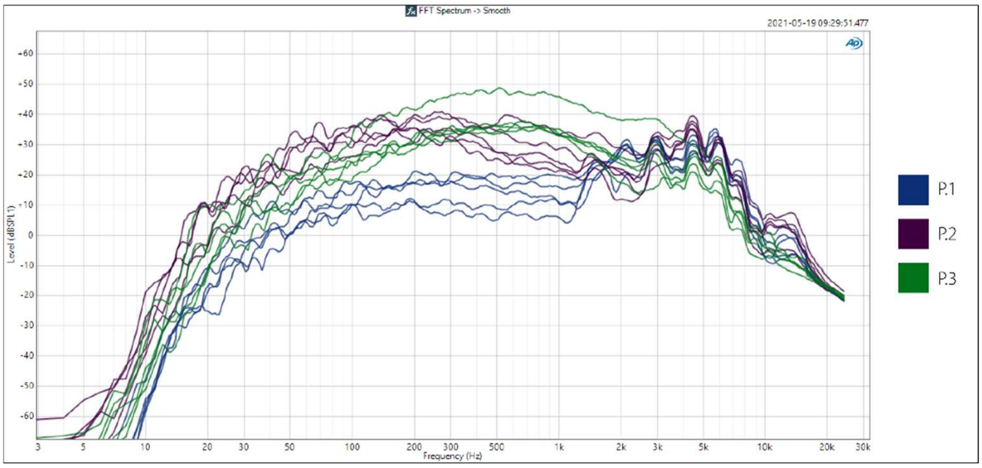


Figure 6.10 A-weighted frequency response curves of wind noise of the three prototypes, mounted on wall in different wind directions.

Figure 6.10 shows the noise's frequency response through the three prototypes, divided by color. There are five lines in each color, where each line represents the noise response from one direction. All curves varied naturally below 2 kHz, but above this frequency all curves followed a similar pattern with peaks at specific points. This was deemed to be caused by unwanted noise created in the air flow generator through the air flow pipes. This is further examined in a following paragraph after the result analysis of the frequency response. The results above 2 kHz could, by that reason of disturbing pipe noise, not be trusted and conclusions of the performance of prototypes could just be drawn up to that frequency. This span below 2 kHz is although where the wind noise is the most prevalent.

For a well-designed port, the wind noise level was desired to be as low as possible. The frequency response up to 2 kHz in Figure 6.10 showed that wind noise could be heard through all three prototypes. In Appendix F the curves in Figure 6.10 are divided into one figure per prototype (F.1, F.2 and F.3), showing what curve is representing each wind direction. The following analysis takes the data from Appendix F into account.

Concept one, the conical port facing downwards, gave the lowest average wind noise volume in the spectrum of human speech (from 125 Hz) and can therefore be concluded as giving the best results of the concepts. In terms of resistance to wind direction it was shown that most wind noise was given when exposing wind in the directions of 315°, 270° and 0°. Slightly lower volume was given for the other two directions.

Concept two, the conical port with mesh facing frontwards, picked-up a volume of wind noise of approximately 20 dB higher than concept one. The highest levels of wind noise were given in the directions of 0° and 90°. The difference in noise levels were although less in higher frequencies.

Wind noise from the third concept, which represents a port of the company today, did for four out of the five directions also have a noise volume roughly the same as concept two. However, for the direction of 90° a remarkable increase of wind noise was shown. In this regard it could be seen as less wind direction resistant. Another difference with concept 3 was a higher general noise volume response in higher frequencies, above 500 Hz, where concept one and two both performed better.

To investigate the unwanted noise that was described earlier, one of the wind noise files was analyzed through the audio editing software Adobe Audition. In Figure 6.11 the frequency intensity during the time of an audio clip with generated wind noise can be seen.

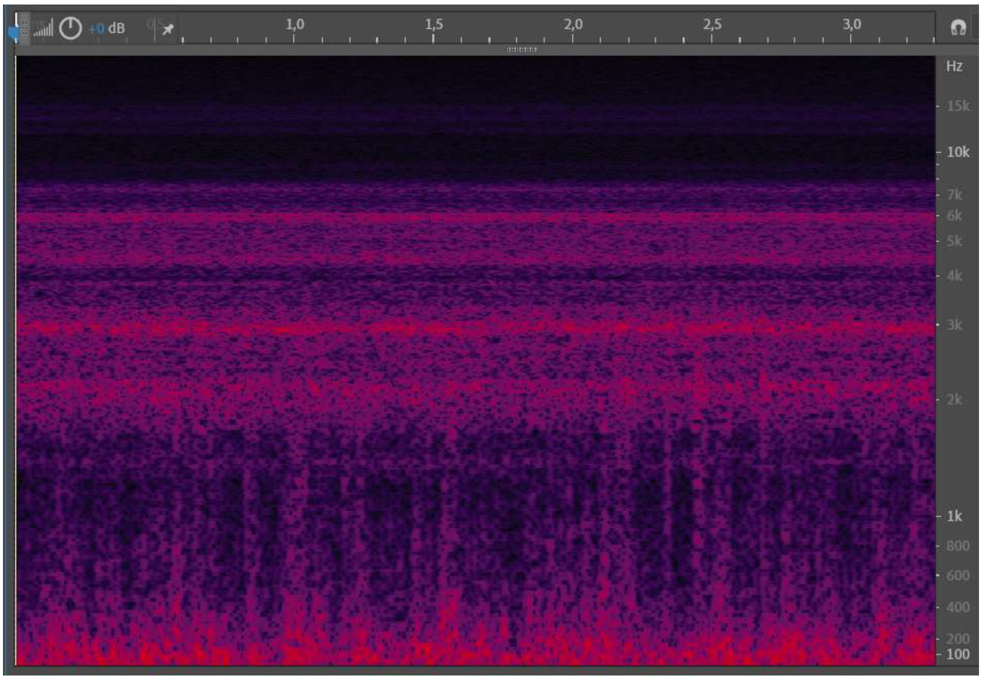


Figure 6.11 Spectral frequency of a SIN file.

The amplitude of the sound is color graded with louder amplitude of sounds having a brighter color. Wind noise is a constantly existing but varying sound that stretches over the whole of the time span. The noise is the most intense at the very bottom of the figure, in low frequencies where the wind noise normally is located. However, stripes at 2, 3, 4.5 and 6 kHz visualizes another constant noise. This was discovered to be a consequential sound of the creation of air flow by the air flow generator and the pipes the air flow was transported through into the anechoic chamber. This could be stated by seeing that the wind was varying during different time spans, whereas the unwanted "pipe sound" remained constant. The peaks in higher frequencies in

Figure 6.10 did also translate well into the frequencies of the stripes of constant noise in Figure 6.11. To further confirm this, an outdoor test could be conducted or using a different wind generation method. Those options were however not further examined in this project.

Wind direction analysis of prototype mounted on pillar.

All three concepts were tested when mounted on a pillar and challenged by wind from the same five directions. The same peaks resulting from the pipes of the air-flow generator were expected and detected again in the A-weighted frequency responses shown in Figure 6.12. Analysis of the behavior of the curves could be drawn up to 2 kHz as previous. In Appendix F the curves in Figure 6.12 are divided into one figure per prototype (F.4, F.5 and F.6), showing what curve is representing each wind direction.

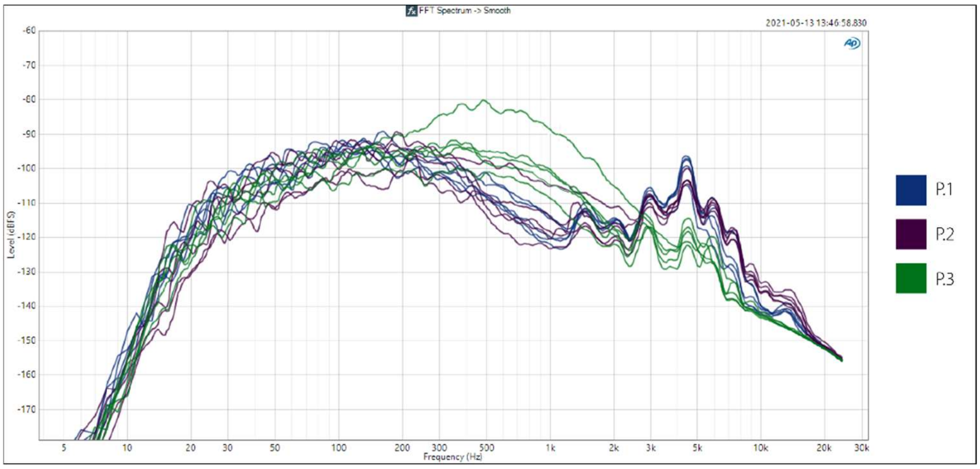


Figure 6.12 A-weighted frequency response curves of wind noise of the three prototypes, mounted on pillar in different wind directions.

