Development and testing of a demonstrator for an Acoustic Module for the IceCube Upgrade

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Abstract

The IceCube Neutrino Observatory is a cubic kilometer scale neutrino detector, capable of detecting neutrinos of energies ranging from a few GeV to PeV and above. IceCube-Gen2 is a planned large-scale upgrade to enhance the sensitivity for the highest energy neutrinos. As a first step, the IceCube-Upgrade is being prepared. It involves inclusion of additional sensor strings and calibration devices in the central detector region. IceCube-Gen2 will entail larger spacing of optical sensor modules, for which the current calibration scheme of the geometry by means of optical trilateration becomes challenging. As a promising alternative method, trilateration by acoustic signals is being developed. This system will consist of acoustic receivers tentatively planned to be incorporated inside the upgraded optical sensors-pDOMs, and standalone acoustic modules. The working principle of the acoustic system will be verified and optimized at shorter distances in agreement with the optical signals during the IceCube Upgrade. The concept and design of a demonstrator for the acoustic modules is presented in this work.
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Chapter 1

Introduction

The IceCube Neutrino Observatory is a detector built in the Antarctic ice at the South Pole. Its main purpose is the detection of neutrinos and characterization of their astrophysical sources [1]. This cubic kilometer scale detector has been a major contributor to the field of neutrino physics and multi-messenger astronomy.

Following its successes, a second generation of the detector IceCube Gen-2 has been proposed. It is expected to have approximately 10 times the existing detection volume resulting in a significant improvement in the sensitivity of the detector [2]. However, this extension entails a challenge in the geometry calibration of the detector due to the large distances involved. An elegant way to achieve a good calibration system is by taking advantage of the acoustic properties of ice. Previous experience with the South Pole Acoustic Test Setup (SPATS) [3] provided promising results supporting the use of acoustics in the Antarctic ice.

A first step towards the realisation of the second generation is the IceCube Upgrade [4]. This thesis is focused on the development of a demonstrator for the acoustic modules planned to be included in the IceCube Upgrade. The main aim of these modules is to achieve geometry calibration of the detector using acoustic trilateration independent of the currently used optical trilateration. It will be instrumental in providing a proof of concept and relevant data crucial for the design and optimisation of the future calibration system for IceCube Gen-2.

An overview of the existing detector and its geometry calibration is discussed in Chapter 2. A proposal of an acoustic calibration system for the upcoming Upgrade, along with a brief description of the operational principle is motivated in Chapter 3. An overview of the previously developed technology during the EnEx-RANGE [5] project which inspired the acoustic system, is also included in this chapter. The concept and realisation of the mechanical design of these modules with relevant considerations for their inclusion in the IceCube detector is presented in Chapter 4. Following the construction of the demonstrator, the measurements for its electrical characterisation are discussed in Chapter 5. Finally, the measurements performed for the acoustic characterisation of the demonstrator are presented in Chapter 6. A discussion of the obtained results and future possibilities is included in the final Chapter 7.
Chapter 2

IceCube Neutrino Observatory

The IceCube Neutrino Observatory is a cubic-kilometer detector built in the Antarctic ice near the Amundsen-Scott South Pole Station. Its primary goal is the detection of neutrinos and characterisation of their astrophysical sources in the universe [1]. Other science objectives include indirect detection of dark matter, searches for other exotic particles, studies of neutrino oscillation physics, and detection of the neutrino bursts from a Galactic core-collapse supernova [1].

2.1 Neutrino Detection

Figure 2.1: Demonstration of multi-messenger particle propagation; Neutrinos travel undeflected and unscattered pointing back to their sources [6].
Neutrinos are nearly massless elementary particles. They are electrically neutral and only interact weakly \[7\]. Due to these characteristics, they act as important carriers of information as they arrive undeflected and unscattered from their places of origin \[8\] (see Fig. \[2.1\]). Due to this small interaction cross-section and low fluxes expected at Earth from astrophysical objects \[9\], large scale detectors are required to detect a significant number of neutrinos.

The IceCube detector uses the phenomenon of Cherenkov radiation to detect neutrinos \[10\]. While traversing the volume of the detector, although very rarely \[9\], secondary charged particles are produced from neutrino interactions with the molecules of water in the glacial ice. These secondary particles are responsible for the Cherenkov light detected by IceCube.

While propagating through an optically transparent dielectric material, a charged particle polarizes the medium locally. When the velocity of this charged particle exceeds the speed of light in the medium, i.e, \[\beta > 1/n\], a net polarisation appears in the form of a distinctive, conically shaped wavefront with respect to the traversing particle. This emission of electromagnetic radiation is called Cherenkov radiation \[11\]. The concept is briefly demonstrated in Fig. \[2.2\].

![Figure 2.2: Charged particle moving at relative velocity \(\beta = v/c > 1/n\); In given time \(t\), photons traverse a shorter distance than the charged particle resulting in light emission in conical shape \[12\].](image)

### 2.2 In-Ice Array

The IceCube Neutrino Observatory consists of a subsurface in-ice array comprising of Cherenkov light detectors suspended on vertical strings as shown in Fig. \[2.3\] \[1\]. It also includes a more densely instrumented DeepCore sub-array, and the IceTop surface array allowing it to serve as a multipurpose experiment \[1\].
2.2. IN-ICE ARRAY

Figure 2.3: The IceCube detector in-ice array; The air shower array, IceTop at the top and the densely instrumented sub-detector DeepCore in the middle region are included. The positioning of the strings in a hexagonal pattern can be seen [13].

The in-ice array consists of 86 strings deployed between 1450 m to 2450 m below the surface of the Antarctic ice, each consisting of 60 Digital Optical Modules (DOMs) with 17 m spacing. These modules are the Cherenkov light detection units [1]. The strings are positioned in a hexagonal pattern, strategically placed to instrument a volume of one cubic kilometer of ice. The detector is suitable for detection of neutrinos from tens of GeV to PeV energies [1].

The DOMs, as shown in Fig. 2.4, are essentially glass pressure spheres containing a 10″ photomultiplier tube (PMT) each, along with embedded high-voltage generation, a light-emitting diode (LED) flasher board and a main board containing the analog and digital processing circuitry for PMT pulses [14]. The PMT is encapsulated by a mu-metal grid to shield magnetic fields and is optically coupled to the glass vessel with room temperature vulcanizing (RTV) gel [14]. Digitized timestamped PMT signals sent from the DOMs on detection of light are recorded and analysed at the surface.
The DeepCore sub-array is responsible for the detection of low energy neutrinos on the order of 10 GeV. It is situated at the bottom center of the existing In-ice array \cite{16}. The module density in DeepCore is about five times higher compared to the rest of the array. It uses the surrounding array to veto against the copious downward-going cosmic-ray muon background \cite{16}. IceTop is an extensive air shower array on the surface of the IceCube detector. It consists of Cherenkov tanks filled with ice, each containing two DOMs. These tanks are used to detect showers of secondary particles generated by interactions of high-energy cosmic rays in the atmosphere \cite{17}.

The IceCube detector has been a contributor of major successes in the field of neutrino physics. Two of the many achievements include the first detection of astrophysical neutrino flux in 2013 \cite{2}, and a high energy event of 290 TeV suspected to come from a blazar TXS+0506-056 in 2017. The latter was also found to be coincident in time and direction with gamma ray flare from this source \cite{18} leading to the exciting advancements in the field of multi-messenger observations. The number of high energy neutrinos measured, however, is limited by the current operational volume of the detector. In order to improve our understanding of the sources of the observed neutrino flux, a significant increase in the detected events is required. This can be achieved by an increase in the instrumented volume of the detector \cite{19}. For this purpose, a second generation, IceCube-Gen2 is proposed (see Sec. 2.3).

## 2.3 IceCube-Gen2

IceCube-Gen2 is planned as a substantial enhancement of the existing detector by an approximate order of 10 in size. As a consequence, it will significantly improve the sensitivity of the detector to high energy neutrinos of all flavours \cite{2}.

IceCube measurements show that the absorption length of Cherenkov photons detected by the DOMs is greater than 100-200 m. This makes it possible for the next generation array to have
new strings at greater distances, leading to a greater instrumentation volume at comparable costs to the existing infrastructure. Modifications are planned which will realise improvements focused on modernization, efficiency, and cost savings [2]. Various new components are planned to be included in the IceCube-Gen2. While a radio array will be devised to detect cosmogenic neutrinos exceeding 100 PeV, a large upgrade of IceTop surface array [20] will be included for vetoing the air-showers. Furthermore, a dense infill in the DeepCore region, PINGU [21], for precision measurements of the atmospheric oscillation parameters and the determination of the neutrino mass hierarchy will lower the threshold further to a few GeVs. The fate of the IceCube-Gen2 has not yet been finalised, and changes to the presented plan can be expected. However, a first step towards the second generation, IceCube Upgrade, is in motion.

2.3.1 IceCube Upgrade

The first step towards the realisation of IceCube-Gen2 is the IceCube Upgrade, planned to be deployed in 2022/23 Antarctic summer. Seven new strings will be deployed in the already dense area of the Deepcore infill region with a decreased string spacing of 20 m. The light sensors will be placed at a distance of 3 m in contrast to the existing 7 m in the DeepCore, along each string (see Fig 2.5), with approximately 700 sensors in total [22].

![Figure 2.5: Footprint of the detector magnified at the DeepCore region. Red dots depict the new strings for the Upgrade [22].](image)

The Upgrade has a two-fold objective: improvement in the calibration of the detector, and enabling better reconstruction due to increased light detection [4]. The DeepCore is responsible for lowering the energy threshold due to decreased string and DOM spacings. The new strings which will have three times smaller spacing will therefore, contribute to a significant
improvement in IceCube’s performance at the lowest energies [4]. Furthermore, the decreased vertical spacing between the light sensors will facilitate improved understanding of the optical properties of the glacial ice.

New and improved optical modules namely, the mDOMs (multi-PMT DOMs), an upgrade of the existing light sensors, the pDOMs and the Dual optical sensors in an Ellipsoid Glass for IceCube-Gen2 D-Egg, will be installed in the physics region of the Upgrade. They are designed to improve the detection efficiency and calibration capabilities of the detector [22]. Other special devices like POCAM, radio sensors, fibre-communication module, acoustic modules and pencil beam etc. will also be a part of the Upgrade [22].

2.4 Detector Calibration

In the existing IceCube detector, apart from PMTs for light detection, DOMs are also equipped with flasher boards consisting of twelve 405 nm LEDs [23]. This board is used to emit controlled light flashes to be detected by the rest of the array. These flashes are used for calibration of the DOM positions with the time of arrival of light pulses, and an improved understanding of optical properties of the ice [1]. Other calibration devices include Sweden cameras for understanding the optical quality of the refrozen ice, dust loggers for determination of the stratigraphy, inclinometers, and standard candles [23].

2.4.1 Geometry Calibration

The geometry of the detector is determined with the help of data collected while drilling and construction of the detector. The sideways displacement of the DOMs along a string is considered to be small and hence, the surface location of the drill hole is taken as the co-ordinates for the DOMs [1]. Additionally, as the DOMs are placed at fixed positions on the strings, the depth of each string is corrected by an offset with respect to the reference co-ordinate system at the surface of the drill hole. From the flasher data the depth offset is further corrected using inter-string flasher timing measurements [23]. This offset varies for each string, but typically lies within 0.2 m [1]. The concept of trilateration is used for this offset correction with the help of the flasher data. For the whole detector volume, the absolute uncertainty in the vertical positioning is 1 m [1].

Although the default geometry assumes perfectly vertical strings, from the Bachelor thesis by Lilly Peters [24], potential problems were identified with this approach. As shown in Fig. 2.6 obtained using the position data of a bore hole, the deviations in the x and y co-ordinates is presented. This deviation from the ideal geometry influences the muon track reconstruction by atleast 1° [24]. Additionally, these uncertainties are expected to become more significant for the Upgrade because of the decreased string spacing. Therefore, an improvement in the geometric calibration of the detector is essential.
2.4. DETECTOR CALIBRATION

Figure 2.6: Borehole data from hole 4 with DOM positions [24]; The DOMs are not plotted to scale.

2.4.2 Upgrade

As discussed earlier, one of the main objectives of the Upgrade is improvement in calibration of the IceCube detector. Therefore, various calibration devices are planned to be included in the Upgrade. The new optical modules mDOM’s and D-Egg’s will also contain many new calibration devices, apart from the improved detection machinery. These are fast LEDs, CCD cameras [25], on-board pressure, temperature, magnetic field sensors, and accelerometers [22].

