
Sound control in windy weather

Master Thesis
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Electronic Engineering and IT

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Preface

This report is composed by Jonas Buchholdt during the 10th semester of Electronic Engineering and IT at Aalborg University. The general purpose of the report is *Signal Processing and Acoustics* .

For citations, the report employs the Harvard method. If citations are not present by figures or tables, these have been made by the authors of the report. Units are indicated according to the SI standard.

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Glossary

AC Air Conduction. 3, 4, 25

ACE Air Conduction Earphones. 25

BC Bone Conduction. 3, 4, 25

BCT Bone Conduction Transducer. 3, 4, 25

FOH Front Of House. 11

HINT Hearing in Noise Test. 25

Chapter 1

Introduction

Human sound perception has typically been based on airborne sound for a majority of situations. However, bone conducted sound has been extensively used for diagnostic purposes [ISO 389-3:2016]. The main application of Bone Conduction (BC) is to perform pure-tone audiometries in subjects with hearing loss. In conjunction, with Air Conduction (AC) audiometry, it can be assessed, where the damage is situated. It has been established that BC circumvents the outer and the middle ear, which allows for conclusions based on a difference between AC and BC audiometry.

This medical use leads to the question of whether the use of BC could be extended further to day-to-day applications. This expansion of usage could range from leisure activities, such as music playback, to specialised usage, such as communications systems, that do not block the user's ears or conversely, that are used in noisy environments, where hearing protection is an imperative. With this objective in mind, the project at hand is proposed by RTX A/S, as foundational research for the usage of BC in communication systems.

The focus of the project is testing the feasibility of incorporating Bone Conduction Transducer (BCT) in communications equipment by comparing its performance with classic AC-based systems. However, there are different applications within this research area, such as utilising a BCT in order to not block the ear canals and maintain environmental awareness in high-risk situations (e.g. firefighters and law enforcement). Another possible application is to substitute AC transducers in equipment used in high noise level environments, adding the possibility to isolate the user's ears with both earplugs and protective headphones and thus reducing the risk of hearing damage (e.g. helicopter pilots and F1 mechanics). For any of these situations, the main concern is the assessment of intelligibility of the transmitted signal.

1.1 Problem Statement

It has been decided to constrain the scope of the project and focus on BCT use in noisy environments. Comparing its performance to the one of an AC-based system

in terms of a subject-based speech intelligibility test. In the course of doing so, the following aspects will be investigated:

- How does BC differ from AC in terms of speech intelligibility?
 - Which intelligibility test method is suitable for the task at hand?
 - Can it be ensured that the perceived level is the same for AC and BC?
- What types of BCT are available at the moment?
- Where should the BCT be placed?

Part I

Problem Analysis and Requirements

Chapter 2

Analysis of sound propagation in outdoor venue

2.1 Live venue sound challenges

This section is to explore the challenges of producing live concert in a outdoor venue. The challenge of producing a good sound experience for the audience will be analysed from the calibration of the system to the end of the concert. What is affection the sound doing the concert and does the calibration change over time.

2.2 Homogeneous atmospheric conditions

The aim of this section is to analyses the sound wave propagation in a homogeneous atmospheric conditions. It is well known that the propagation is highly depending on the atmospheric conditions, and the effect is not linear in frequency for some type of atmospheric condition. The wave propagation is highly depending on atmospheric pressure, wind temperature, humanity, where the two latter also is frequency dependent. The attenuation difference in frequency can be above 80 dB [Corteel et al., 2017]. The resulting attenuation is expressed as an frequency depending absorption coefficient in dB pre meter. The following sections will make a short introduction to the homogeneous atmospheric conditions effect on sound propagation. All section will be based on far field of the speaker, which mean that the spreading loss is 6 dB per doubling of distance, when the atmospheric conditions is excluded [Bauman et al., 2001], and a plan wave.

2.2.1 Humanity and temperature impact

The temperature and humanity has two impact on wave propagation, speed of sound and a lowpass effect. The following description starts with the latter. The effect of humanity and temperature is a lowpass filter, where it mostly not affect the low frequency. In other words, attenuation in the high frequency range per doubling of

distance in far field will depends not only on the spreading loss, but also on temperature and humidity. Therefore, for long distance, the atmospheric conditions has a high effect on the frequency spectrum delivered to the audience. The humidity and temperature attenuation is already well studied and standard [ISO 9613-1:1993] gives an overview of calculating the frequency attenuation with respect to the distance, temperature and humidity. The article [Corteel et al., 2017] gives some examples of attenuation at a distance of 100 m. The article [Corteel et al., 2017] shows, if the humidity increases proportional to the temperature, the lowpass effect is small. If the change in temperature and humidity is opposite of each other, for example the high temperature but dry, the attenuation in the high frequency is significant.

The second impact is the speed of sound. At temperature range from 0 °C to 40 °C the speed of sound with respect to humidity change is spars and mostly only depend on temperature change. The speed of sound is raises approximate by 0.6 m/s for every degree Celsius. The speed start at 331 m/s at 0 °C and 0 % humidity. The following TABEL show the speed of sound with respect to humidity and temperature.