Concept one performed in a similar manner in all wind directions and can therefore be stated as direction resistant. A difference that could be seen in comparison with the wall mounting was that concept one was clearly performing better at reducing wind noise when mounted on a wall. It performed more in line with the other concepts when mounted on a pillar.

As for concept two, it performed very similar in noise volume in comparison to the wall mounting. It can also be seen to be slightly more sensitive to wind direction change than concept one, performing least favorably in 90° wind.

Concept three gave a small difference compared to the results of wall mounting. Same levels of noise as the other concepts in low frequencies, but higher than the other two in the higher spectrum. As seen in wall mounting as well, a 90° wind increased the volume of wind noise and can be seen throughout the measurable spectrum of speech frequencies (125-2000 Hz).

In conclusion, the first concept was most resistant to different wind directions both when mounted on a wall and on a pillar. The second concept gave small differences in directions and can be stated as the second-best concept. Largest differences were given from the third concept where the performance in 90° wind was remarkably bad.

6.3.2.2 Mounting

The impact of mounting was analyzed through the A-weighted frequency response curves of wind noise discussed in previous chapter, presented in Appendix F. Further analysis was made with figures in Appendix G created through Continuous Sweep, showing frequency response curves of the picked-up sine-signal when prototype mounted on a wall versus on a pillar.

A detailed analysis of the mounting is presented in Appendix G. The analysis could conclude that the first concept, conical port facing frontwards, gave biggest difference of wind noise in the two mountings, and therefore the concept least resistant to how it is mounted. The second concept, conical port with mesh facing frontwards, is most resistant to any mounting change, by performing in a similar way on both wall and pillar. Third concept, cylindrical port facing frontwards, is performing in the second-best way regarding mounting.

Concept one did nonetheless give the same amount of noise volume when mounted on a pillar as the other concepts and performed best of any concepts in any mounting setting when mounted on a wall.

6.3.2.3 Wind Speed

To investigate how the prototypes responded to different levels of wind speed another noise test was conducted. All prototypes were challenged by 4 m/s, 5 m/s and 6 m/s wind when mounted on a wall in a 0 degrees direction. The wind noise was recorded, through an A-weighting filter and the files were analyzed graphically. The resulting frequency response curves can be seen in Figure 6.13. The test was performed in order to understand how much more wind noise that would be generated through each prototype by each extra meter per second wind.

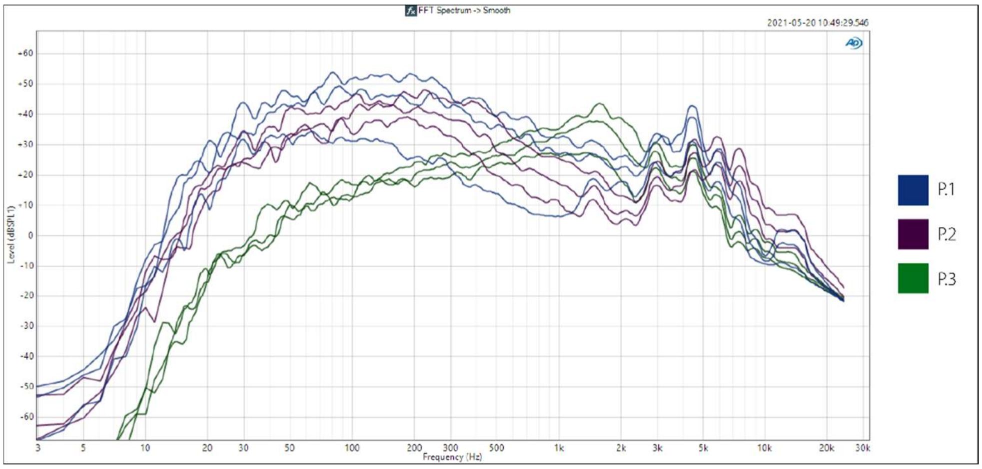


Figure 6.13 A-weighted frequency response curves of each prototype exposing wind in three speeds.

Two changes in the result were identified in comparison of the wind direction result in Figure 6.10. A comparison could be made since the concepts in the wind direction test, were challenged by 4,5 m/s wind in the same direction and in the same mounting position as in the speed test. Firstly, concept one, that significantly produced the least noise when mounted on a wall in the previous tests, produced a different level of noise, more in line with concept two in the speed test. The second big difference from the direction result in Figure 6.10 was that the reference concept, concept three, generated much less noise in lower frequencies in this test than in the comparable results of the wind direction tests. Both results surprised the authors and a direct reason for the large difference in results were hard to conclude, but it was assumed that the acoustic vent installation or quality might have played into effect.

The results of the speed tests were evaluated within each prototype individually, see Appendix H. Few conclusions between the concepts were drawn from the results since they were deemed too uncertain. From the individual results it was discovered that concept one produced the biggest noise variation of about 25 dBSPL. Concept two varied the least between each wind speed, a maximal variation of generated noise was approximately 15 dBSPL. Concept three produced a very even level of wind noise in lower frequencies but had a large variation in the higher spectrum between 800-2000 Hz, with a maximal difference of approximately 20 dBSPL.

Through this test the belief of the authors that wind speed was the biggest factor for generating wind noise was confirmed.

An additional recording was made in all wind speeds for all prototypes with a speech file being played from the mouth speaker to gain further knowledge of how big effect the wind speed had on speech clarity. The recording was only listened to by the authors, not tested in an additional SIN test. The increase in wind noise through increasing the wind speed was easily heard in all concepts. The wind noise in concept three, even if it was lower in low frequencies, did however distort the speech clarity the most. The believed reason was that the noise floor at the speech frequencies, 125 Hz and above, was in general higher in concept three.

6.3.3 Result summary and reflection

When reflecting on the results of the noise factor tests it was shown that the concepts were affected by the factors in different ways.

Concept one, a conical and downward-facing port was able to show good resistance to wind direction change both mounted on a wall and on a pillar. Mounting and wind speed changes were able to yield a larger difference in wind noise generation, but the concept was never concluded to be especially underperforming in any regard.

Concept two, a conical and front-facing port with a metallic mesh, was believed to produce the most stable results when looking at the combination of the tests. The concept provided almost identical results from the two mounting positions. It showed acceptable resistance to wind direction changes, where only a 90-degree wind yielded a significant change in output. The concept was also the most resilient against an increased wind speed.

The reference concept, a small, cylindrical and front-facing port was measured against the two concepts to understand how a higher speech intelligibility could be detected in the graphs, as well as to give results of how well a current solution of the company handles changes in noise setups. In the wind direction analysis, it was shown to generate a vast amount of wind noise when exposed by a 90-degree wind with an increase of 12-15 dBSPL compared to the other directions. This made the concept perform least favourably by all the concepts in this analysis. When measuring its resistance to mounting changes it performed in a positive manner. The result from the wind speed test was different compared to the results of the other two tests and are discussed with some caution. It did however produce unexpectable good noise reduction in lower frequencies in this test even if it was worse in the higher spectrum. The variation in the result of the speed test for this concept was quite low.

A general takeaway from all the tests was that the reference concept generated the most wind noise in higher frequencies. It was concluded that this was the biggest factor why the other two concepts provided better speech intelligibility. Good speech intelligibility could be produced when wind noise did not affect the same frequencies as the speech.

7 Discussion

This chapter discuss the development methods that were used, sources of errors that were encountered during the project, the results the project produced and a proposal for future research within the subject.

7.1 Robust Design Methodology

The Robust Design method, which is developed to improve a design in relation to a chosen problem, was in hindsight an overall good method of development for this project. By identifying what in a design that could be changed and what needs to be assessed in the product environment, clear boundaries could be set for the project. The DOE Matrix produced an overview of what would be tested for each cycle and could be used as a manual of which prototypes to design and noise setups to construct. The method created a good framework that could be easily tweaked for new development cycles. The first conducted design cycle revealed that working with too many control and noise factors produced, in this case of noise factors, somewhat unreliable results when not every possible test was made. This led to a lowering of noise factors in the second cycle. The change was proved successful in that more information could be gathered about the remaining noise factors and conclusions about them could be drawn.

7.2 SIN Testing

Conducting the SIN tests made it possible to get metric values of how the prototyped port designs performed. SIN testing required participants. For most tests, a larger sample size of data will provide more reliable results. Ten people participated in each test cycle and having more people would have made the results more reliable. Fewer tests did however provide a faster development process which made it possible to conduct a second test cycle.

For the second cycle the ten participants had already taken part in a pilot or actual SIN test in the first cycle. The choice of having participants familiar with the test layout was based on that it would minimize the sources of error traced to the participant's learning process of the test.