In addition to those enclosed inside the optical modules, many standalone calibration devices on the new strings are also planned as a part of the Upgrade. These will include optical devices namely POCAM [26] and pencil beam, as well as acoustic modules [27]. The tentative plan of the placement of all the modules in the upgrade is shown in Fig. 2.7. The physics region which spans from 2100-2400 m will be densely instrumented with these modules.
Figure 2.7: Positioning of the devices on the new strings in the physics region for the Upgrade [28]
2.5 Motivation

For IceCube Gen-2, the string spacing is expected to be as large as 300 m [2]. As previously stated, the current geometrical calibration involves optical trilateration using the flasher data for offset correction in the z-direction. For Gen2, this optical trilateration is expected to be insufficient for such large string spacing because of the limit of $\approx 200$ m on the absorption length of the optical signals [1].

A promising alternative for the geometry calibration of the detector is acoustic trilateration due to the large attenuation lengths of acoustic signals. Based on the findings of the South Pole Acoustic Test Setup (SPATS) [3], the attenuation lengths of the acoustic signals have been measured to be 300 m in the Antarctic ice. In addition, the acoustic modules can also be instrumental in the detection of transient signals from the ultra-high energy neutrino events [29].

An acoustic calibration system consisting of acoustic modules and sensors is being developed by the IceCube group of Physics Institute IIIB at the RWTH University, Aachen. This thesis is focused on the development of a demonstrator for the acoustic modules. The main objective of these modules will be geometrical calibration of the detector array independent of the optical calibration devices. These acoustic modules will be deployed in the Upgrade in order to demonstrate the acoustic calibration at a comparable or even smaller uncertainty compared to optical data.
Chapter 3

Acoustic Calibration System

The acoustic calibration system is being developed with the aim to achieve a spatial resolution of the order of $\approx 10\,\text{cm}$ for positioning of the optical modules, which is comparable to the resolution expected from optical calibration in the dense region of the Upgrade. Implementation of the acoustic calibration will provide an independent system for verification of the existing calibration, and facilitate an improved system for large distances concerning the whole volume of the detector [27]. Finally, as motivated in the previous chapter, the acoustic calibration will be useful for IceCube-Gen2 scale distances. Therefore, implementation of the acoustic calibration system in the upcoming Upgrade will provide an important proof of method and relevant data for the in-situ performance that are crucial for the design and optimization of the future system for IceCube-Gen2 [27].

This chapter will briefly present an overview of the acoustic system in Sec. 3.1 along with a description of the calibration concept in Sec. 3.2. Furthermore, the previously developed technology which inspired such a system will also be discussed in Sec. 3.3.

3.1 System Overview

The Acoustic Calibration System will consist of a network of acoustic modules and sensors. While the acoustic modules are planned as standalone devices, the sensors are tentatively expected to be included in the improved versions of the existing light detectors, pDOMs. The acoustic modules will be designed for the dual purpose of emitting and receiving acoustic signals. The sensors, on the other hand, will be able to detect acoustic signals from these high power acoustic modules [30] spread out throughout the Upgrade volume. The system, as a whole will use the concept of trilateration of the measured propagation times of the acoustic signals for position reconstruction. This will provide an improved and complementary geometry calibration with respect to the previously used methods that are based on optical trilateration [27].

As presented previously in Fig. 2.7, the new strings in the Upgrade will host a number of special devices. They are all mainly situated in the physics region at the depths between 2150 m and 2425 m, where the glacial ice is the clearest and the atmospheric muon background is low [22]. Fig. 3.1 presents a more detailed version of the proposed placement of the devices on the Upgrade strings. The acoustic modules and pDOMs have been distinctly marked in the figure. The acoustic modules will be strategically positioned in order to cover the whole volume.
CHAPTER 3. ACOUSTIC CALIBRATION SYSTEM

of the detector. Each string will include one acoustic module, in the physics region. Three additional modules will be placed in the non-physics region for glaciology measurements and acoustic positioning at greater distances apart from the dense physics region. The modules are also planned to be placed near the optical calibration devices, POCAMs in order to achieve a direct co-relation of the optical and acoustic propagation times and hence, position reconstruction [27].

This thesis will give a detailed description of the design and development process of a demonstrator for the acoustic modules as acoustic emitters.

Figure 3.1: The placement of acoustic emitter modules on the Upgrade strings; The acoustic modules are shown with black arrows, while the pDOMs are encircled. The x-axis is depicting the new string numbers [28].
3.2 Trilateration

The acoustic calibration is based on the geometrical concept of Trilateration. It is the process of determining absolute or relative locations of points by measurement of distances. It is commonly used for surveying and navigation, including global positioning systems (GPS) [31].

Using this concept, the three dimensional co-ordinates of a point located at the intersection of three causality spheres (with known centres and radii) can be deduced. A 2D projection to explain the concept is shown in Fig. 3.2. The known positions and radii have been shown as \((x_i, y_i, z_i)\) and \(r_i\) respectively. The unknown position \((x_R, y_R, z_R)\) can then be deduced using a system of equation describing the three spheres [32].

\[
\begin{align*}
    r_1 &= \sqrt{(x_R - x_1)^2 + (y_R - y_1)^2 + (z_R - z_1)^2}, \\
    r_2 &= \sqrt{(x_R - x_2)^2 + (y_R - y_2)^2 + (z_R - z_2)^2}, \\
    r_3 &= \sqrt{(x_R - x_3)^2 + (y_R - y_3)^2 + (z_R - z_3)^2}.
\end{align*}
\]

Figure 3.2: Trilateration with unknown position \((x, y, z)\), and three known spheres with co-ordinates \((x_i, y_i, z_i)\)

Assuming that sound propagates spherically in homogeneous ice, we can localise acoustic modules using this concept. In the acoustic calibration system, the individual acoustic modules and sensors act as the points with unknown co-ordinates while localisation. In that case, the sound fronts generated by the rest of the modules can be described as the intersecting spheres. The modules or sensors being localised detect the time of arrival of the signals emitted by the rest of the modules. The distance traversed by the acoustic signals is then deduced using \(d = c \cdot t_n\), where \(c\) is the speed of sound in ice and \(t_n\) are the times of arrival from \(n^{th}\) modules. Although, the positions of the modules are predetermined while deployment, there is still an uncertainty involved in their positions and mutual distances between two modules. The speed of sound also varies with the quality of ice and hence, acts as an additional degree of freedom. As a result,
atleast five intersecting spheres are required for the positioning of such a system. Furthermore, all modules have a limited range due to the attenuation of the acoustic signals in ice.

An over-constrained system is desired for a good position reconstruction. The over-constraintment facilitates a multi-trilateration, where multiple time of arrivals from many emission positions result in redundant measurements. It also allows for reduction of uncertainties by minimisation of errors in the measurements. A $\chi^2$-minimisation can be used for this purpose.

### 3.3 State of the Art

The EnEx group at RWTH Aachen, was involved in the EnEx-RANGE project [5] of the German Space Administration during which a system for navigating melting probes in glacial ice was developed. This project is a part of a large scale future space mission with the aim to send an autonomous lander to the Saturn moon, Enceladus, in order to extract water samples expected to be found beneath its icy surface [5]. During this project, a total of 13 Acoustic Positioning Units (APUs) (see Fig. 3.3) were developed at the RWTH University in close collaboration with IMA & IfU Cybernetics lab. Multi-trilateration was implemented using these units to perform acoustic positioning of a melting probe called the IceMole developed in a previous project. The positioning system is shown in Fig. 3.4. Multiple APUs melt through the ice and are positioned at different locations. The times of arrival of the acoustic signals is then used to determine relative distances and finally, trilaterate the position of the probe.

![Figure 3.3: The Acoustic Positioning Units developed during EnEx RANGE](image)

![Figure 3.4: Trilateration of the IceMole with several APUs](image)
The APUs consist of various subsystems ranging from a melting head and monitoring system to acoustic sensors and pinger system. The acoustic modules for IceCube were inspired from the pinger system of the APUs. A cross-sectional view of the pinger in the APUs is shown in Fig. 3.5.

Figure 3.5: A cross-sectional view of the APU pinger \[33\].

It comprises of a mechanical transducer attached to the front of the APUs. It is based on the concept of a Tonpliz body force transducer, which will be discussed in detail in Sec. 4.2. The melting head of the APUs is used as area of contact with the acoustic medium for emission of sound. A drive stack of 8 piezo discs is used to convert the supplied electrical energy into sound energy. The heavy body mass along with a dedicated middle mass, is cleverly instrumented for high acoustic output. Finally, an additional circuit allows the pinger system to act as an acoustic receiver.

The positioning system developed during the project EnEx-RANGE was successfully tested in many field tests that took place on glaciers \[33\]. Due to its application in ice medium, it is expected to work quite favourably for the purpose of IceCube detector calibration. The technology developed during this project inspired the acoustic calibration system for IceCube.
Chapter 4
Mechanical Design

The design of the Acoustic Modules is based on the APUs developed in the EnEx project. Various modifications to the APU design have been made in order to obtain a suitable system for IceCube. This chapter will entail a brief description of these design considerations (see Sec. 4.1) and present a design for a demonstrator of the acoustic modules (see Sec. 4.3). A method for characterising the emitter system using an electro-mechanical equivalent circuit will also be discussed (see Sec. 4.2).

4.1 Design Considerations

4.1.1 Operational Environment

The modules should be able to withstand extreme environmental changes during shipping, storage, deployment and finally, operation in the Antarctic ice.

The temperature change is quite significant for different stages. While shipping, the temperatures might be as high as 40\(^\circ\)C, whereas storage at Antarctica requires a temperature tolerance of about \(-50\)\(^\circ\)C \[1\]. At deployment, the emitter modules are lowered into the drilled holes where the temperature slowly decreases after refreezing, to approximately \(-30\)\(^\circ\)C \[1\]. Additionally, modules are required to be operational at room temperatures for assembly and preliminary tests. Therefore, the modules are developed to withstand a range of -50 to +40\(^\circ\)C.

A maximum static pressure of 250 bar is applied on the devices due to the surrounding ice during operation. This is approximately equivalent to 2.5 km of water depth \[1\]. However, a pressure of up to 690 bar acts on the devices during the refreezing of the melted ice in the drill holes \[1\]. The modules should, therefore, be developed to withstand approximately 700 bar of pressure. The dimensions and materials of the modules should be suitable for this pressure range, but also convenient for handling and shipping, e.g., the weight of each module should not exceed 20 kg.

Additionally, random shocks and vibrations can be caused due to unpredictable motion while shipping of the modules. In the final stage or quality check, the modules should be tested for 5 G vibration and 5 G shocks in order to prevent any damage \[31\].
4.1.2 Performance Requirements

As established previously, the acoustic modules along with the expected acoustic receivers in pDOMs, should be able to determine the positions of the optical modules independent of the optical calibration devices. They will function as both- acoustic emitters and receivers, in order to perform these position measurements.

The power consumption should be carefully monitored and minimised for each module deployed at the IceCube detector due to limited resources. A predefined limit of 5 W has been provided for each module \[35\]. This is enough for a continuous operation for the calibration measurements. However, it is also advantageous to have a burst operational mode in which signals are sent for a short amount of time at high power. In case of a burst mode, storage capacitors will be used to store the provided 5 W power for a short amount of time before the burst cycles. When not in operation, the standby mode will be provided for the modules in order to minimise consumption to as low as 0.5 W.

Another important factor of consideration is the frequency range of operation. A range of 5-40 kHz was chosen for the acoustic modules. A wide bandwidth as well as high gain is desired for the receivers, while a high output acoustic power is essential for the modules. The attenuation length of sound in ice decreases with increase in frequency resulting in a low gain \[36\]. Therefore, a 40 kHz upper bound on the frequency range is chosen. Additionally, characterisation of the modules at lower frequencies can be challenging because of the limitations on the achievable signal to noise ratio due to the electronics.

In order to obtain a good resolution on the position measurements we need a synchronous timing of the system. An uncertainty of about 28 µs in the clock time, leads to a calculated position uncertainty of about 10 cm for a speed of 3500 m/s \[32\] in ice. Therefore, an accuracy of at least 10 µs has been chosen for the modules.

The position measurements should be carried out for large distances of up to 200 m in order to communicate with the modules at distant strings. Since, the modules are also placed at different depths in ice, the emitted signals should be omni directional in order to cover the whole volume of the detector. An elaborate description of the design considerations can be found in the internal documents \[34\].