2.2.2 Wind impact

The wind impact is complex and is not homogeneous with respect to sound source. The impact is depending on the angle of the wind direction with respect to the direction of sound propagation. When the wind gradient is going the same or opposite direction as the sound propagation, the relation between the speed of sound and the speed of wind is a linear system. Therefore the speed of wind shall just be added to the speed of sound. In all other cases the impact is complex since the wind deflect the sound waves.

2.2.3 Pressure impact

The effect of atmospheric pressure change is low compare to wind, humidity and temperature impact. The average attenuation from 4.0 kHz to 16.0 kHz with fixed temperature was 2 dB while going from 54.02 kPa to 101.33 kPa. The atmospheric pressure then only have a negligibility impact is on sound and is generally not frequency dependent.

2.2.4 Homogeneous speed equation

The following Equation 2.1 calculate the speed of sound based on temperature and wind speed.

$$c = u \cos(\theta) + 331 \sqrt{1 + t/273} \quad (2.1)$$

Where:

c	is the speed of sound	[m/s]
u	is the speed of wind	[m/s]
t	is the temperature	[°C]
θ	is the angle of wind with respect to the wave propagation	[°]

2.3 Inhomogeneous atmospheric conditions

The aim of this section is to analyse the sound wave propagation in an inhomogeneous atmospheric conditions. In an inhomogeneous atmosphere the pressure and speed are a function of position. By this fact, the modelling of sound wave is very complex and depend on various variable such as temperature and wind speed. The analysis will be limited to constant direction or a moment. Therefore wind turbulence is a subject for it self and will not be covered in this section. The following sections will make a short introduction to the effect at inhomogeneous atmospheric conditions. As in the previous section, it will be based on far field condition and a plan wave.

2.3.1 Atmospheric refraction

When the speed of wind, the temperature and humidity is assumed to be homogeneous in the sound field, the sound is travelling in a straight path. Often this is not the case, the wind speed increases logarithmically with the height from the ground to the geostrophic wind [Yang, 2016] and the temperature and humidity is inhomogeneous. The geostrophic wind is founded from approximately 1 km above the ground [Association, 2003]. In such situation the change of sound wave propagation is directly caused by the atmosphere temperature or wind gradient. This often result in a curved path of the sound wave and is defined as atmospheric refraction. For small distances, the atmospheric refraction have a sparse effect on the sound traveling path, because the speed of sound is much higher than the change by the wind and temperature. Generally distance up to 100 m is often assumed to have no significant refraction effect [de Oliveira, 2012]. For distances larger than 100 m the refraction is assumed to have a significant impact specially when the source and receiver is close to the ground. The refraction occurs because the temperature and humidity will change with respect to time along the day. The sun heats the ground, and when the sun set and the concert area is full of audience. The earth and audience radiate warm air, which make the air at a low height warm, but the temperature at a higher height cooler. As explained in section 2.2.1 the speed of sound depend on the temperature and therefore the speed of sound will in this situation decay with respect to height and result in an upwards refraction. The following Figure 2.1 illustrate the phenomena when the temperature decay with height.

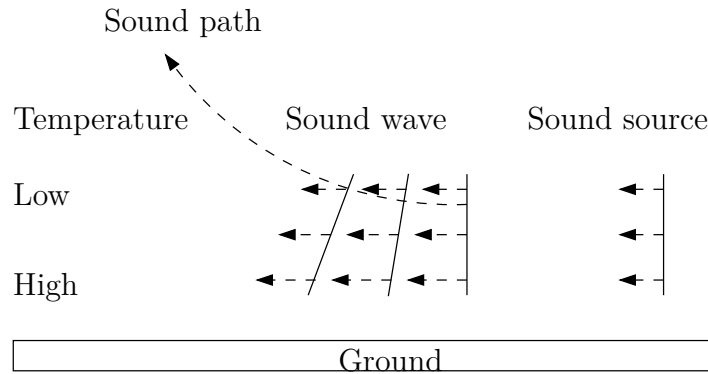


Figure 2.1: Wave refraction in inhomogeneous temperature

With respect to wind speed, a concert area is often a protected area with for example barrier, stage and building and so thourgth. This blogage slows down the wind speed close to the ground, and from the nature it self the wind speed is often raise with respect to the hight. When the stage is playing in along with the wind the the atmospheric refraction is down wards, where agenst the wind the atmospheric refraction will be downwards. The following Figure 2.2 shows the phenomena both against and with the wind.