The difference in difficulty of sentences did also affect the result which was reflected on in Chapter 5.1.4. The problem was mitigated through having two different sentences recorded with each prototype and not having two sentences with four key words for one prototype. To reduce it even more an idea could be to have sentences in the native language of the participants. In this way the lack of knowledge in the language should not affect the result.

Some research was made in the beginning of the project for other tests methods, primarily different signal-to-noise software's that could analyze the signal and score the signals clarity through a background noise. Some software was found to do these sorts of analyzes but only with less magnitudes of noise. An example could be PESQ (Perceptual Evaluation of Speech Quality), which do signal-to-noise tests, but focuses mainly on how well a voice signal is retained though a telecommunication transfer and how much is lost through connection issues (Rix et al, 2001). A main reason to go for a real, participant-based test was that it provided a better understanding of what the results meant in terms of level of quality in the audio files.

The use of a speech intelligibility test instead of an analysis of wind noise provided valuable information of how the noise affected and distorted the speech. In some cases, a sentence could be well understood in a port where the noise level was relatively high, where the noise affected other frequencies than those of the voice and therefore did not distort it. The SIN test in this project was therefore measuring how the speech stands out against the wind noise and not the amount wind noise that was recorded. With that said, in most cases, low wind noise resulted in a higher speech intelligibility.

7.3 Test Setup

This part of the discussion reviews the material and equipment that were used to produce SIN files, frequency sweeps and noise tests.

Material

The most essential test material were the plastic 3D-printed prototypes. The port prototypes were through cycle one printed in a FDM printer and in the second cycle through a MultiJet printer, for more information see Chapter 4.2. The generic intercom box was throughout the development process printed in the FDM printer. The switch between printers in the middle of the project was not intended, but instead necessary since the first printer were taken out of operation at the office. The surface quality of the parts between the two cycles did differ which possibly altered the outcome of results. However, all ports within each cycle were printed with the same printer. In this way the same finish was measured against each other and only the construction of the port differed. The high-quality MultiJet printer, that was used for the second cycle and for the concept design, was believed to produce the most reliable prototypes for testing microphone ports since the surfaces were smoother. It was consequently therefore assumed that the results of the second cycle and the concept design were more reliable than the first cycle regarding the prototypes. When looking at the Continuous Sweep curves between the two cycles both setups did although provide stable and clear results, implying that any differences in performance between the 3D printers were minor. To further understand the impact of the material and construction process, the same model could have been produced through both printers and been tested and compared to each other with Continuous Sweep.

Other materials that were used to produce the prototypes were metal mesh and foam windscreen. The metallic mesh had been validated by the company this thesis cooperated with for use towards wind reduction, see Chapter 2.5.2 and the windscreen was developed by a dedicated company for wind mitigation purposes. No further investigation was put in this project on the effects of different meshes or windscreens and no comparison was made against other similar products. The project only focused on understanding the general effects of the use of mesh or windscreen. No additional information was gathered if the ones chosen were particularly good or bad for this specific purpose other than the mesh being validated by the company. There is a possibility that the selected mesh was more suited for this experiment than the windscreen was since it had been tested and validated for the specific purpose of wind reduction in a microphone port by other engineers at the company.

Test equipment

The recordings of audio files through the different port parts were produced in the anechoic chamber. The intercom box together with one of the port prototypes was screwed on to a wooden board, the wall. A gasket was fixed between the prototype and the wall to secure an airtight construction inside of the intercom. There was however no gasket between the intercom frame and the port part and there could have been gaps that have let air flow into the prototype that affected the result. The parts were however designed to fit properly with each other to avoid any major airflows.

When placing the measurement microphone in the port it was sealed with reusable adhesive against air flow, due to the hole in the baffle, the simulated wall, see Figure 4.6. Sealing with reusable adhesive was a method that had previously been used by the company. How successful the sealing was in this project could have been different between the ports since it was applied manually between each test setup. The application of reusable adhesive could have been more reliable by facilitating it better in the inner construction of the intercom surrounding the mic.

To generate wind in the anechoic chamber an air flow generator was used. The generator did generate wind noise but did also generate another noise from the pipes where the air went through. The “pipe noise” differed between the recordings but was always present and hearable. The noise was investigated in Chapter 6.3.2 and clearly visualized in Figure 6.11. The “pipe noise” increased with wind velocity and was not possible to reduce by wind noise reduction techniques. This meant that the problem was bigger in the second cycle than in the first one. Instead, with better and better wind noise reduction by the port this pipe sound became more distinct. The sound has clearly affected the judgement of the SIN files negatively in some way since it is an additional noise and spanning over the frequencies of speech. The scale of the impact on the judgement is unknown and future research is needed on this topic.

Moreover, the average speed of the generated wind was not always the same every time the wind generator was started. It was measured and readjusted manually between each time it was restarted to create as equal noise between tests as possible. The speed that was to be set to vary around a specific velocity may have differed slightly between the recordings, affecting the noise level and the result.

7.4 Results

The result of each prototype for each cycle was based on ten people’s answers in the SIN tests. As mentioned in Chapter 7.2 the results would probably be more reliable the more participants performing the test. The reliability is also depending on the test setup mentioned in Chapter 7.3.

The conical port shape which received the best scores in the first cycle was included in the second cycle as well together with two smaller sizes. The smaller sizes had the same inner port diameter and port angle, but the length differed. It was shown that the big conical port performed the best and the two smaller slightly worse. A single geometrical factor important for the design of the conical port is still however unknown since changing the port length also changed the inner-to-outer diameter ratio. More studies are needed to further understand which geometrical factor of the conical port that is most important regarding noise reduction and speech clarity. The conical shape was in any case identified as one of the most important design features for a wind resistant port.

In the first cycle some prototypes were mounted both on a wall and on a pillar. The small amount of test setups did result in vague results in how the different mountings affected wind noise. For the second cycle the wall was chosen as the only mounting setting due to limitations in number of test setups possible to fit in a reasonable SIN test. The final concepts were although tested mounted both on a wall and on a pillar in several wind directions to get a comprehensive analysis. If the chosen concepts, selected from the second cycle, were performing well in speech intelligibility on a pillar was never determined. More investigation is needed to confirm specifically what sort of port design is least affected by mounting changes.

Another discussion point regarding the result is the placement of the port between the cycles. For the first cycle the placement was set to the bottom edge of the object according to background theory. For the second cycle the company was interested in the effects of placing it on the front-facing side. The conical port that got the best result in cycle one was put on the front to be tested. It did produce a good result, but if this is the most advantageous geometry for a port on the front cannot be confirmed through this project since only one shape facing forward was SIN tested.

After constructing two final concepts their noise reduction performance was compared to a port construction from the company today. The results were given through frequency response curves and not through a human-centered SIN test as in the development process. This meant that wind noise was the measured performance metric and not the speech intelligibility in this round of testing. The tests were conducted to find out what correlated from the results of SIN testing into wind noise testing, to understand what sort of noise reduction increased speech intelligibility. One clear pattern was identified where both designed concepts from the project were able to reduce wind noise better in all test setups in frequencies in the spectrum of 300 Hz and above. This information coupled with the research conducted during the test cycles made the authors believe that this could be the significant difference that yielded good speech intelligibility. To confirm this hypothesis more research would need to be conducted in the area.

It was during the testing shown that the final concepts performed differently between two different test occasions even if they were placed in the same setup. The speed test was conducted at another time than the first tests which seems to have made an impact. What was different that time cannot be concluded, but it was assumed that the setup installation and the quality of the acoustic vent could be the reason. The results did because of this possible error need to be evaluated with a bit of caution. If more time were left until the deadline of the project after the tests had been evaluated, the noise tests of the final concepts would have been remade to doublecheck the results.

7.5 Future Research

This project focused its effort in finding out what mechanical parameters can be used in port designs to enhance a microphones audio input in windy conditions. Some important parameters were identified but other remain to be investigated. As for almost any design process it would benefit from several more iterative development cycles since it would continue to improve the resulting designs. In this project's case, if a next cycle would have been possible to conduct, further testing on different shapes for a front-facing port would have been investigated.

If the presented well performing port designs in this project would be applied in real products, some key investigations would need to be conducted before they were launched. The research would mainly focus on what were outside of the delimitations of this project. The first one would be to investigate the effects of using an intercom applicable microphone, such as an electret or MEMS microphone. The aim would be to understand if the different kinds of microphones handle wind noise differently and if certain designs and placements work better for specific microphone types.

A second investigation would be conducted to understand how the port designs interact with applied noise reduction software that is in place in a standard intercom product. Examples of such software would be DSP or echo cancellation, which reduces acoustic feedback from the intercom speaker. The research would produce information if any port designs were particularly compatible and if any design rules could be applied to facilitate the use of such software.