4.2 Tonpilz Transducer

A Tonpilz transducer is a piston-type transducer which is typically operated in the frequency range of 1-50 kHz \[37\]. A cross-section of a Tonpilz transducer is shown in Fig. 4.1. The main components include:

- Drive stack: consists of four piezo rings stacked with alternating polarities with electrodes sandwiched between them
- Tail mass: a heavy mass typically made of steel
- Head mass: comparatively lighter than the tail mass, typically made of aluminium
4.3. MECHANICAL DESIGN

- Threaded bolt (Pretension rod): applies pretension to the drive stack
- Housing: protects the inside electronics from external pressure

The alternating voltage applied to the driving stack leads to compression and expansion of the piezo discs due to the piezoelectric effect \[38\]. As a consequence, the electrical energy is converted into mechanical energy which leads to movement of the tail and head mass. The kinetic energy of these masses gets transmitted in the form of acoustic signals into the medium in contact. Since, the head mass is lighter, it moves with a greater velocity compared to the tail mass. The tail mass is confined inside the housing, where it dissipates energy into air. The head mass is coupled to the acoustic medium and emits sound into the medium. Hence, a heavier tail mass facilitates more acoustic output. A tail to head mass ratio of 2 to 4 is normally used \[39\].

![Cross sectional view of a Tonpilz transducer](image)

**Figure 4.1: Cross sectional view of a Tonpilz transducer** \[33\]

### 4.3 Mechanical Design

Each component of the demonstrator was 3D modelled using a CAD software called Autodesk Inventor\(^1\). Various characteristic features for preliminary studies and design, e.g. weight, dimensions etc, were deduced from these models. The individual parts were then assembled to obtain a final demonstrator design. The mechanical design process consisted of two iterations: In the first iteration elementary alterations to the APU pinger were made to obtain a design for a primary working system. In the second iteration the design was further improved to obtain a demonstrator realisable for laboratory measurements.

\(^1\)AutoCAD is a registered trademark, in the USA and other countries. This work is independent of Autodesk, Inc., and is not authorized by, endorsed by, sponsored by, affiliated with, or otherwise approved by Autodesk, Inc.
4.3.1 Design Concept

The demonstrator design was based on the Tonpilz transducer (see Sec. 4.2) similar to the emitters of the APUs. The head mass was considerably simplified as the melting head was no longer required. The tail to head mass ratio was designed to be to 2:1. Additionally, Belleville washers were introduced for uniform distribution of the pretension torque. In order to achieve pressure tightness, the thickness and material of the pressure housing were also changed. The design developed during the first iteration is shown in Fig. 4.2.

The main components included a pressure housing, a stainless steel tail mass of 5 kg and a head mass of 2.5 kg and a driving stack. The driving stack consisted of eight piezo discs of material Sonox P4 by CeramTec [40], stacked together with opposite polarity. Copper electrodes of thickness 0.3 mm were sandwiched between the piezo discs to which an alternating input voltage could be applied. An M14 threaded rod was used to apply mechanical pretension to hold the piezo disks under compression, by applying a torque of 70 Nm on the pretension nut. This was done to prevent unwanted dynamic effects like shear, and bending stresses etc. [41]. The stainless steel pressure housing was designed to be 100 mm in diameter and 400 mm in height, with a thickness of 15 mm. The thickness of the pressure housing was determined by stress calculations for a given outside pressure using Lamé’s equations [42]. With this thickness the demonstrator would be able to withstand an external pressure of up to 250 bar. Further improvements with respect to pressure requirements can be achieved by using thicker material which has a greater yield strength for future iterations for acoustic modules [43].

The demonstrator would inhabit a mechanical transducer, along with the electronics including the high voltage driving circuit, a circuit for communication to the surface etc., in the empty space above the threaded bolt, as shown in the Fig. 4.2. Six o-ring seals were included in the system to make the system pressure tight. Groves were introduced on the tail mass, the end cap, and the head mass for these O-rings. Holding screws of size M4 were incorporated for assembly purposes, see Fig. 4.3).
4.3. MECHANICAL DESIGN

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4.3.2 Demonstrator

Following the conception of the design idea for the demonstrator in the first iteration, many improvements were immediately introduced. The previously obtained design was further simplified, in order to obtain a system fit for laboratory measurements. The improvements introduced during the second iteration are listed below:

1. The tail mass was decoupled from the hull completely in the second iteration. This was done to avoid direct coupling of the tail mass to the head mass due to high external pressure.

2. The structure of the head mass was further altered to a cylindrical disk like structure, almost identical to the end cap. This allowed for a lighter head mass, and a better head-to-tail mass ratio.

3. The number of o-rings required was reduced to four, decreasing the possible points of failure and improved convenience in construction.

4. The number of piezo disks was increased to sixteen and the pretension applied on the stress rod was increased to 100 Nm, for an optimal output admittance as suggested by preliminary measurements.

The improved design as a result of the second iteration can be seen in Fig. 4.4. The tail to head mass ratio was maintained at 2:1, with a head mass of 1.4 kg, and a tail mass weighing 2.8 kg. A high grade stainless steel 1.4571 was used for the cylindrical pressure housing, with a thickness of 14.5 mm and height 216 mm. The technical drawings of the components can be seen in Appendix A. The demonstrator was shortened to minimise costs, as it did not have to house any electronics at the stage. A 3 pin-Subconn connector was used for supplying the alternating voltages to the drive stack.
4.3.3 Design Commissioning

The demonstrator was built for studying the acoustic properties of the emitter in different media. This was achieved by electrical and acoustical measurements. The electrical impedance measurements were carried out in air, water and ice, while, the acoustic measurements were carried out in water. They will be discussed in detail in the chapter 5 and 6.

The mass and the material of the tail and the head masses strongly affect the performance of the emitter. Therefore, two different tail and head masses, and consequently four combinations were tested during the laboratory measurements. The two tail masses varied in mass, while, the head masses were of also varied material. One of the head mass was made from aluminium, which was chosen because of its transmission coefficient which is higher compared to stainless steel in water which results in a better impedance matching. A summary of these combinations and their mass ratios is shown in the table 4.3.3.

Table 4.1: Left: Head and Tail masses; Right: Different combinations for measurements with tail to mass ratio

<table>
<thead>
<tr>
<th>Components</th>
<th>Mass</th>
<th>Version</th>
<th>Combinations</th>
<th>Mass Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel Head</td>
<td>H1 1.40 kg</td>
<td>1</td>
<td>H1T1</td>
<td>1.88:1</td>
</tr>
<tr>
<td>Aluminium Head</td>
<td>H2 0.53 kg</td>
<td>2</td>
<td>H1T2</td>
<td>1:1</td>
</tr>
<tr>
<td>Heavy Tail</td>
<td>T1 2.74 kg</td>
<td>3</td>
<td>H2T1</td>
<td>5.1:1</td>
</tr>
<tr>
<td>Light Tail</td>
<td>T2 1.40 kg</td>
<td>4</td>
<td>H2T2</td>
<td>2.6:1</td>
</tr>
</tbody>
</table>
4.4 ELECTRO-MECHANICAL LUMPED EQUIVALENT CIRCUIT

After the completion of the design process, the components were produced by the mechanical workshop, and assembled as well as tested in the Aachen acoustics lab in the Physikcentrum. The assembled demonstrator with and without pressure housing are shown in the Fig. 4.5.

Figure 4.5: Demonstrator without housing (Left) and with housing (Right)

4.4 Electro-Mechanical Lumped Equivalent Circuit

Tonpilz transducer is an electro-acoustic transducer which converts the electrical energy into acoustic energy. This transduction also includes mechanical work done by the drive stack on the masses [46]. An electrical equivalent of the acoustic and mechanical properties of the emitter can be obtained from an electro-mechanical equivalent circuit [47]. This circuit facilitates analysis and designing of these systems by electrical simulations. Such an equivalent circuit is discussed in the subsequent sections.

4.4.1 Mechanical Lumped Equivalent Circuit

The transducer components can be depicted as shown in Fig. 4.6. The driving stack behaves like a spring of stiffness $K = \frac{1}{C}$ (where $C$ is compliance). The head mass $M_1$ and the tail mass $M_2$ are displaced by $x_1$ and $x_2$ due to the voltage dependent force $F$. The coupling of the masses to the acoustic medium is given by $R_1$ and $R_2$.

Figure 4.6: Mechanical equivalent of the Tonpilz transducer: driving stack is shown as the spring with stiffness $K$ [37]
The equations of motion of the masses are given by:

\[
M_2 \cdot \frac{d^2 x_2}{dt^2} = F - K(x_2 - x_1) - R_2 \cdot \frac{dx_2}{dt} \quad (4.1)
\]

\[
M_1 \cdot \frac{d^2 x_1}{dt^2} = F - K(x_1 - x_2) - R_1 \cdot \frac{dx_1}{dt} \quad (4.2)
\]

For a sinusoidal force \( F = F_0 e^{j\omega t} \) and velocity \( u = u_0 e^{j\omega t} \), the equations can be written as:

\[
R_2 u_2 + j\omega M_2 u_2 = F - \frac{K}{j\omega} (u_2 - u_1) \quad (4.3)
\]

\[
-R_1 u_1 - j\omega M_1 u_1 = F - \frac{K}{j\omega} (u_2 - u_1) \quad (4.4)
\]

The impedance analogy, where the input voltage \( V \) is considered equivalent to force \( F \), and the velocity \( u \) of the masses equivalent to current \( I \), can be used to further define the system in terms of an electrical circuit \[37\]. The masses can be substituted by inductors. Similarly, the resistances and compliances can be depicted as resistors and capacitors respectively. Using the Kirchoff’s rules, and the equations \(4.3\) and \(4.4\) an electrical circuit as shown in Fig. 4.7 can be defined. The relative velocity of the two masses is given by the difference \( (u_2 - u_1) \).

![Electro-mechanical equivalent circuit of a Tonpilz transducer](image)

The circuit in Fig. 4.7 can be used to deduce the same equations of motion as from the mechanical system shown in Fig. 4.6. Hence, it is called an electro-mechanical equivalent circuit. This circuit can be further simplified. The tail mass is covered by the housing, and vibrates in air leading to a negligible resistance \( R_1 \approx 0 \). If \( R_2 \) is also small, such that \( R_2 << \omega(M_1 + M_2) \), the system can be defined by a circuit consisting of an effective mass \( M^* \) and resistance \( R^* \). The reduced circuit is shown in Fig. 4.8

\[
M^* = \frac{M_1 M_2}{M_1 + M_2} \quad (4.5)
\]

\[
R^* \approx \frac{R_2}{(1 + M_2/M_1)^2} \quad (4.6)
\]
The resonance frequency of this system is given by:

\[ \omega_r^2 = \frac{K}{M^*} = \left( \frac{K}{M_2} \right)^2 \left( 1 + \frac{M_2}{M_1} \right)^2 \]  

(4.7)

The quality factor \( Q_m \) is defined as:

\[ Q_m = \omega \frac{M^*}{R^*} = \frac{\omega_r}{\omega_2 - \omega_1} \]  

(4.8)

Where, \( \Delta \omega = \omega_2 - \omega_1 \), is the bandwidth. Additionally, \( \omega_1 \) and \( \omega_2 \) are the frequencies at half power compared to the power at resonance frequency [37].

### 4.4.2 Piezoelectric Ceramic Lumped Equivalent Circuit

The piezoelectric transduction is motivated more clearly in this section. Furthermore, an electric equivalent is developed for obtaining the equivalent circuit for the whole transducer system. The 33 mode of operation is relevant for our system[48]. In this mode the motion and electric field are in the direction of polarisation, leading to a longitudinal expansion and contraction due to the driving voltage \( V \).

Strain \( S \) acts on the system for an applied electric field \( E_3 \) leading to an electric displacement \( D \) and stress \( T \). The lateral dimensions of ceramic are very small compared to the wavelength of longitudinal waves in the material, and there is no load on the sides of the ceramic. Therefore, the stress along the sides is essentially zero \( (T_1 = T_2 = 0) \). Since, the ceramic only moves longitudinally, the lateral stresses are also considered to be negligible [37]. The equations to describe such a system are:

\[ S_3 = s_{33}^E T_3 + d_{33}E_3 \]  

(4.9)

\[ D_3 = d_{33}T_3 + \epsilon_{33}^T + E_3 \]  

(4.10)

where, \( s^E \) is the short circuit elastic modulus, \( \epsilon^T \) is the free dielectric constant and \( d \) is the piezoelectric charge constant. The sub-script 33 stands for the mode of operation. The strain \( S_3 \), can be described as the relative change in length of the piezoceramic, i.e, \( S_3 = \frac{\Delta L}{L} \). Also, for a ceramic smaller than quarter wavelength, the electric field is constant and can be written
as $E_3 \approx \frac{V}{L}$ \[37\]. The force $F$ applied by the piezo of length $L$ and cross section $A_0$ on a mass can then be given by $F = -A_0 T_3$. $T_3$ can be calculated from eq. \[4.9\]

$$F = -A_0 \frac{E_{33}}{s_{33} L} \Delta L + A_0 d_{33} \cdot V$$
$$F = -K^E \Delta L + NV$$ \[4.11\] \[4.12\]

where, $K^E$ is the short circuit stiffness, and $N$ is the electromechanical turns ratio. We can therefore see the dependence of the force due to piezoceramic on the stiffness, and a voltage driven force term. These assumptions were already used in the previous section to describe the drive stack. Hence, we can characterise the mechanical properties of the drive stack using eq. \[4.9\] and eq. \[4.12\].