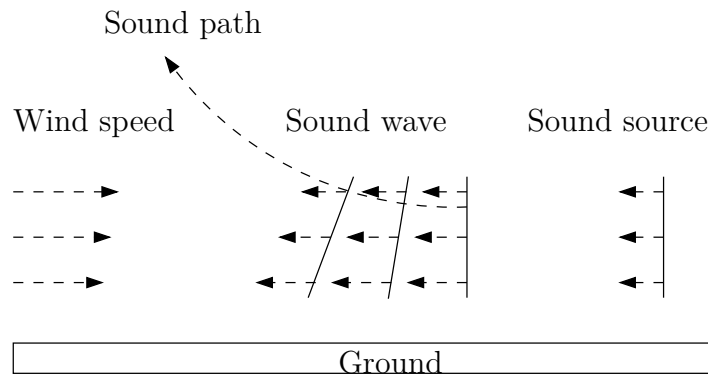


Figure 2.2: Wave refraction in inhomogeneous wind

Due to the refraction, the sound might propagate faster at the ground under the desriped condition. The consequence is a change for direction of the sound path bending upwards. This change of direction create whats called a shadow zone. This is a zone where the sound pressure from the source is zero as shown in Figure 2.3

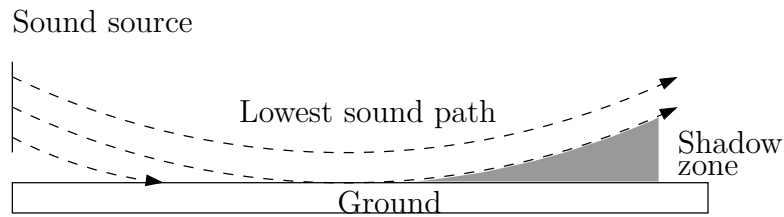


Figure 2.3: The figure illustrate the shadow zone ocourse from a up-wards refraction

The sound refraction will be identically for a omnidirectional source with respect to temperature, The refraction with respect to wind will depend on the wind direction. In Figure 2.3 the wind gradient is pointing in the oppersite direction of the shadow zone [Yang, 2016]. On the left side of the source the refraction will be downwards.

2.3.2 Crosswind

In the case of crosswind where crosswind is the wind gradient orthorgonal to the direction of wave propagation, the refraction is zero [de Oliveira, 2012].

2.4 Atmospheric condition at a concert

A concert sound system is often calibrated in the middle of the day when the stage is finished. The concert often starts in the evening and goes along to the late evening. at night the refraction goes the downwards direction

The concert area is dense packed with audience. The concert area might therefore be warmer nears the ground and cooles down with respect to the hight. This atmospheric condition refract the sound up in the air and not to the audience.

2.5 Calibration of sound system

This section analysis the calibration method, which is used by a selection of some Danish sound company. By expirience of the athor of this master projet, the hypothesis is that the sound system is calibrated in one point and the microphone is placed just in front of the Front Of House (FOH). The FOH is often a little tent, where the sound engineer control the sound system. The tent is only open in the direction of the stage and reflection might occore from the tent celling to the calibration microphone.

2.6 Sound pressure level measurement doing the concert

Chapter 3

Summary of Problem Analysis

Three effect of atmospheric conditions have been observed on the analysis, pure attenuation, lowpass effect and refraction effect

Chapter 4

Problem statement

Based on the knowledge founded in chapter 2 and the conclusion drawn from ?? a problem statement can be made. For the rest of the project the following will be the focus.

Is it possible by signal processing or physical adjustment with an line source array and an array of wind and temperature sensors to minimise the sound shadow zone created by atmospheric refraction. calculate the max distance before delay tower

4.1 Deimitation

The following deimitation is made for the search for a solution of atmospheric atmospheric.

Part II

Test Design

Chapter 5

Design

Part III

Results

Chapter 6

Results

Chapter 7

Discussion and conclusion

7.1 Conclusion

As stated in section 1.1, the main objective of this study is to assess the performance of a Bone Conduction (BC)-based communications channel, as compared with an Air Conduction (AC)-based one, in terms of intelligibility. In order to do so, it has been decided to design and perform a subject-based perceptual intelligibility test to obtain relevant data. However, extensive literature research about the matter of BC sound and the state of the art in transducers was needed beforehand. During the course of the project, the questions presented in section 1.1 have mostly been answered, and all relevant data for the final intelligibility evaluation has been extracted. Based on relevant literature, the RadioEar B81 Bone Conduction Transducer (BCT) was chosen for all subsequent applications placed on the condyle. A key point of the project has been finding a way of linking the perceived levels from both the BCT and the Air Conduction Earphones (ACE) for the intelligibility test. In order to do so, a level matching routine has been developed, and although it does not provide exact data about excitation of the basilar membrane caused by the BCT, it provides a framework in which the inter-subject assessment of intelligibility can be performed by looking at the relative performance difference for each individual subject. The final decision has been made on the type of test to perform. Based on the potential application and the background of the project proposal, the Hearing in Noise Test (HINT) was deemed to be most suitable both in terms of obtainable results as well as practical feasibility. This test is based on short sentences, that are unknown to the test subjects.

After analyzing the results from the HINT, it can be concluded that there is a tendency, that the performance of BCT regarding intelligibility might be worse than the performance of ACE-based systems. With the obtained data, this tendency could not be shown to be statistically significant. A higher variance of the performance of subjects could be observed for the BCT. However, the difference in performance appears not to be so drastic, so that the difference does not render BCT as an invalid option for communication applications. The performance could likely be further

increased by flattening the frequency response of the BCT with signal processing. Also a possibility of combining AC and BC in hybrid systems in order to increase the overall performance seems feasible as a subject of future research.

Part IV

Appendix

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