A third investigation would further cover the use of different acoustic vents and the different materials. From the noise factor tests of the final concepts the use of acoustic vents had a large impact on noise levels, as well as general sound levels. The big effect surprised company representatives and research should be put in gathering more information about acoustic vent installations and a possible change of vent materials to one more acoustically transparent, without compromising the product's IP classification.

Lastly, the microphone ports tested in this project were 3D-printed plastic constructions. Testing if the results would replicate through other materials such as pressed sheet metals, would further validate the designs and increase their usability.

The project also further developed, in parallel to the design process, a method of testing speech intelligibility in wind through SIN tests. The test method produced easily understood results and is recommended by the authors to be further developed by the company. Some research should however be put on other possible ways to generate wind noise, with less generation of additional unwanted noise that might create faulty results.

8 Conclusion

This project's purpose was to enhance the functionality of microphones within intercoms affected by wind and wind noise. The strategy to succeed in this purpose was to identify specific mechanical design elements that could be applied to the construction of a microphone port to reduce the amount of wind noise that reached the microphone.

The project could through the development method of Robust Design, as well as SIN testing, come to the following conclusions that could benefit the future development of microphone ports for the company:

- When designing a port that is meant to be wind noise resistant it needs to be tested in several wind directions, since direction can have a large impact on the amount of wind noise that is generated.

- Destructive interference from any reflective surfaces within proximity to the port needs to be investigated, since it can distort speech input in the microphone.

- To reduce wind noise input in a microphone it needs to be protected from high wind speed and turbulent air flows. This is most effectively done through constructions that slows down and calms the air around the microphone. Designs that through this project succeeded in creating a calm environment could all be constructed following the presented design guidelines in Chapter 6.

References

Adorama. (n.d.) Sennheiser MZW01 Basket Windshield for MKE 1 Microphone, Black. Retrieved February 7, 2021, from https://www.adorama.com/semzw01bk.html

Audio Precision. (2012) More about Continuous Sweep. Retrieved: April 20, 2021, from https://www.ap.com/technical-library/more-about-continuous-sweep/

Beckmann. P. (2016). How Digital Signal Processing Can Enhance the Utility and Performance of Microphones. Retrieved February 11, 2021, from https://dspconcepts.com/sites/default/files/digital_microphone_processing_paper.pdf

Beranek, L. & Mellow, T. (2019). *Acoustics: Sound Fields, Transducers and Vibration (2nd ed.)*. London, United Kingdom, New York, United States: Elsevier Inc.

Berg, R. E. (2020). Sound. Retrieved February 1, 2021, from https://www.britannica.com/science/sound-physics

Biamp. (2020). Equalizing loudspeakers in a sound system. Retrieved May 18, 2021, from https://support.biamp.com/General/Audio/Equalizing_loudspeakers_in_a_sound_system

Bojinov, H., Boneh, D., Michalevsky, Y. & Nakibly, G. (2014). Mobile Device Identification via Sensor Fingerprinting.

Bradley, S., Wu, T., von Hünerbein, S. & Backman J. (2003). The mechanisms creating wind noise in microphones. *AES Convention 114*. Paper No. 5718.

Britannica, T. Editors of Encyclopaedia. (2020). Wind. Retrieved February 1, 2021, from https://www.britannica.com/science/wind

Creality. (n.d.). Creality3D Ender-5 PLUS 3D Printer. Retrieved February 11, 2021, from https://creality3d.shop/collections/new-arrival/products/creality3d-ender-5-plus-3d-printer

Dickason, V. (2020). Audio Precision APx500 Flex Audio Analyzer — Hands-On. Retrieved: April 20, 2021, from: https://audioxpress.com/article/audio-precision-apx500-flex-audio-analyzer-hands-on

Ecophon, (n.d.). Generating and understanding speech. Retrieved May 11, 2021, from: https://www.ecophon.com/en/about-ecophon/acoustic-knowledge/basic-acoustics/generating-and-understanding-speech/

ETSI, (2015). ETSI ES 202 739 V1.4.1 (2015-03). European Telecommunications Standards Institute https://www.etsi.org/deliver/etsi_es/202700_202799/202739/01.04.01_60/es_202739v010401p.pdf

GRAS Sound & Vibration. Frequency range of a microphone. Retrieved April 1, 2021, from https://www.grasacoustics.com/microphone-guide/frequency-range

GRAS Sound & Vibration, Product Catalogue Measurement Microphones Q1-2020. (2020) Retrieved: February 11, 2021, from https://www.grasacoustics.com/files/GRASProductCatalogue_WEB.pdf

Halliday, D., Resnick, R., Walker, J. (2003). *Fundamentals of Physics, Part 1 (Chapters 1-11)* (7th ed.). United States of America: Wiley.

Hill, J. R. (2005). Development of a weatherproof windscreen for a microphone array. (M. S. Thesis, Department of Mechanical Engineering, Brigham Young University, Provo)

Infineon Technologies AG. (2018) MEMS microphone mechanical & acoustical implementation.

Interacoustics. (2016). The Variety of Decibel. Retrieved May 19, 2021, from https://www.interacoustics.com/guides/basics/the-variety-of-decibel-basics

Iridian. (n.d.) Gain Flattening Filter (GFF) Tutorial. Retrieved May 18, 2021, from https://www.iridian.ca/technical-resources/application-notes/gain-flattening-filter-gff-tutorial/#

Jackson, I. Kendrick, P. Cox*,* T. Fazenda*,* B. Li, F. (2014). Perception and automatic detection of wind-induced microphone noise. *The Journal of the Acoustical Society of America,* vol 136, issue 3.

Morcelli, A. & Widder J. (2014) Acoustic Design for MEMS Microphones, Retrieved February 12, 2021, from https://www.edn.com/acoustic-design-for-mems-microphones/

Morgan, S. & on outdoors*. The Journal of the Acoustical Society of America,* vol 92, issue 2.

Owsinski, B. (2005). *The Re*Raspet, R. (1992). Investigation of the mechanisms of low-frequency wind noise generati*cording Engineer's Handbook*. Boston: Thomson Course Technology PTR.

Picheny, M. A. Durlach, N. I., & Braida, L. D. (1985). Speaking clearly for the hard of hearing I: Intelligibility differences between clear and conversational speech. *Journal of speech and hearing research*, *28*(1), 96–103.

Portnuff, C. & Bell, B. Effective Use of Speech-in-Noise Testing in the Clinic. *The Hearing Journal: May 2019*, Volume 72, Issue 5.

ProSoundWeb. (2010). Real World Gear: Handheld Condenser Microphones. Retrieved April 28, 2021, from https://www.prosoundweb.com/real-world-gear-handheld-condenser-microphones/

Pyzdek, A. (n.d.). Wavelength. Retrieved February 12, 2021, from https://acousticstoday.org/wavelength/

Rehm, B., Schubert, J, Haghshenas, A. Pakneja, A. S & Hughes, J. (2008). *Managed Pressure Drilling.* Houston, Texas: Gulf Publishing Company.

Rix, M. Beerends, J. Hollier, M. Hekstra, A. (2001). Perceptual evaluation of speech quality (PESQ)-a new method for speech quality assessment of telephone networks and codecs, *2001 IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol 2 pp. 749-752

Schomer, P. Raspet, R. Wagner, M. Douglas, W. Marchall, D.Brunner, J. (1990). Methods for detecting low-frequency signals in the presence of strong winds. *Construction Engineering Research Laboratory*, Champaign, Illinois. pp. 55-56

Shure. (2017) Mic Basics: What is Frequency Response?. Retrieved: April 29, 2021, from https://www.shure.com/en-US/performance-production/louder/mic-basics-frequency-response

Swedish Transport Administration. (2020). Mått för ljudnivåer. Retrieved May 18, 2021, from https://www.trafikverket.se/for-dig-i-branschen/miljo---for-dig-i-branschen/buller-och-vibrationer---for-dig-i-branschen/Fakta-om-buller-och-vibrationer/matt-for-ljudnivaer/

Ulrich, K. T. & Eppinger, S. D. (2012). *Product Design and Development* (5th ed.). London, United Kingdom: McGraw-Hill.

Walker, K. T. & Hedlin, M. A. H. (2010). A review of wind noise reduction methodologies. In A. Le Pichon, E. Blanc & A. Hauchecorne. *Infrasound Monitoring for Atmospheric Studies*. pp. 141–182. New York. Springer.

Wanhao 3D Printer*,* (n.d.). WANHAO Duplicator i3 V2.1. Retrieved February 11, 2021, from https://www.wanhao3dprinter.com/Unboxin/ShowArticle.asp?ArticleID=70

Western Electric Co. (1969). *Fundamentals of Telephone Communication Systems* (Revised Edition). New York: Western Electric Co.