In order to obtain the electrical properties of the system, eq. \[4.10\] can be used. The charge $Q$ on the piezoceramics is described as $Q = A_0 D_3$. Substituting for $T_3$ in eq. \[4.10\] and multiplying by $A_0$:

$$Q = A_0 d_{33} \frac{E_{33}}{s_{33} L} \Delta L + A_0 \frac{e_{33}^T}{s_{33} L} \left[1 - \frac{d_{33}^2}{e_{33}^T s_{33}^E}\right] V$$ \[4.13\]

For an input sinusoidal voltage $V(t) = V e^{j\omega t}$ and velocity $u_3 = \frac{dL}{dt}$, the current $I$ can be deduced by:

$$I = \frac{dQ}{dt} = A_0 d_{33} \frac{E_{33}}{s_{33} L} \Delta L + j\omega A_0 \frac{e_{33}^T}{s_{33} L} \left[1 - \frac{d_{33}^2}{e_{33}^T s_{33}^E}\right] V \frac{C_0}{C_f}$$ \[4.14\]

where $C_0$ is the clamped capacitance of the system. The clamped capacity is related to free capacity $C_f$ by the electromechanical co-efficient $k$. This coefficient gives the measure of electrical or mechanical energy converted by the transducer relative to the input energy stored in the transducer.

$$C_0 = C_f \left(1 - k_{33}^2\right)$$ \[4.15\]

The eqs. \[4.15\] and \[4.14\] together give the expressions for $C_f$ and $k_{33}$:

$$C_f = \frac{\epsilon_{33}^T A_0}{L}$$ \[4.16\]

$$k_{33}^2 = \frac{d_{33}^2}{\epsilon_{33}^T s_{33}^E}$$ \[4.17\]

After characterising the electrical and mechanical properties of the piezos, we can see from eqs. \[4.12\] and \[4.14\] that the electromechanical turns ratio $N$ connects the electrical and mechanical quantities. The electrical dissipation for the piezoelectric ceramic material can be described by the electrical loss conductance quantity, $G_0 = \omega C_f \tan\delta$. $\tan\delta$ is the dissipation factor for the material. Finally, the piezo stack is in contact with the head mass which dissipates sound energy into the acoustic medium. This leads to forces due to the radiation mass $M_r$ in the medium, as well as radiaion resistance $R_r$. 
We can now modify the electro-mechanical circuit from Fig. 4.7 to accommodate the properties of the piezo-stack. The transformation of electrical input to mechanical output can be shown by a transformer of $1 : N$ ratio. The modified circuit can be seen in Fig. 4.9. The circuit to the right hand side of the transformer is called the motional part. In the Fig. 4.9 the electrical part of the circuit represents the electrical admittance under conditions where $u = 0$. Additionally, the mechanical part of the system has an associated mechanical impedance to it. Finally, the due the radiation into the acoustic medium, the acoustical part of the circuit has a characteristic mechanical radiation impedance.

![Figure 4.9: Modified electro-mechanical equivalent circuit; The electrical, mechanical and acoustical parts of the transducer can be distinguished [33].](image)

The circuit can be simplified by converting the motional elements to electrical elements using the ideal transformer of turns ratio $N$, as shown in the Fig. 4.10. The circuit in Fig. 4.10 is identical to the previous circuit, with the $N^2$ factor due to the transformer. This version of the circuit is very useful for electrical simulations of the system.

![Figure 4.10: The electro-mechanical equivalent circuit without transformer [33](image)

For the case of $R_r << \omega(M_h + M_t)$, the circuit can be simplified similar to the previous section to Fig. 4.11 using the reduced mass $M^*$ and reduced resistance $R^*$.
The electrical admittance of the simplified circuit is:

\[
Y(\omega) = \frac{I}{V} = G_0 + j\omega C_0 + \frac{1}{\frac{j\omega C_0}{j\omega C_0} + j\omega L_e + R_e}
\]  

(4.18)

The conductivity is maximum at resonance and minimum at anti-resonance. Neglecting \(G_0\), the maxima and minima for eq(4.18) is given as:

\[
\omega_{\text{min}} = \frac{-R_e}{2L_e} \pm j \sqrt{\frac{1}{C_e L_e} - \frac{R_e^2}{2L_e}}
\]  

(4.19)

\[
\omega_{\text{min}} = \frac{-R_e}{2L_e} \pm j \sqrt{\frac{1}{C^* L_e} - \frac{R_e^2}{2L_e}}
\]  

(4.20)

where \(C^* = \frac{C_0 C_e}{C_0 + C_e}\). The resulting quality factor \(Q_m\), resonance (\(\omega_r\)) and anti-resonance (\(\omega_a\)) frequencies are:

\[
Q_m = \frac{1}{R_e} \sqrt{\frac{L_e}{C_e}}
\]  

(4.21)

\[
\omega_r = \sqrt{\frac{1}{C_e L_e}}
\]  

(4.22)

\[
\omega_a = \sqrt{\frac{1}{C^* L_e}}
\]  

(4.23)

In air the damping effects are negligible. The measured resonance \(f_r\) and anti-resonance frequency \(f_a\) at resonance in air can be used to calculate the effective dynamic coupling coefficient, by using eq. 4.22 and eq. 4.23 [37].

\[
k_{33}^2 = 1 - \frac{f_r^2}{f_a^2}
\]  

(4.24)

The voltage drops only across \(R_e\) (cancels across \(C_e\) and \(L_e\), short circuit condition). \(R_e = \frac{R_t}{N^2}\), where \(R_t = R + R_r\) is a sum of the mechanical and radiation resistance. In air, the radiation resistance is negligible. The admittance at resonance can be written as:

\[
Y(\omega_r) \approx \frac{1}{R_e} \approx \frac{1}{R}
\]  

(4.25)
In case of \( n \) piezo discs of length \( L \) and thickness \( t \), as in case of the drive stack, the spring constants \( K_i^E \) add up in parallel and the free capacitance of each disc \( C_f, i \) adds up linearly [47]. The parameters of the equivalent circuit can be summarised as follows:

\[
G_0 = \omega C_f \tan \delta, \quad N = \frac{d_{33} A_0}{s_{33}^E t}
\]

\[
C_f = n \varepsilon_{33}^T A_0 \frac{t}{t}, \quad C_0 = C_f (1 - k_{33}^2),
\]

\[
k_{33}^2 = \frac{d_{33}}{\varepsilon_{33}^T s_{33}^E}, \quad C^E = \frac{n s_{33}^E t}{A_0}
\]

\[
L_e = \frac{M^* + M_r}{N^2}, \quad R_e = \frac{R^*}{N^2}
\]
Chapter 5

Electrical Characterisation

5.1 Impedance Measurement

In order to characterise the demonstrator, various electric and acoustic measurements were carried out. This chapter will focus on the electrical characterisation of the demonstrator by performing impedance measurements. From these measurements, four parameters, namely, resonance frequency $f_r$, anti-resonance frequency $f_a$, quality factor $Q_m$, and the effective dynamic coupling coefficient $k_{\text{eff}}$ of the system were determined. All four configurations of the demonstrator introduced in the previous chapter were tested in two acoustic media - air and water. Furthermore, each configuration was tested with and without the pressure housing to improve our understanding of the influence of additional masses on the emitter system. The demonstrator will be interchangeably addressed as an emitter in the following text.

5.1.1 Experimental-Setup

The circuit diagram for the Impedance measurement is shown in Fig. 5.1. The emitter was connected in series with a measurement resistance $R_m$, which was further connected to a voltage supply. The impedance of the emitter is given by $Z = 1/Y$, where $Y$ is the admittance. Consequently, $R_m$ and the emitter form a voltage divider. The voltage across the resistance can then be used for impedance calculations.

![Circuit diagram for the impedance measurement of the emitter](image)

Figure 5.1: Circuit diagram for the impedance measurement of the emitter
A sinusoidal time dependent signal $V(t)$, with a defined frequency of $\omega = 2\pi f$ was supplied using a RIGOL DG5072 function generator. The input voltage $V_1(t)$ and the voltage drop across the resistance $V_2(t)$, were recorded using a RIGOL DS1054Z oscilloscope. The setup was operated using a software written in python via USB connections to the devices. The water measurements were carried out in a large tank of dimensions $1.5 \times 1.5 \times 2.5 \text{ m}^3$. The setup can be seen in Fig. 5.2.

![Image](image.png)

**Figure 5.2:** The setup for impedance measurement of the emitter; A USB connection to the measurement computer from the oscilloscope and function generator facilitates the automation of the measurement.

Electrical Impedance of a circuit is a complex quantity and can be defined as:

$$Z = |Z| e^{j\theta} = R + jX$$

(5.1)

where $|Z|$ is the magnitude and $\theta$ is the phase. $R$ and $X$ are the resistance and reactance of the system respectively. Quantitatively, the impedance of a two-terminal circuit element, is defined as the ratio of the complex representation of a sinusoidal voltage between its terminals to the complex representation of the current flowing through it [51]:

$$Z = \frac{V(t)}{i(t)}$$

$$Y = \frac{i(t)}{V(t)}$$

(5.2)

The voltages $V_1$ and $V_2$ are time dependent complex quantities of the form:

$$v_1 = V_1(t) = |V_1| e^{j(\omega t + \phi_1)}$$

$$v_2 = V_2(t) = |V_2| e^{j(\omega t + \phi_2)}$$

(5.3)
5.1. IMPEDANCE MEASUREMENT

The current $i$ passing through the emitter is given as the ratio of voltage drop across the resistance $\Delta v = v_1 - v_2$ to the resistance $R_m$ itself,

$$i = \frac{\Delta v}{R_m} = \frac{v_1 - v_2}{R_m} \quad (5.5)$$

The impedance and admittance of the circuit can thus be deduced by substituting $[5.5]$ in $[5.2]$. The calculations for admittance are discussed in the further text to characterise the system.

$$Y = \frac{1}{R_m} \left( \frac{|V_1|}{|V_2|} \cdot e^{j\Delta \phi} - 1 \right) \quad (5.6)$$

where $\Delta \phi = (\phi_1 - \phi_2)$ is the phase difference. The real and imaginary terms of the admittance are obtained by expanding the exponential term and re-arranging:

$$Re(Y) = \frac{1}{R_m} \left( \frac{|V_1|}{|V_2|} \cdot \cos \Delta \phi - 1 \right) \quad (5.7)$$

$$Im(Y) = \frac{1}{R_m} \left( \frac{|V_1|}{|V_2|} \cdot \sin \Delta \phi \right) \quad (5.8)$$

The real part of the admittance is known as conductance, and the imaginary part is the susceptance of the system. The magnitude and phase information of admittance can be calculated using these terms:

$$|Y| = \sqrt{Re(Y)^2 + Im(Y)^2} \quad (5.9)$$

$$\tan \theta = \frac{Im(Y)}{Re(Y)} \quad (5.10)$$

The magnitude of admittance $|Y|$, is maximum at resonance and hence, the maximum amount of electrical energy can be converted into mechanical energy near the resonance. Similarly, it becomes minimum at anti-resonance. We can determine admittance magnitude $|Y|$, resonance frequency $f_r$ and anti-resonance frequency $f_a$ directly from the impedance measurements.

Another important quantity for determining the behaviour of the emitter is the mechanical quality factor $Q_m$. It is a measure of the sharpness of the resonant response curve and is defined as:

$$Q_m = \frac{f_r}{f_2 - f_1} = \frac{f_r}{\Delta f} \quad (5.11)$$

where $f_1$ and $f_2$ are frequencies at half power relative to the power at resonance, i.e., within 3 dB of the output power at resonance. $\Delta f$ is referred to as the bandwidth of the system. A low $Q_m$ value is desired for a wide band system.