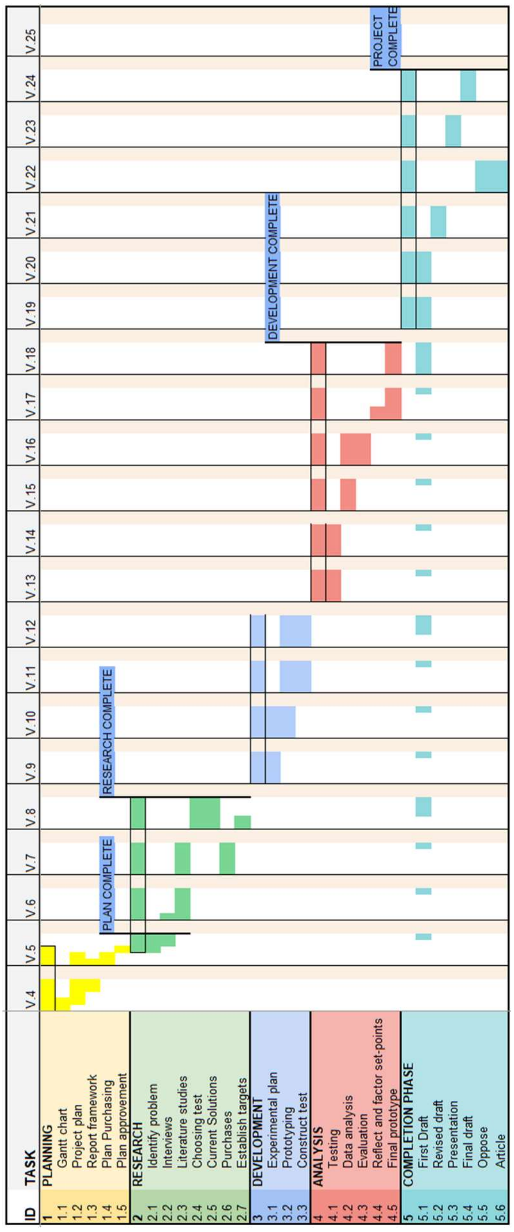
Woolf, C. & Prudden, O. (2000). Windnoise measurement using real wind. Paper 5269, Journal of the Audio Engineering Society. Convention 109, Paper 5269.

Zhao, S. Dabin, M. Cheng, E. Qiu, X. Burnett, I. Liu, J. C. (2017). On the wind noise reduction mechanism of porous microphone windscreens. *The Journal of the Acoustical Society of America,* vol 142, issue 4.

Zhao, S. Niu, F. Qiu, X. Zhang, D. (2020). A note on wind velocity and pressure spectra inside compact spherical porous microphone windscreens. *The Journal of the Acoustical Society of America,* vol 147, issue 1.

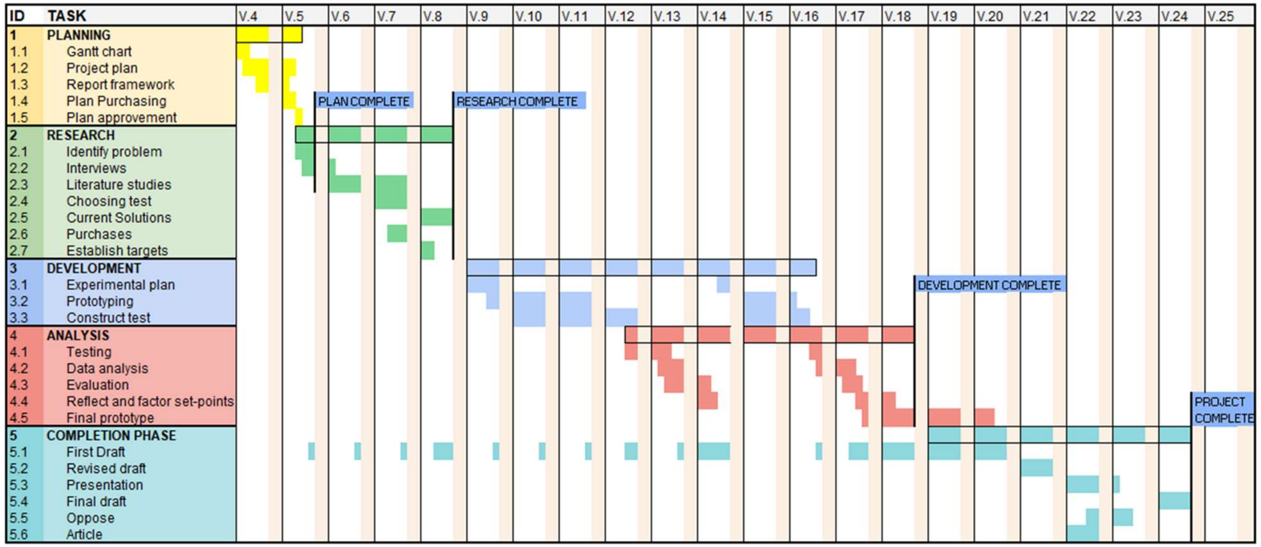
Zheng, Z. C. & Tan B. K. (2002) Reynolds number effects on flow/acoustic mechanisms in spherical windscreens. *The Journal of the Acoustical Society of America,* vol 113, issue 1.

Appendix A Time plan



Proposed project timeline

Elapsed project timeline



ID	TASK
1	**PLANNING**
1.1	Gantt chart
1.2	Project plan
1.3	Report framework
1.4	Plan Purchasing
1.5	Plan approvement
2	**RESEARCH**
2.1	Identify problem
2.2	Interviews
2.3	Literature studies
2.4	Choosing test
2.5	Current Solutions
2.6	Purchases
2.7	Establish targets
3	**DEVELOPMENT**
3.1	Experimental plan
3.2	Prototyping
3.3	Construct test
4	**ANALYSIS**
4.1	Testing
4.2	Data analysis
4.3	Evaluation
4.4	Reflect and factor set-points
4.5	Final prototype
5	**COMPLETION PHASE**
5.1	First Draft
5.2	Revised draft
5.3	Presentation
5.4	Final draft
5.5	Oppose
5.6	Article

Appendix B Material List

A detailed material list of the equipment, software's and file settings used within the project.

Prototype development:

3D-printers:

- Duplicator i3 from Wanhao 3D Printer
- Creality3D Ender-5 PLUS 3D Printer from Creality
- ProJet MJP 2500 from 3D-systems

Test equipment:

Measurement microphone: GRAS 46BD

Mouth: GRAS 44AA Mouth Simulator

Air-flow generator: Air flow Generator (230 V, 50/60 Hz) from 3B Scientific

Speakers: Genelec 8020

Headphones: SRH940 from Shure

Audio recording and analysis software:

- Audacity
- APx500
- Adobe Audition

Format of audio files: 24-bit WAV with 48 kHz sampling rate and a scale factor of 0dBFS = 320 mVrms input signal via the AP analyzer.

Appendix C Test Instruction

This Appendix includes the test instructions that were included in all SIN tests, since the tests were made for Swedish participants, the instructions were written in Swedish.

”Du ska nu lyssna på totalt 20 korta ljudklipp. I varje ljudklipp kommer du höra en röst som säger en mening utan betydelse på engelska, en så kallad "nonsense sentence". Ett exempel på en sådan mening är “His base would shift with the stages”. Det kommer även vara en del bakgrundsljud.

METODIK:

Till den första frågan börjar du med att klicka på länken och lyssna på ljudklippet som poppar upp. Lyssna endast EN gång på filen.

Gå sedan tillbaka till formuläret och skriv vad du tror att rösten sa i svarstexten. Efter att du skrivit ditt svar får du INTE ändra det.

Till den andra frågan ska en bedömning göras på hur tydligt du tyckte att du hörde meningen som sades på en skala på 0-10. För denna bedömning är du tillåten att gå tillbaka till länken och lyssna på ljudfilen flera gånger om du önskar.

När du lyssnat och bedömt ett ljudklipp går du vidare till nästa avsnitt och upprepar processen.

Det första två ljudklippen är till för att öva.

Tack för din medverkan och lycka till!”

Appendix D Nonsensical Sentences

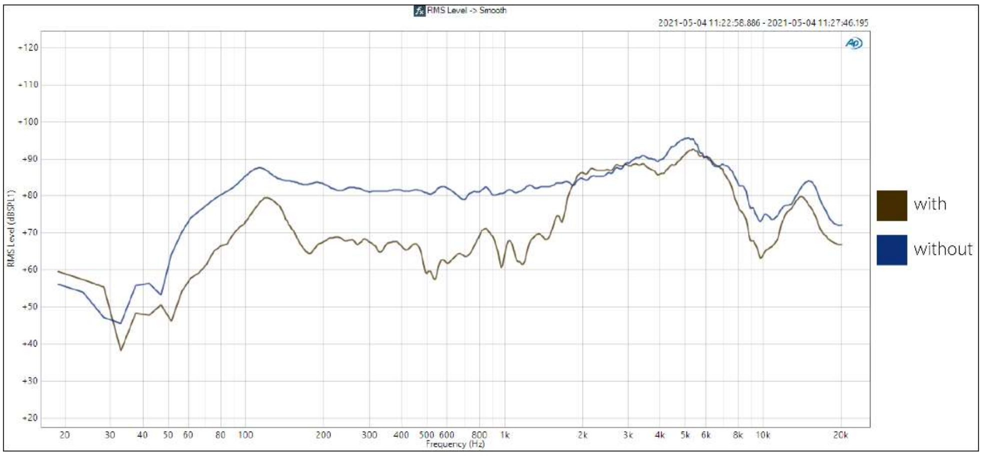
The nonsensical sentences used for speech-in-noise testing. Underscored words are the sentence's keywords.

Test cycle one	**Test cycle two**
The east stone can face your paste.	A debt can sweep up our lens.
His quick world must pass in a flag.	My doors can dance with her foods.
His slow screw may compete for our blames.	Our top throws at their fury.
Her lobby must drill the cook.	Her blind chain would stay at their cream.
Her dolls can crack on your turn.	Your tense chooses our merit.
The troop will tremble at his ring.	A manner tied in a notch.
Their loan may lift up our yells.	Their light should smooth his arm.
Our inn may convey his candles.	A cheese should stir in your zincs.
His bulb backed the neighbor.	Her sore spy cracked on his veil.
His book creeps to your brain.	Our brisk cheer would betray my track.
His green chests seek for her discounts.	Her temple strived for the planter.
Our big gains sink in his role.	Her blond shore grins at her manner.
The pixie could halt at his code.	A seat could warn my dolls.
Their hot protein can pace on our breakdowns.	Our deaf ads traced my ants.
Our friendships should sweep up the crack.	Their growths would rip my vectors.
A plan shaves her toll.	Their pail bails my tone.
The mounts bore his ladies.	My witty metal should blame his luck.
Our foreign course would spell your wax.	The new cross must engage the language.
Her mail wheels your fork.	Her gains nailed in their seed.
The evil lunch portrayed their sadness.	An award will attack her barge.

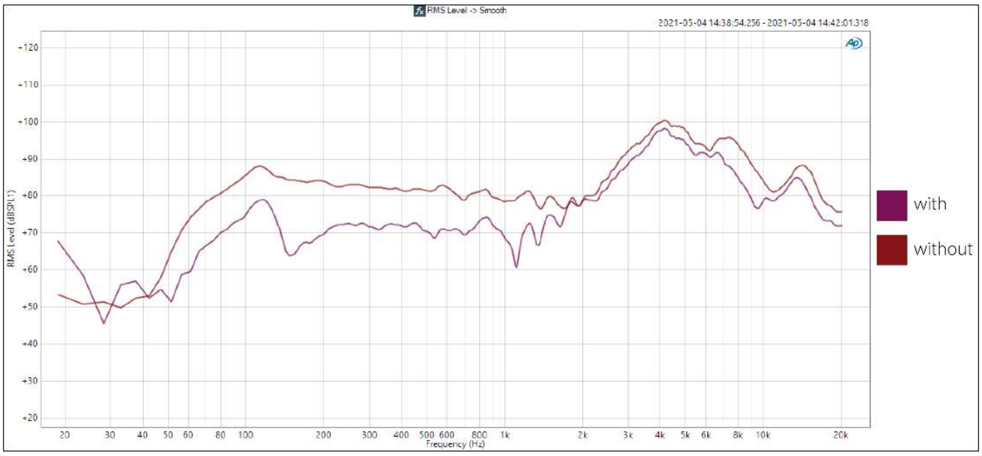
His drinks glow by a subject.	My orange evoked the pine.
Our doll smelled a beach.	Their wits will view a date.
A stark pea could glance at our blast.	His volume could repeat his warmth.
Your bark revised his thread.	A northern wake throws at your surge.
Their sleep decided on our outset.	Our proof can switch with a nephew.
Their hut elected my shortstop.	A landlord should proclaim to his fames.
The stand assists the drought.	His strange guy can help my seams.
My pea quotes their pig.	Our rabbits throw our lumps.
His travels show in our fear.	My merit could call to my mouth.
The plays would grumble at his thumb.	His last arm shakes at their case.
My bare cheer waves at her purse.	Her sick stand should see our strife.
His saints coped with our ban.	Your passion would gain her size.
His mobile sweater may dare our covers.	Their spectral steak screams at her hour.
Their guns bent to my tree.	My ledges stretch on a trust.
Your sad throw can warn the fight.	The grand bride will mind a help.
A debt can sweep up our lens.	Your perfect throat can bring in her tomb.
My doors can dance with her foods.	Our code could carry our gardens.
	Their curse will side with a squad.
	My minute storms would avoid the rug.
	Her beats shift with your peer.
	Your lush stone must fix his frontiers.

Appendix E Continuous Sweep of Final Concepts - Acoustic Vent

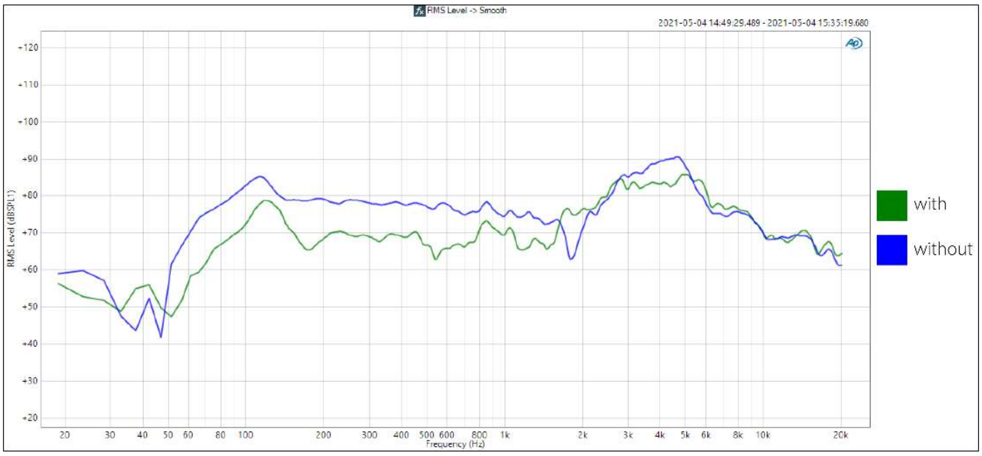
The following figures are showing frequency responses of sine-signal made through Continuous Sweep from the final concepts. The concepts were mounted on a wall and recorded the sine-signal both with and without presence of an acoustic vent.



E.1: Concept one: Conical port on the bottom edge of the intercom.



E.2: Concept two: Conical port with mesh on the front of the intercom.

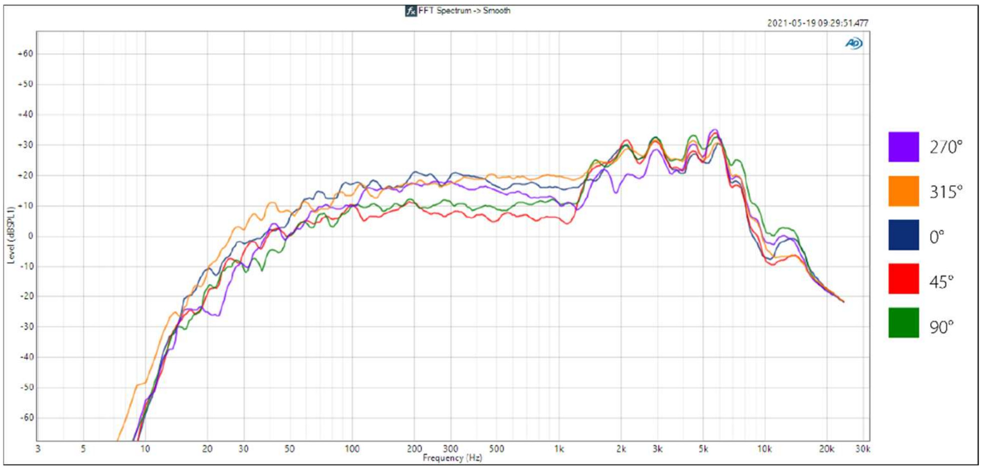


E.3 Concept three: Port on the front of the intercom following today’s guidelines of the company.