In order to deduce the quality factor, active power $P$ for a constant input voltage is required. It is given by:

$$P = Re(S) = Re \left( \frac{|V_2|^2}{Z} \right) = Re \left( \frac{1}{Z} \right) \cdot |V_2|^2 \quad (5.12)$$

$$P = Re(Y) \cdot |V_2|^2 \quad (5.13)$$

$$Re(Y) = \frac{P}{|V_2|^2} \quad (5.14)$$
where $S$ is the apparent power of the system. As can be seen from the above equations, for a constant $V_2$, $P$ is directly proportional to $Re(Y)$. But this is not the case for our measurement setup. Due to the voltage drop across $R_m$, the voltage through the emitter module is load dependent. Therefore, we correct for $V_2(t)$, and use $Re(Y)$ for deduction of bandwidth for determining $Q_m$.

5.2 Preliminary Measurements

The robustness of the measurement was examined by testing it for a commercially available spherical transducer, Neptune D17 from Neptune Sonar Ltd [52] as a part of the preliminary measurements. It is a spherical projector built for under-water applications. The obtained measurement results were compared to data sheet values provided by the manufacturers.

The measurement was carried out in the water tank. The Neptune was suspended into the water with the help of aluminium profiles as shown in Fig 5.3. It was immersed nearly 70 cm below the water surface and at a similar distance from the walls. The setup for the measurement was presented in Fig. 5.2. A signal of the form $S(t) = V_{off} + V_{amp} \cdot \sin(2\pi ft + \phi)$, was supplied to the projector. Its amplitude was set to 10 V and the offset was set to 0 V. The measurement was performed for frequency ranging from 1 kHz to 30 kHz in steps of 50 Hz. Around the resonance, for improved accuracy, this step size was decreased to 10 Hz. The probes used for the measurements were X1 probes, and the attenuation on the oscilloscope was set to unity. Finally, the output impedance of the function generator was set to a low value of 50Ω to avoid loading effects.

Figure 5.3: Neptune suspended into water from aluminium profiles for impedance measurement; The verification of the impedance measurement method was done using Neptune in water medium, as it is primarily suitable for operation in water.
The data from the oscilloscope was stored on the measuring computer and a sinusoidal curve fit was implemented to obtain the relevant parameters namely amplitude, frequency, offset, and the phase of the signal. An example of such a transient for a given frequency is shown in Fig. 5.4. The voltage of the transient is plotted on the vertical scale against time on the horizontal scale. The fitting is shown by the solid blue line. Initial parameters for the fitting were provided from the oscilloscope’s measurement feature.

![Figure 5.4: Sine wave fit to the recorded data; The raw data was fit with a sinusoidal curve fit function to extract parameters along with fit uncertainties $\sigma_f$.](image)

The fit error associated with the parameters, shown in the Fig. 5.4 was obtained from the co-variance matrix. A $\chi^2$ minimisation for determining the goodness of fit was obtained to be $\chi^2/ndf = 0.926$. Systematic error associated with the measurement due to the quantization in the vertical scale, and the sampling in the horizontal scale were taken into account. The quantization error for a 5V vertical scale of 8 bit ADC in the oscilloscope resulted in $\sigma_V = 40V/2^8 = 0.16V$. The sampling error was $\sigma_t = 4 \mu s$. An uncertainty of $\pm 25$ Hz on the frequency of each transient was also taken into account due to the step size for frequencies used for the measurements. The errors were propagated for further calculations by implementing gaussian error propagation. A set of 20 measurements was carried out for which the standard deviation was calculated of the derived quantities. An average of the results from these 20 sets was obtained.

In Fig. 5.5 the conductance versus frequency plot is presented. The measured values are shown in blue. The conductance obtained from the datasheet is plotted in red. It is measured in Siemens. The measured resonance frequency was observed to be 17.75 kHz, while the datasheet value was 17.88 kHz, resulting in an error of 0.73%. It is marked on the x-axis with a green dotted vertical line. The maximum conductance of the projector was measured to be $6.688 \pm 0.014 \text{ mS}$. A dotted horizontal line along the y-axis represents this value.
The susceptance of the projector was also calculated and compared to the datasheet values (see Fig. 5.6). It was also measured to be within $\approx 1\%$ of the expected values. A reason for the ripples in the measured data could be the confined nature of the surrounding medium in which the measurements were performed. The results, however, agreed quite well with the datasheet values, and hence were used for further measurements and analysis. The compared results are summarised in the following table.
5.3. AIR MEASUREMENTS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Datasheet</th>
<th>Measured Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_r$</td>
<td>17.88 kHz</td>
<td>17.75 ± 0.030 kHz</td>
</tr>
<tr>
<td>$Y_{re}$</td>
<td>6.737 mS</td>
<td>6.688 ± 0.014 mS</td>
</tr>
<tr>
<td>$Y_{im}$</td>
<td>7.340 mS</td>
<td>7.495 ± 0.024 mS</td>
</tr>
</tbody>
</table>

Table 5.1: Summary of the measured and expected parameters from Neptune Impedance measurements

5.3 Air Measurements

The four configurations of the demonstrator were first tested in air. This section will give a detailed description of the measurement results for one of the configurations, $V2 : H1T2$. Finally, a summary of calculated quantities for all four configurations will be presented.

The impedance measurements were carried out for two cases. The first case included measurements done without the pressure housing and the end cap in the demonstrator assembly. This was done, to compare the system to an ideal tonpilz transducer model, for which predictions from the equivalent circuit could be made. In the second case, the pressure housing, and the end cap were included, in order to study the effects of the additional masses on the electrical behaviour of the system.

5.3.1 Case 1: Without Pressure Housing

The demonstrator was suspended with the help of a rope and aluminium profiles as shown Fig. 5.7. Five measurement sets were taken for all configurations, in the frequency range of 0 to 30 kHz. The measurements were taken for frequency in steps of 50 Hz, and lowered to 10 Hz around the resonance. The measurement setup described previously was used.

Figure 5.7: Emitter of V2:H1T2 without housing suspended with rope

The data retrieved from the oscilloscope was evaluated by fitting a sinusoidal function and the corresponding parameters were obtained for each frequency. The signal amplitudes obtained across the measurement resistance $R_m$, namely $V_1(t)$ and $V_2(t)$ are plotted against frequency
in Fig. 5.8. The load dependent voltage drop can be seen in the figure. This drop is expected to occur around the resonance frequency of the emitter, as the impedance of the system is minimum at resonance. The input voltage $V_1(t)$ is shown in red, while the voltage drop due to the emitter $V_2(t)$ is shown in blue.

![Figure 5.8: Voltages across the measurement resistance $V_1(t)$ and $V_2(t)$; The voltage drop corresponding to the resonance frequency of the demonstrator is clearly visible.](image)

The magnitude of admittance $|Y|$ with respect to a change in frequency was deduced using eq. 5.9. The maximum admittance of $|Y|_{\text{max}} = 124.71 \pm 5.40 \text{mS}$ was obtained at the resonance frequency $f_r = 8.820 \pm 0.025 \text{kHz}$. The measured anti-resonance frequency was $f_a = 9.701 \pm 0.026 \text{kHz}$. The admittance of the emitter with respect to the frequency range is shown in Fig. 5.9. The admittance $|Y|$ is presented on a logarithmic scale. The maximum admittance magnitude is marked with a red horizontal dotted line along the y-axis. The resonance $f_r$ and anti-resonance $f_a$ frequencies are shown with green vertical lines. In air the effective coupling coefficient can be calculated using eq. 4.24. For the case of $V_2$, it was calculated to be $k_{\text{eff}} = (0.416 \pm 0.007)$.

The equivalent circuit predicts the magnitude of admittance to peak at resonance followed by a drop at the anti-resonance frequency as discussed in sec. 5.1.1. The obtained results are in agreement with this expectation. Furthermore, from eqn. 4.7 using the reduced mass and, the value of mechanical compliance for the case of 16 piezo discs, a prediction on the resonance frequency can be made using the equivalent circuit. The value of the mechanical compliance used for this purpose was $C_E = (358.19 \pm 2.49 \cdot 10^{-12}) \text{m/N}$ for 8 discs [33]. A conservative error on the measured tail and head masses of about 0.21 kg was considered. The reduced mass $M^*$ for this configuration was calculated using the eq. 4.5 to be $M^* = 0.700 \pm 0.074 \text{kg}$. The expected resonance frequency was then deduced to be $f_{\text{exp}} = 7.110 \pm 0.377 \text{kHz}$. The observed value was within 20% of the expected value.
5.3. AIR MEASUREMENTS

Figure 5.9: $|Y|$ against frequency for $V2 : H1T2$; Logarithmic scale for the magnitude is used to demonstrate the prominent resonance and anti-resonance peak.

Fig. 5.10 shows the conductance of the emitter as a function of frequency. The maximum conductance was measured to be $Re|Y| = 123.90 \pm 5.40 \text{ mS}$, depicted by the red horizontal line. The resonance frequency obtained from the conductance plot depicted by the green horizontal line, was in agreement with the $f_r$ value obtained from the admittance plot. The peak of the conductance plot is a measure of the active power as discussed in eq. 5.14. A closer view of the peak obtained for the conductance versus frequency plot is shown in Fig. 5.11.

Figure 5.10: Conductance of $V2 : H1T2$ for frequencies ranging from 1 to 30 kHz
Fig. 5.11 presents the half power frequencies $f_1$ and $f_2$ with respect to the peak power at $f_r$, all marked with green horizontal lines on the plot.

A horizontal line at the half power depicts the spread of the peak. The bandwidth of the system was be calculated from the conductance peak as shown in the Fig. 5.11. It was observed to be $\Delta f = 110 \pm 35.35$ Hz. Additionally, the quality factor was calculated using eq. 5.11 to be $Q_m = 80.18 \pm 25.77$. The error in the bandwidth and consequently the quality factor was obtained by using gaussian error propagation.

As discussed in equation 4.25, the radiation resistance is negligible in air, leading to an inverse proportionality of the magnitude of admittance to the mechanical resistance of the system. Therefore, sharper resonances are desired in air loading to minimise frictional losses [37]. The mechanical resistance, $R_e$ using eq. 4.25 was determined to be $8.07 \pm 0.352 \Omega$.

**Results and Discussion**

The observed and derived quantities for all versions of the demonstrator for the case of air measurements without pressure housing are summarised in the following tables. The corresponding plots for each of the version are included in the appendix 3.

<table>
<thead>
<tr>
<th>Version</th>
<th>$M^*$ (kg)</th>
<th>$f_{exp}$ (kHz)</th>
<th>$f_r$ (kHz)</th>
<th>$f_a$ (kHz)</th>
<th>$Y_{max}$ (mS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>0.927 ± 0.095</td>
<td>6.181 ± 0.318</td>
<td>7.430 ± 0.026</td>
<td>8.050 ± 0.026</td>
<td>79.290 ± 4.40</td>
</tr>
<tr>
<td>V2</td>
<td>0.7 ± 0.074</td>
<td>7.111 ± 0.377</td>
<td>8.820 ± 0.025</td>
<td>9.701 ± 0.025</td>
<td>124.71 ± 5.40</td>
</tr>
<tr>
<td>V3</td>
<td>0.444 ± 0.148</td>
<td>8.927 ± 1.482</td>
<td>9.550 ± 0.026</td>
<td>10.100 ± 0.026</td>
<td>66.05 ± 3.01</td>
</tr>
<tr>
<td>V4</td>
<td>0.385 ± 0.112</td>
<td>9.594 ± 1.393</td>
<td>10.720 ± 0.030</td>
<td>11.600 ± 0.030</td>
<td>169.40 ± 11.50</td>
</tr>
</tbody>
</table>

Table 5.2: The quantities obtained from the impedance measurements in air
### 5.3. AIR MEASUREMENTS

<table>
<thead>
<tr>
<th>Version</th>
<th>$\Delta f$ (Hz)</th>
<th>$Q_m$</th>
<th>$R_m$ (Ω)</th>
<th>$k_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>89.99 ± 35.35</td>
<td>82.56 ± 32.43</td>
<td>12.815 ± 0.755</td>
<td>0.385 ± 0.010</td>
</tr>
<tr>
<td>V2</td>
<td>110 ± 35.35</td>
<td>80.18 ± 25.77</td>
<td>8.07 ± 0.352</td>
<td>0.416 ± 0.007</td>
</tr>
<tr>
<td>V3</td>
<td>150 ± 35.35</td>
<td>63.66 ± 15.005</td>
<td>15.242 ± 0.715</td>
<td>0.325 ± 0.010</td>
</tr>
<tr>
<td>V4</td>
<td>70 ± 42.42</td>
<td>153.14 ± 77.883</td>
<td>5.977 ± 0.422</td>
<td>0.380 ± 0.008</td>
</tr>
</tbody>
</table>

Table 5.3: Derived quantities for the case of air impedance measurements without pressure housing

The observed resonance frequencies lie within 20% of the expected values. The deviation can be explained by the dependence of the expected resonances on the compliance of the individual discs, which could vary considerably. An increase in the resonance frequencies was observed with decrease in the tail mass. The resonance frequency shifted from 7.4 to 8.8 kHz for V1 to V2, and from 9.55 to 10.72 kHz for V3 to V4, with a decrease of 50% in tail mass from T1 to T2. This is in agreement with the expectation from the equivalent circuit (eq. 4.7), as the resonance frequency of the emitter depends inversely on the reduced mass. The V4 configuration was observed to have the maximum $Q_m$ value. Consequently, the mechanical resistance of this system was minimal. This is a desirable result as the frictional losses of such a system are minimised. Furthermore, the magnitude of the admittance for V4 was much larger than that for the other configurations. This can be explained by eq. 4.25 of the equivalent circuit, where the impedance is inversely proportional to $R_m$ at resonance which is approximately equal to the mechanical resistance in case of air loading. The configuration V4 of the demonstrator, due to its low mechanical resistance is expected to have a high admittance. The effective coupling coefficient for all the version was observed to be roughly between 0.32 to 0.42, which is a measure of the amount of electrical energy converted into mechanical energy by the systems.

### 5.3.2 Case 2: With Pressure Housing

For further measurements, the pressure housing and the end cap were included in the assembled demonstrator. The emitter was suspended in air with the help of ropes, aluminium profiles and a handling screw, as shown in Fig. 5.12. The connection to the drive stack was established with the help of a Subconn 3-pin connector [45].

The magnitude of the admittance of the emitter against frequency ranging from 1 to 30 kHz is presented in Fig. 5.13. As can be seen in the plot, multiple resonances arise after the addition of the housing and the end cap to the system. These resonances can be explained by the complexity of the assembled system. They are expected to arise as a result of the coupling of the head mass to the housing and in turn the end cap and can be accounted as mechanical resonances of the system. The resonance peaks are marked in the Fig. 5.13 and later summarised in a tabular format. Corresponding to multiple resonances, multiple peaks in the conductance calculations were also observed and are presented in Fig. 5.14. The higher resonance peaks were observed to have wider bandwidths. The magnitude of admittance and conductance for the system were also observed to be smaller than the previous case. This can be explained due to the frictional losses introduced by the additional masses.
Figure 5.12: The fully assembled demonstrator of configuration $V2$ for impedance measurements in air

Figure 5.13: Admittance of $V2$: $H1T2$ for frequencies ranging from 1 to 30 kHz in case of pressure housing
5.4. WATER MEASUREMENTS

Figure 5.14: Conductance of $V^2 : H1T2$ for frequencies ranging from 1 to 30 kHz in case of pressure housing.

The results for all the demonstrator versions are summarised in the Table 5.4. The corresponding plots for each version is included in the appendix B.

<table>
<thead>
<tr>
<th></th>
<th>Peak1 (kHz)</th>
<th>Peak2 (kHz)</th>
<th>Peak3 (kHz)</th>
<th>Peak4 (kHz)</th>
<th>Peak5 (kHz)</th>
<th>Peak6 (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>3.820 ± 0.025</td>
<td>7.900 ± 0.025</td>
<td>11.900 ± 0.030</td>
<td>15.200 ± 0.030</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>V2</td>
<td>4.25 ± 0.025</td>
<td>8.45 ± 0.025</td>
<td>11.75 ± 0.03</td>
<td>14.6 ± 0.03</td>
<td>18.00 ± 0.030</td>
<td>25.000 ± 0.030</td>
</tr>
<tr>
<td>V3</td>
<td>3.265 ± 0.025</td>
<td>8.100 ± 0.025</td>
<td>12.00 ± 0.030</td>
<td>15.150 ± 0.030</td>
<td>22.500 ± 0.030</td>
<td>-</td>
</tr>
<tr>
<td>V4</td>
<td>4.050 ± 0.025</td>
<td>8.650 ± 0.026</td>
<td>13.500 ± 0.030</td>
<td>15.850 ± 0.030</td>
<td>18.100 ± 0.030</td>
<td>25.100 ± 0.030</td>
</tr>
</tbody>
</table>

Table 5.4: Summary of the peak frequencies obtained for all versions of the demonstrator for impedance measurements in air.

Discussion

For the case of a fully assembled demonstrator, multiple peaks were observed. They are expected as a result of the coupling of the pressure housing, and end cap to the head mass which produce mechanical resonances. The peaks followed a general trend of increase in corresponding frequencies with decrease in the tail mass for the electrical resonance peaks in agreement with the theoretical expectation from eq. 4.7. The first resonance peaks were observed to match with prediction from the equivalent circuit, for a head mass equivalent to the sum of the original head mass, the pressure housing which weighed $M_h \approx 6.7$ kg and the end cap of $M_c \approx 1.54$ kg for that system. The eq. 4.5 was used for the calculations. Furthermore, the magnitude of the admittance for each of the system was significantly lowered. This is expected due to the frictional losses introduced by the complex system as well as increased reduced mass.
5.4 Water Measurements

The impedance measurements were also performed in the water tank described in section 5.2. Similar to the air measurements, the water impedance measurements were also carried out with and without the pressure housing and end cap in the demonstrator assembly. This section will discuss the measurement results for $V_2: H1T2$ in detail as an example. A summary of the results for all the configurations will be presented at the end.

5.4.1 Case 1: Without Pressure Housing

In case of measurements for the emitter without housing, the head mass was dipped into water maintaining the area of contact with the acoustic medium. The rest of the emitter was kept above the water level to prevent damage to the drive stack. The emitter was suspended by rope and aluminium profiles, as shown in Fig. 5.15.

![Emitter of $V_2 : H1T2$ without pressure housing suspended in water for impedance measurements](image)

Figure 5.15: Emitter of $V_2 : H1T2$ without pressure housing suspended in water for impedance measurements

A set of five measurements was carried out for a frequency range of 0 to 30 kHz. The frequency step remained 50 Hz and was decreased to 10 Hz around the resonance. The standard deviation and mean of the required quantities were calculated as described in Sec. 5.2.

The admittance magnitude as a function of frequency measured for the configuration $V_2 : H1T2$ without housing is shown in Fig. 5.16. The admittance is presented on a log scale. The maximum admittance value in water was observed to be $35.44 \pm 0.910 \text{mS}$. The observed resonance and anti-resonance frequencies were $f_r = 8.790 \pm 0.025 \text{kHz}$ and $f_a = 9.700 \pm 0.026 \text{kHz}$ respectively. The admittance of the system was observed to be lower in water compared to that in air. This can be explained by the high acoustic impedance of water. The radiation resistance in water becomes significant leading to a decrease in the admittance magnitude as can be expected from eq. ??}. It can also be seen that that the resonances are not as sharp in water as in air. This
is again explained by the contribution of the radiation resistance, due to which the damping terms become significant (see eq. 4.19). The effective coupling coefficient in water was obtained to be $k_{\text{eff}} = (0.423 \pm 0.008)$ which was higher than in case of air.

Figure 5.16: Admittance of $V_2 : H1T2$ for frequencies ranging from 1 to 30 kHz in case of water as acoustic medium

The conductance of the emitter against the frequency, obtained from the water measurements is shown in Fig. 5.17. The maximum conductance was observed to be $|Y|_{\text{max}} = 35.04 \pm 0.47 \text{ mS}$. A closer view of the conductance for the bandwidth calculations is shown in Fig. 5.18. The half power frequencies with respect to the resonance frequency are depicted by vertical dotted lines on the plot. The bandwidth obtained from the measurements for this version was $400.00 \pm 35.35 \text{ Hz}$. The quality factor was then calculated to be $Q_m = 21.97 \pm 1.940$. The bandwidth of the emitter increased considerably for the water measurements leading a low value of the $Q_m$. This is a favorable result as the contribution of radiation resistance is responsible for this decrease in the quality factor. The radiation resistance should not be confused with the mechanical resistance or friction, which should be minimum for the system. In fact, a large radiation resistance is desired for the system, because it results in more acoustic emission.
Figure 5.17: Conductance of $V_2: H1T2$ for frequencies ranging from 1 to 30 kHz in case of water as acoustic medium

Figure 5.18: Closer view of the conductance for bandwidth calculation

Results and Discussion

The measurement results along with the derived quantities for all versions of the demonstrator are presented in tables 5.5 and 5.6. The corresponding plots can be found in the appendix B.
5.4. WATER MEASUREMENTS

<table>
<thead>
<tr>
<th>Version</th>
<th>( f_r ) (kHz)</th>
<th>( f_a ) (kHz)</th>
<th>( Y_{max} ) (mS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>7.600 ± 0.025</td>
<td>8.100 ± 0.025</td>
<td>25.790 ± 0.280</td>
</tr>
<tr>
<td>V2</td>
<td>8.790 ± 0.025</td>
<td>9.700 ± 0.026</td>
<td>35.44 ± 0.910</td>
</tr>
<tr>
<td>V3</td>
<td>8.700 ± 0.026</td>
<td>9.750 ± 0.026</td>
<td>17.120 ± 0.21</td>
</tr>
<tr>
<td>V4</td>
<td>10.250 ± 0.030</td>
<td>11.350 ± 0.030</td>
<td>17.360 ± 0.22</td>
</tr>
</tbody>
</table>

Table 5.5: The quantities obtained from the impedance measurements in water

<table>
<thead>
<tr>
<th>Version</th>
<th>( \Delta f ) (Hz)</th>
<th>( Q_m )</th>
<th>( k_{eff} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>198.99 ± 35.35</td>
<td>38.193 ± 6.786</td>
<td>0.346 ± 0.012</td>
</tr>
<tr>
<td>V2</td>
<td>400.00 ± 35.35</td>
<td>21.975 ± 1.940</td>
<td>0.423 ± 0.008</td>
</tr>
<tr>
<td>V3</td>
<td>1080 ± 35.351</td>
<td>8.065 ± 0.264</td>
<td>0.452 ± 0.007</td>
</tr>
<tr>
<td>V4</td>
<td>799.99 ± 42.42</td>
<td>12.828 ± 0.568</td>
<td>0.430 ± 0.008</td>
</tr>
</tbody>
</table>

Table 5.6: Derived Quantities for the case of water impedance measurements

The maximum value of the admittance for all configurations was observed to be lower than in case of air. This result agrees with the equivalent circuit, for which an increase in the radiation resistance due to the acoustic impedance of a medium, leads to a decrease in the admittance. The bandwidth for each configuration was observed to have increased significantly for the case of water measurements. As a consequence the \( Q_m \) quality factor had lower values compared to the air measurements. The coupling coefficients were observed to be roughly within 0.34 to 0.45.

5.4.2 Case 2: With Pressure Housing

The water impedance measurements for the emitter with the pressure housing and the end cap are presented in this section. The demonstrator was hung in the large water tank with aluminium profiles and rope. It was immersed completely inside the water, roughly at a depth of 20 cm. It is shown in Fig. 5.19.

Figure 5.19: The fully assembled emitter of V2 : H1T2 immersed in water for impedance measurements
As expected for the complex system, multiple resonances were observed as shown in Fig. 5.20. The admittance of the emitter obtained for a given frequency range is presented. The resonance peaks were observed to be lower in magnitude with respect to the peaks obtained in case of air measurements. The peaks were observed to be less defined and wider in bandwidth.

![Admittance of V2 : H1T2 for frequencies ranging from 1 to 30 kHz in case of water as acoustic medium for fully assembled emitter](image1)

Figure 5.20: Admittance of $V_2 : H1T2$ for frequencies ranging from 1 to 30 kHz in case of water as acoustic medium for fully assembled emitter

The conductance of the demonstrator is presented in Fig. 5.21. The conductance heights of the emitter were also observed to be smaller than the case of air impedance. This was in agreement with the expectation from the equivalent circuit.

![Conductance of V2 : H1T2 for frequencies ranging from 1 to 30 kHz in case of water as acoustic medium for fully assembled emitter](image2)

Figure 5.21: Conductance of $V_2 : H1T2$ for frequencies ranging from 1 to 30 kHz in case of water as acoustic medium for fully assembled emitter
The results for all four configurations are presented in the following table. The corresponding plots for each configuration can be found in the appendix B.