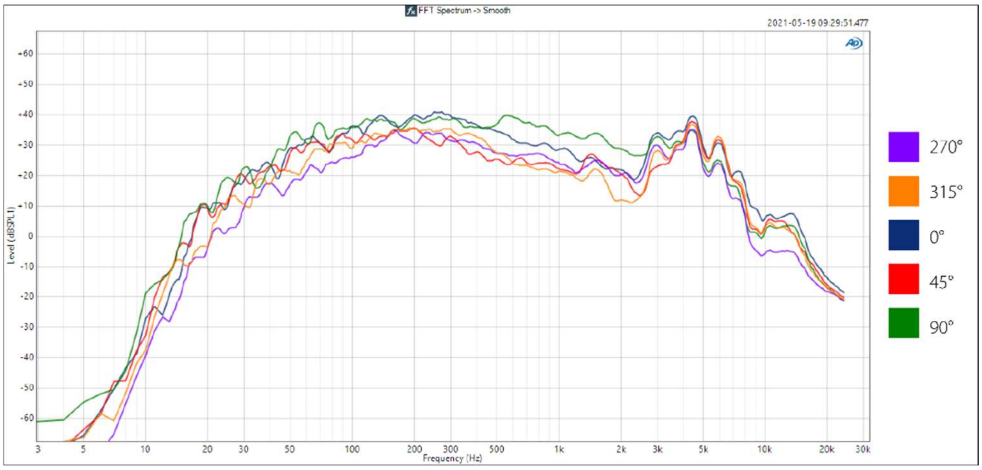
Appendix F Frequency Response of Wind Noise - Wind Direction

Following figures are showing A-weighted frequency response curves of wind noise only from each prototype exposed of wind in five directions.

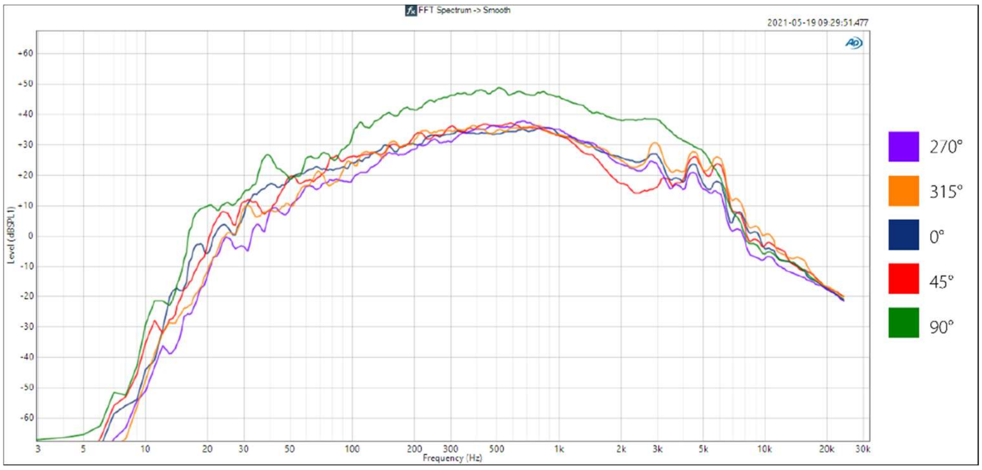
Concepts mounted on wall:



F.1 Concept one.

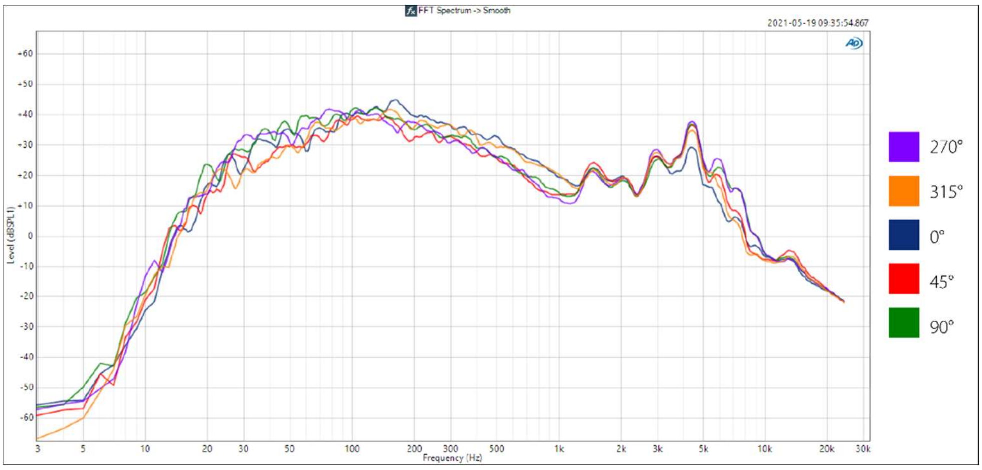


F.2 Concept two.

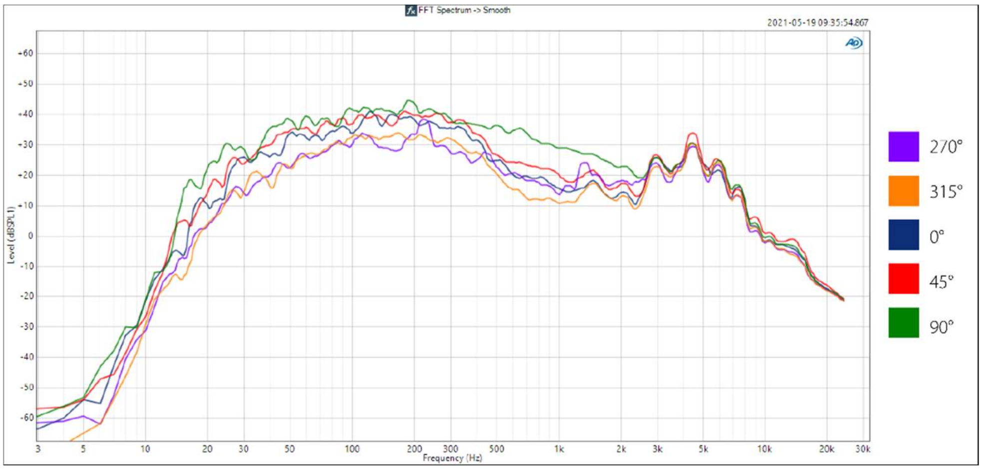


F.3 Concept three.

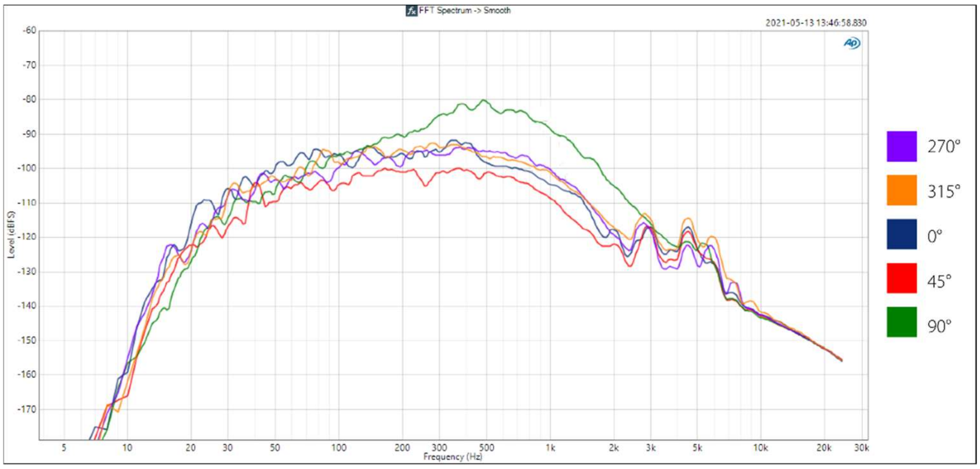
Concepts mounted on pillar:



F.4 Concept one.



F.5 Concept two.



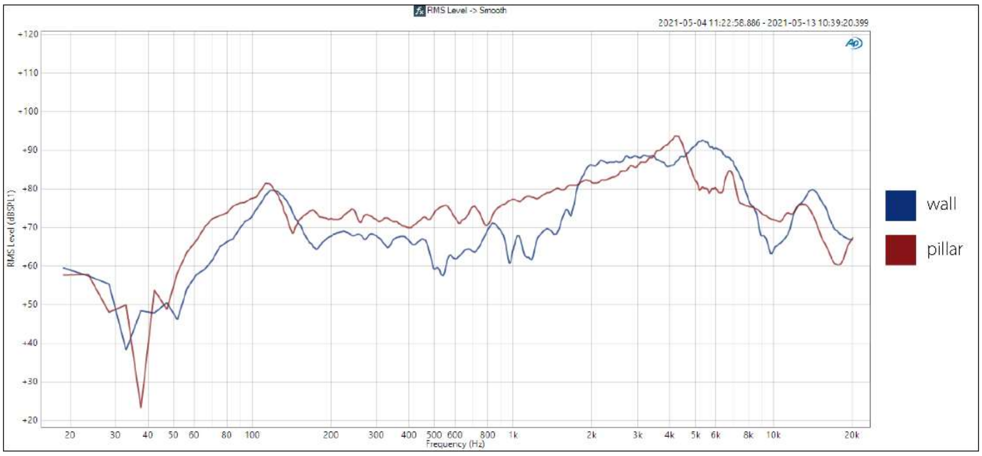
F.6 Concept three.