<table>
<thead>
<tr>
<th></th>
<th>Peak1 (kHz)</th>
<th>Peak2 (kHz)</th>
<th>Peak3 (kHz)</th>
<th>Peak4 (kHz)</th>
<th>Peak5 (kHz)</th>
<th>Peak6 (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>3.830 ± 0.025</td>
<td>7.750 ± 0.025</td>
<td>11.600 ± 0.030</td>
<td>15.050 ± 0.030</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>V2</td>
<td>4.300 ± 0.025</td>
<td>8.335 ± 0.025</td>
<td>11.90 ± 0.03</td>
<td>14.75 ± 0.03</td>
<td>18.30 ± 0.030</td>
<td>25.000 ± 0.030</td>
</tr>
<tr>
<td>V3</td>
<td>3.255 ± 0.025</td>
<td>7.750 ± 0.025</td>
<td>11.750 ± 0.030</td>
<td>14.900 ± 0.030</td>
<td>22.700 ± 0.030</td>
<td>-</td>
</tr>
<tr>
<td>V4</td>
<td>4.050 ± 0.025</td>
<td>8.300 ± 0.026</td>
<td>12.850 ± 0.030</td>
<td>15.400 ± 0.030</td>
<td>25.05 ± 0.030</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5.7: Summary of the peak frequencies obtained for all versions of the demonstrator for impedance measurements in water

5.5 Summary

The electrical characterisation by impedance measurement carried out in air and water acoustic media was successfully performed. The measurement setup was verified with a reference commercial projector in the preliminary measurements, which resulted in a reasonable agreement with the expected behaviour.

The measurements carried out in the air medium, agreed quite nicely with the predictions from the equivalent circuit discussed in Chapter 4. A shift in the resonance frequencies with change in the reduced mass of the system, as well as the dependance of the admittance magnitude on the mechanical resistance of the system were observed. The version V4 was observed to have the minimal frictional losses, and high admittance response in the air. Mechanical resonances were observed for the more complex case of fully assembled demonstrators in air. The agreement with the equivalent circuit was still persistent. Further investigation is required to completely understand the behaviour of such a system.

In case of the measurements for water, the results agreed with the equivalent circuit predictions as well. The influence of radiation resistance could be examined closely. A decrease in the admittance magnitude was observed as per expectation from the equivalent model, for each of the configurations. The coupling in case of water was observed to slightly improve than for air. The multiple resonant system was also studied.

Although, the coupling of each of the configurations was quite similar, the version V4 was be expected to be a favorable candidate, due to the low mechanical resonance observed from the air impedance measurements, and a high radiation resistance which could be observed by the decrease in the admittance magnitude in water impedance measurements.
Chapter 6

Acoustic Characterisation

The impedance measurements provided an insight into the acoustic behaviour for the different versions of the demonstrator. Acoustic measurements were carried out for verifying these results and acoustically characterising the demonstrator. The aim of the measurements was to study the angular sound emission characteristics of the emitter and to determine the best candidate for maximum acoustic output. These measurements were performed in water. Ideally, ice medium would be beneficial for constructing the most relevant environment. However, this would require a large scale setup, example a glacier test which was out of the scope for this thesis.

In the first stage, the measurements were carried out in a water tank. After determining the interesting candidate for further studies, the acoustic measurements were performed in a bigger water body, a swimming pool, to verify the laboratory results and eliminate reflections in the acoustic medium.

6.1 Experimental Set-Up

The measurement setup consisted of a hydrophone for receiving and an emitter for transmitting the acoustic signals, both contained in the large water tank previously used for impedance measurements. A RIGOL DG5072 [49] function generator was used to supply electrical signals of a defined frequency, to the emitter. For retrieving output data from the hydrophone a RIGOL DS1054Z [50] oscilloscope was used. The experimental setup can be seen in the Fig. 6.1 and Fig. 6.2

The hydrophone used for the measurements was ITC-1001 [53]. It is a spherical projector, similar to the Neptune D17. It was equipped with a custom designed amplifier circuit with a differential output, to minimise the noise. The gain of the amplifier circuit is 1440 for a bandwidth of 1.6 to 200 kHz for −3 dB [54]. An external voltage supply of 5 V was used to power the circuit. The measurement setup was controlled by a software written in python via USB connections to the devices.

The setup in the water tank was maintained such that the emitter and receiver were both positioned at a fixed distance from the walls as well as surface of the water so that the maximum time delay between the pure acoustic signal and the reflections from these surfaces could be achieved. The dimensions of the water tank were $1.5 \times 1.5 \times 2.5 \text{ m}^3$. The distance to the
walls was thus, maintained roughly at 0.7 m on all sides. Additionally, a distance of about 1 m was maintained between the emitter and the receiver. This was done for convenience in comparison of the measured results to the data sheet values which were also calculated for a hydrophone to projector distance of 1 m, while verifying the measurement method. This distance was maintained for all water tank measurements so that the demonstrator versions output could be directly compared to the commercial option. All these distances were measured using a folding scale and therefore, an uncertainty of about ±0.5 mm can be accounted. The speed of sound in water was taken to be \( \approx 1500 \text{ m/s} \) at room temperature \([55]\).

![Figure 6.1: Measurement Setup for the Acoustic Characterisation](image1.png)

A commonly observed quantity for acoustic characterisation of projectors is the transmitting
6.2 Preliminary Measurements

The acoustic measurement was first verified using a combination of the Neptune D17 as a projector and the ITC-1001 as a hydrophone. The measurement setup is shown in Fig. 6.3. The emission and receiving response of both the transducers were taken from the data sheet provided by the manufacturers [52, 53], shown in Fig. 6.4. The transfer function from the measurements was compared to that obtained from the data sheet values.

Figure 6.3: The Neptune and ITC spherical transducers for verification of acoustic measurements
The acoustic measurement was carried out for the frequency range of 3 to 30 kHz. It was performed for a frequency step of 50 Hz. For frequencies lower than 3 kHz, the signal to noise ratio of the measured output voltage amplitude was less than 5 and hence, a reliable measurement was not feasible. The trigger output from the function generator was used for timing synchronisation to the oscilloscope. A sine burst signal of defined frequency with 8 cycle repetition after a period of 0.5 s was supplied by the function generator. The data from the oscilloscope was read from the internal memory and the memory depth was set to 3 million points per sample. The data was scanned and recorded for these 3 million points per frequency. An example of a transient for a single frequency can be seen in the Fig. 6.5. The figure shows
6.2. PRELIMINARY MEASUREMENTS

the output voltage as a function of time, for a given input frequency. This output voltage was calculated by taking a difference of the differential signal recorded by the oscilloscope. The trigger signal from the function generator is also shown in orange. An offset correction is performed for the measured data before further analysis. The beginning of the trigger signal marks the emission from the projector. The volt scale was automatically adjusted for each transient depending on the received amplitude. The systematic errors on the volt scale $\sigma_V = 4V/2^8 = 0.015\, V$, due to the quantization and the timescale of $\sigma_t = 4\, \mu s$ due to the sampling rate were taken into account.

![Figure 6.5: Transient recorded from the oscilloscope for the acoustic measurements](image)

Due to the confined nature of the setup, reflections are expected from the walls of the container as well as the surface of the water. Therefore, a time window was chosen in order to segregate the direct signal. Using the speed of sound in water and distance traversed by direct and reflected signal the time window can be calculated $\Delta t = \frac{1.72\, m}{1500\, m/s} - \frac{1\, m}{1500\, m/s}$. A time difference of $\approx 0.5\, ms$ was obtained for the first reflection with respect to the expected arrival time of the direct signal. The beginning of the time window was determined using the standard deviation of the pre-trigger signal. The beginning of the direct signal was determined using a $5\sigma$ threshold value. The pure signal which was further analysed can be seen in the grey band. The red horizontal line depicts the $5\sigma$ threshold value. A detailed view of analysed transient is shown in Fig. 6.6. The pre-trigger signal has been shown by the pink band for which a standard deviation $\sigma$ was calculated.
Finally, a standard deviation of the output voltage was calculated for each frequency to quantify the output recorded by the hydrophone. The statistical error on these values was calculated by performing the analysis for $4\sigma$ and $6\sigma$ threshold values and taking the standard deviation for these cases. The errors were then propagated using gaussian error propagation. The standard deviation of the pre-trigger signal was also added to the statistical error for each transient. The standard deviation of the direct signal for the total frequency range in case of neptune is presented in Fig. 6.7. The peak height of the transfer curve is marked with point $P_1$.

Figure 6.6: Transient recorded from the oscilloscope for the acoustic measurements

Figure 6.7: The standard deviation of the output voltage obtained for Neptune
6.3. DIRECT SIGNAL MEASUREMENTS

This plot is a statistical measure of the transfer function of Neptune as an emitter. The peak was obtained to be $0.541 \pm 0.007 \text{V}$ at frequency $18.550 \pm 0.025 \text{kHz}$. The supplied signal amplitude was $0.15 \text{V}$. The error on the frequency is obtained from the sampling step of the frequency which was $50 \text{Hz}$. Additionally, the speed of sound in water was calculated from the transients recorded during acoustic measurements. A mean of the time difference between the beginning of the trigger signal to the time window for each frequency was calculated to be $695 \pm 1.23 \text{µs}$. The speed of sound for a distance of $1 \pm 0.05 \text{m}$ was then obtained to be $c_s = 1438.57 \pm 71.971 \text{ m/s}$. This was within $1\sigma$ of the expected speed of sound in water at room temperature.

The measured results can now be compared to the data sheet values. For this purpose, the measured transfer function was calculated for a reference $1 \text{V}$ input voltage and converted to decibels using $dB = 20 \cdot log_{10}(V_{out}/V_{in})$. The transfer function from the data sheet were calculated by taking a sum of the hydrophone and projector sensitivity curves. The measured transfer function was also rescaled for comparison as it is a statistical measure and not the absolute output amplitudes. However, the expected response of the curves should still be comparable. The comparison plot is shown in Fig. 6.8.

![Comparison Plot](image)

Figure 6.8: The measured transfer curve with respect to the expected curve

The measured results agree quite well with the expected transfer function which implies that the measurement method works for the setup. Therefore, further measurements were performed using the same measurement setup. The sound pressure in the medium emitted by the projector can be calculated using the projector sensitivity and the transfer curve. However, since the hydrophone used throughout the measurements for all versions of the demonstrator was ITC, a comparison of the measured transfer curves provided a reasonable comparison of the acoustic emission of demonstrators.
6.3 Direct Signal Measurements

The transfer characteristics were measured for a direct signal along the longitudinal axis for which the response is maximum, with the help of a hydrophone at a radial distance in the far field where the pressure variation is expected to be proportional to $1/r$ and the beam pattern does not change with distance [37]. The far field distance can be calculated using the $r \geq D^2/\lambda$ where $D$ is the dimension of the radiating area of the projector and $\lambda$ is the wavelength of the emitted signal. For a radiating surface of any shape the far field distance can be estimated as the square of the maximum dimension divided by $2\lambda$ [56]. For our case, the distance 1 m was much greater than the far-field threshold, given the dimensions of the order of 10 cm of the emitter. Furthermore, the maximum response of a tonpilz type emitter is for head on emission, i.e, when the radiating head mass is at 0° with respect to the hydrophone. This is because tonpliz transducers have a strong forward directionality [37]. Therefore, the direct signal measurements for all the versions were performed.

The emitter was lowered into the water with the help of aluminium profiles and set on a rotation bench. This bench was controlled using an arduino board and a motor. It was developed at the institute by Simon Zierke for previous measurements involving the APUs [57]. The angle on the rotation bench was set to 0°. The uncertainty on the angle was taken to be ±5°. The emitter was placed in a custom built casing as shown in Fig. 6.9. It was decoupled from the casing with the help of rubber insulation. The complete setup is presented in Fig. 6.10.