Appendix G Continuous Sweep of Final Concepts - Mounting

An analysis of mounting position changes for the three final concepts.

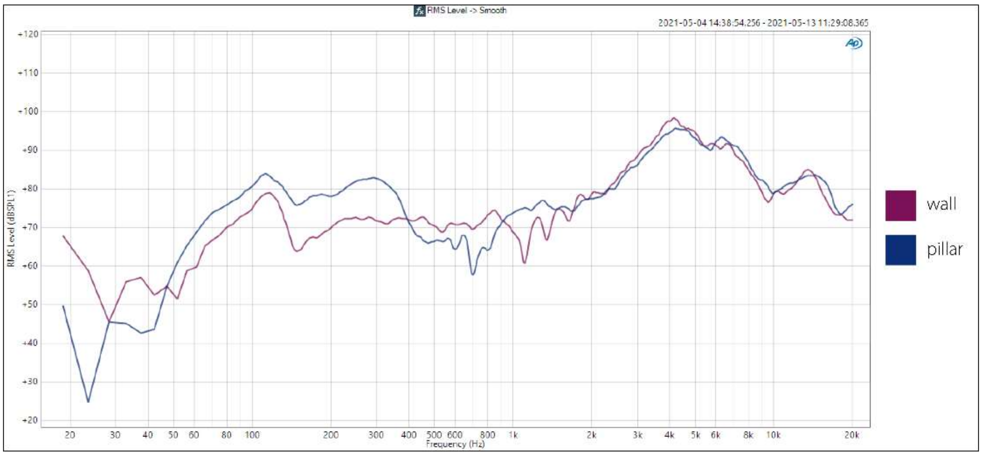
The impact of mounting was analyzed both through the A-weighted frequency response curves of wind noise presented in Appendix F and with figures in this chapter, created through Continuous Sweep. Figures G.1-G.3 belongs to a concept and contains two frequency response curves of the picked-up sine-signal only. One curve is the microphone's recording of the sine-signal when mounted on a wall and the other when mounted on a pillar.

For first concept, comparing the wind noise, it was shown in figures F.1 and F.4 that more wind noise was generated when mounted on a pillar than on a wall. For the wall, the volume of wind noise was approximately on the same level on the range of 100-2000 Hz, whereas when mounted on a pillar the volume was at a high level at 100 Hz and then decreased until 2 kHz. When looking at the sine-signal response in figure G.1 the curve when mounted on a pillar was most stable. The Continuous Sweep results could also confirm that the sounds of lower frequencies were more distorted in the wall mounting.



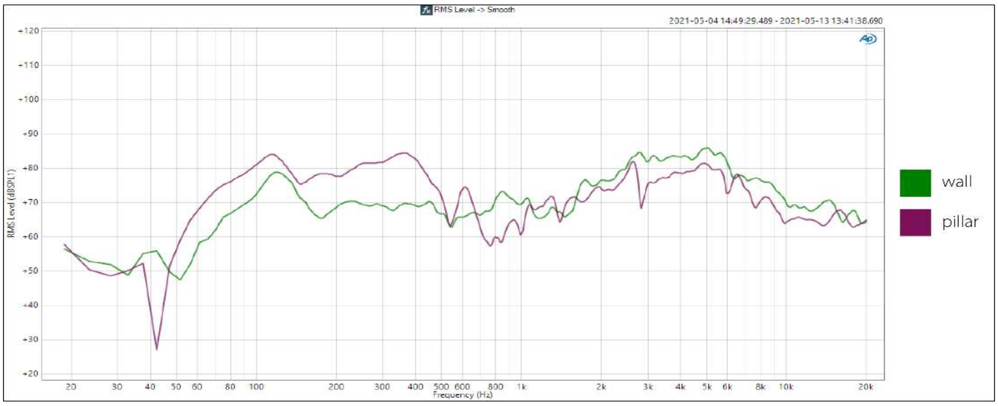
G.1 Concept one.

The second concept gave similar levels of wind noise in both mountings, except for a small difference in the frequencies of 500-2000 Hz where the pillar-mounted volume was decreasing slightly more, shown when comparing figures F.2 and F.5. Figure G.2, the responses of the sine-signal, was showing that both curves were approximately as stable and very similar in the range of 1.5-20 kHz. The results for concept two could therefore conclude that it performed in a good way and was relatively resistant to its mounting.



G.2 Concept two.

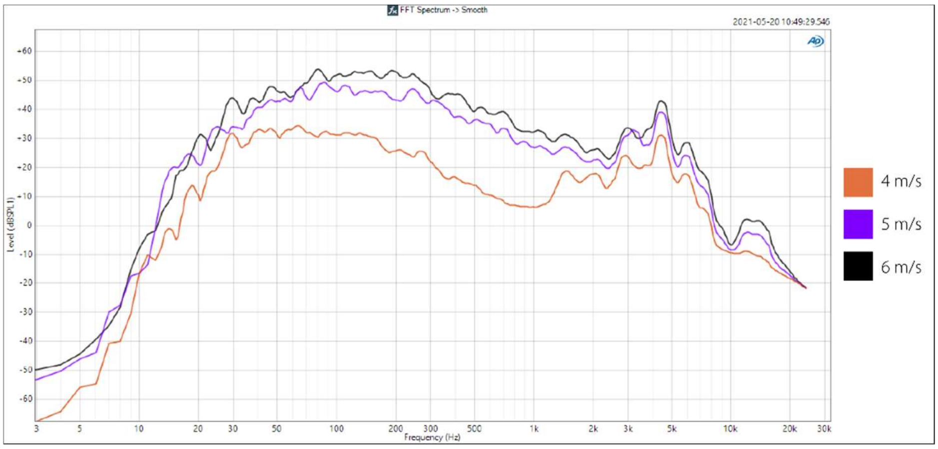
Lastly, third concept was giving similar results as concept two, shown in figures F.3 and F.6. The levels of wind noise were similar in both mountings except for a small difference in the frequencies of 1-2 kHz where the pillar-mounted volume was decreasing slightly more. The frequency response of sin-signals, presented in figure G.3, was showing two uneven curves but a more stable behavior when mounted on a wall than on a pillar. The sweep response in higher frequencies were also significantly lower when compared to the other concepts.



G.3 Concept three

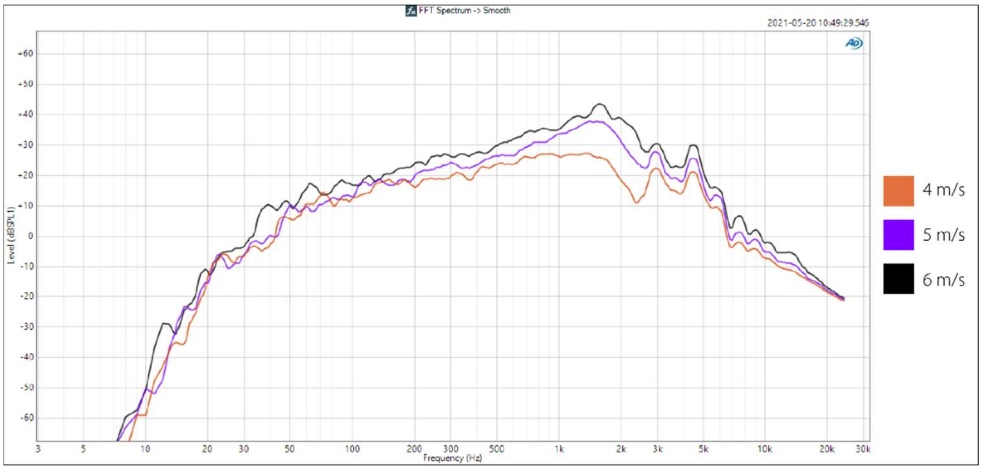
Appendix H Frequency Response of Final Concepts - Wind Speed

Following figures are showing A-weighted frequency response curves for each prototype mounted on a wall exposed of 0°-wind in three different speeds.



H.1 Concept one.

H.2 Concept two.



H.3 Concept three.