![Image](image.png)

Figure 6.9: The emitter enclosed in the custom casing; The decoupling from the casing to prevent alterations to the acoustic output was done using the rubber insulation material.
The data processing was identical to the procedure described for the preliminary measurements. The obtained standard deviation curves for all versions are summarised below. The input signal amplitude was maintained at 0.15 V, and the hydrophone used for each case was the ITC. The curves can therefore, be compared to each other without any alterations. The characteristics of the peaks of the obtained curves are also presented in the corresponding tables. The peaks have been marked with $P_i$ notation the transfer curves. A discussion for the obtained results is included at the end of this section.
Figure 6.11: The standard deviation of output voltage as a function of frequency for $V_1 : T1H1$

Figure 6.12: The standard deviation of output voltage as a function of frequency for $V_2 : T2H1$
6.3. DIRECT SIGNAL MEASUREMENTS

Figure 6.13: The standard deviation of output voltage as a function of frequency for $V_3: T1H2$

Figure 6.14: The standard deviation of output voltage as a function of frequency for $V_4: T2H2$
Table 6.1: The corresponding peak frequencies and standard deviation for $V_1$ shown in Fig. 6.11 is presented

<table>
<thead>
<tr>
<th>Peaks</th>
<th>Frequency (Hz)</th>
<th>$\sigma$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8000 ± 25</td>
<td>0.190 ± 0.027</td>
</tr>
<tr>
<td>2</td>
<td>12350 ± 25</td>
<td>0.278 ± 0.026</td>
</tr>
<tr>
<td>3</td>
<td>16400 ± 25</td>
<td>0.247 ± 0.020</td>
</tr>
<tr>
<td>4</td>
<td>22250 ± 25</td>
<td>0.564 ± 0.022</td>
</tr>
<tr>
<td>5</td>
<td>26750 ± 25</td>
<td>0.160 ± 0.026</td>
</tr>
</tbody>
</table>

Table 6.2: The corresponding peak frequencies and standard deviation for $V_2$ shown in Fig. 6.12 is presented

<table>
<thead>
<tr>
<th>Peaks</th>
<th>Frequency (Hz)</th>
<th>$\sigma$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8700 ± 25</td>
<td>0.250 ± 0.010</td>
</tr>
<tr>
<td>2</td>
<td>12250 ± 25</td>
<td>0.590 ± 0.017</td>
</tr>
<tr>
<td>3</td>
<td>16000 ± 25</td>
<td>0.441 ± 0.021</td>
</tr>
<tr>
<td>4</td>
<td>21050 ± 25</td>
<td>0.263 ± 0.018</td>
</tr>
<tr>
<td>5</td>
<td>26100 ± 25</td>
<td>0.125 ± 0.023</td>
</tr>
</tbody>
</table>

Table 6.3: The corresponding peak frequencies and standard deviation for $V_3$ shown in Fig. 6.13 is presented

<table>
<thead>
<tr>
<th>Peaks</th>
<th>Frequency (Hz)</th>
<th>$\sigma$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8600 ± 25</td>
<td>0.273 ± 0.017</td>
</tr>
<tr>
<td>2</td>
<td>12250 ± 25</td>
<td>0.556 ± 0.017</td>
</tr>
<tr>
<td>3</td>
<td>15550 ± 25</td>
<td>0.469 ± 0.020</td>
</tr>
<tr>
<td>4</td>
<td>23050 ± 25</td>
<td>0.962 ± 0.019</td>
</tr>
</tbody>
</table>

Table 6.4: The corresponding peak frequencies and standard deviation for $V_4$ shown in Fig. 6.14 is presented

<table>
<thead>
<tr>
<th>Peaks</th>
<th>Frequency (Hz)</th>
<th>$\sigma$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8750 ± 25</td>
<td>0.258 ± 0.013</td>
</tr>
<tr>
<td>2</td>
<td>13150 ± 25</td>
<td>0.742 ± 0.009</td>
</tr>
<tr>
<td>3</td>
<td>16450 ± 25</td>
<td>1.130 ± 0.018</td>
</tr>
<tr>
<td>4</td>
<td>25600 ± 25</td>
<td>0.266 ± 0.014</td>
</tr>
</tbody>
</table>
6.3.1  Discussion

A comparison of the transfer curves obtained for each version as well as neptune with respect to the ITC as the receiver is presented in Fig. 6.15.

Figure 6.15: The transfer curves for all versions of the demonstrator as well as the Neptune for comparison

The peaks obtained from the above analysis were observed to agree reasonably with the peaks obtained previously from the impedance measurements in water [5.7] and air [5.4] for the case of fully assembled demonstrator. This allows for a verification of the results obtained from the impedance measurements. The shift in the resonance frequencies with change in the reduced mass agrees with the predictions of the equivalent circuit.

A characteristic peak for the lighter tail mass was observed for both V2 and V4 near 25 kHz. The measured peaks around 8 kHz do not see a significant variation in their heights, leading to a belief that they maybe a characteristic feature of the housing which is constant in all versions. Further investigation is however required to understand the characteristics of these peaks.

It is interesting to note that out of the four versions of the demonstrator, two versions V2 and V3 were comparable in magnitude of the emitted acoustic signals to that of the commercial projector Neptune. The configuration V4 was observed to be nearly twice as loud as the Neptune for a head on emission. This agrees with the impedance measurement results, where the mechanical resistance for V4 was minimum and along with a high radiation resistance observed from water impedance measurements. Finally, as per the predictions from the equivalent circuit, as well as impedance measurements, the version V1 was expected to have low magnitude of the acoustic output, due to the high mechanical resistance. The acoustic measurements agree reasonably with the impedance measurement results.
6.4 Angular Measurements

Following the direct signal measurements, angular measurements were performed for studying the directional response of these demonstrator versions. A total of 8 measurements were taken for 8 angles ranging from 0 to 180° in steps of 22.5°. The setup was identical to Fig. 6.10. A time delay of 5 min between two angular measurements was implemented, so that the vibrations from previous measurements as well as due to change in the angle, could be eliminated. The peaks obtained from the direct signal measurements were investigated for change in the angle of emission with respect to the hydrophone position. The results for each of the configuration are shown in the form of polar plots in Figs. 6.16 to 6.19. Since the demonstrator is of a cylindrical shape, the response of the system from 180 to 360° is symmetrical. Hence, the polar plots for the whole plane was obtained by mirroring the measured results for 0 to 180°.

The characteristic peak heights with the estimated errors have been presented in a tabular form in the appendix C. For V1 configuration, the measured angles were more than 8. The further measurements were restricted to 8 angles due to the time and data storage constraints. Each measurement took 2 hours to collect big data because of a high set memory depth. However, the variation in the output characteristics can be reasonably observed with the measured results.

The angular response of the demonstrator versions has been presented in the form of polar plots. A clear inference from the plots can be the forward boosted emission of the demonstrator. This is expected from the theory of tonpilz transducers. Additionally, it was observed that the versions which included aluminium head mass had a greater output amplitude compared to the ones including the steel head mass. However, the directional response of the versions including the stainless steel mass was more uniform with change in angles.

This can be explained by the transmission coefficients of the two materials and their coupling to the rest of the system. The transmission coefficient of aluminium is greater than stainless steel in water, and hence, most of the acoustic signal is transferred to the water medium. Since, the housing is stainless steel, the acoustic power is decoupled by the housing and a more even distribution in the form of forward and backward emission can be seen, as shown by V1 (Fig. 6.16) and V2 (Fig. 6.17). The resonances of the V1 and V2 are similar due to the common tail mass, which is shifted in case of V3 and V4 for which the tail mass is much lighter. The emission from the V4 demonstrator version was observed to be the loudest. This was in agreement with from previous impedance and acoustic measurements, which was expected to be due to the small mechanical resistance value and a wide bandwidth in water for V4. Further measurements were carried out to verify these results in a swimming pool where the reflections in the medium could be minimised.
Figure 6.16: Polar representation of the directional response of V1 for observed resonances

Figure 6.17: Polar representation of the directional response of V2 for observed resonances
Figure 6.18: Polar representation of the directional response of V3 for observed resonances

Figure 6.19: Polar representation of the directional response of V4 for observed resonances
6.5 Swimming Pool Test

Following the laboratory measurements, the demonstrator version V4 was further investigated in a bigger water body. A swimming pool was chosen for the task. The objective of the swimming pool test was to verify the results from the laboratory measurements for the direct signal measurement with a greater time window. The swimming pool test was carried out at the Ulla Klinger Halle in Aachen. The time allotted for the measurements was limited and therefore, the measurement method had to be modified. A floating raft was built with a provision for two hydrophones at the ends, both equidistant from the an emitter suspended in the middle with an M14 threaded rod. The distance between the emitter and the receivers was maintained at 1 m each. The arrangement is shown in Fig. 6.20.

![Image](image_url)

Figure 6.20: The setup for angular acoustic measurement using floating raft built with aluminium profiles and styrofoam

Two Neptunes were used as receivers for this measurement. A direct signal from these was recorded for each measurement. The amplification circuit with the differential output was not used. The setup was suspended using a wooden rod and floating devices into the water at a distance more than 2 m from the walls of the pool. The emitter and receivers were also immersed 2 m deep. This was done to obtain a time window of 2 ms for obtaining the direct signal with minimum reflections. The complete setup is shown in Fig. 6.21. The setup facilitated acoustic measurement for two opposite angles at the same time. For angular measurements the angle of the emitter was changed manually with the help of a handle at the top of the raft (Fig. 6.20). An uncertainty of ±5° can thus be assumed.
The measurements were carried out for 8 angles from 0 to 180° in steps of 22.5°. Due to the time constraint the angular measurements were carried out for a range of 2 kHz around the peaks obtained from the laboratory measurements in steps of 100 Hz. A full scan for a range of 3 to 35 kHz was also carried out for the direct signal measurement. The resonance peaks observed agreed reasonably with the laboratory resonances, summarised in table 6.5. However, the fourth peak was not as distinguishable as for the laboratory results. Therefore, the peak value for analysis for the fourth peak was taken from the predefined laboratory results. The measured transfer curve is shown in the Fig. 6.22. Due to the dual receiver setup, a comparison of the direct signal measurement to a 180°, i.e, backward emission was possible. The relevant comparison plot is included in appendix C. The input amplitude for these measurements was 20 V. The height of the transfer curve was observed to be (0.057 ± 0.0026 V), at (16.100 ± 0.025 kHz). This was comparable to the laboratory measurements which peaked to (0.0530 ± 0.0032 V) at (16.450 ± 0.025 kHz), without the gain and reference voltage, considering it to be a linear system. The errors for this measurement was observed to be higher, than the laboratory measurements. This was due to the lack of differential output in case of the laboratory measurements for minimising the noise 54.

Table 6.5: The corresponding peak frequencies and standard deviation for V4 shown in Fig. 6.22 is presented

<table>
<thead>
<tr>
<th>Peaks</th>
<th>Frequency (Hz)</th>
<th>σ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9200 ± 25</td>
<td>0.0213 ± 0.0034</td>
</tr>
<tr>
<td>2</td>
<td>13200 ± 25</td>
<td>0.0369 ± 0.0038</td>
</tr>
<tr>
<td>3</td>
<td>16100 ± 25</td>
<td>0.0577 ± 0.0026</td>
</tr>
<tr>
<td>4</td>
<td>25600 ± 25</td>
<td>0.0146 ± 0.0023</td>
</tr>
</tbody>
</table>
Finally, the angular response for the peaks of the transfer curve was obtained, as in Sec. 6.4. It is shown in Fig. 6.23.

The directional response obtained from the swimming pool test was observed to agree with the laboratory measurements for forward emission. The backward emission was observed to vary
from the laboratory measurements. This could be due to the limitation of the water tank setup. The angular spread in the forward direction from the swimming pool test was observed to be of a wider range, with the maximum amplitude around 16 kHz for $\pm 22.5^\circ$.

6.6 Summary

The electrical measurement results were verified with acoustic characterisation of the demonstrator versions in this chapter. The measurement method was successfully verified with the commercial projector Neptune D17. A comparison of the transfer characteristics of the demonstrator versions was possible with the acoustic measurements using ITC-1001 as the receiver for all cases.

In case of direct emission, the maximum response of the emitters was observed. The results were aligned with the electrical measurements for the fully assembled demonstrators. The resonances were observed to agree with the predicted values and shifted with change in masses. The V4 version demonstrator, which consisted of aluminium head mass and the lighter tail mass was observed to have the maximum emitted output for direct signal measurements. On comparing with Neptune (see Fig. 6.15), the acoustic output of V2 and V3 were found to be comparable in magnitude to Neptune. Furthermore, V4 was observed to be almost two times louder than Neptune.

From the angular response measurements, the directional emission of the demonstrator was observed, due to the tonpilz type construction. V3 and V4, with aluminium head masses were observed to be more directional than V1 and V2. This is expected due to the high transmission coefficient of the material. The material of the pressure housing is important for this emission, as the stainless steel head masses are coupled to the housing easily, leading to a uniformly distributed emission. In case of omnidirectional response, V2 can be considered a good candidate. For this project, however, the focus was on the acoustic output amplitude which was maximum for V4. Hence, swimming pool tests were performed.

The swimming pool test verified the forward boosted directional response of the demonstrator. The angular response however had some deviations from the laboratory results, which should be investigated in the future iterations.
Chapter 7

Conclusion and Outlook

The acoustic calibration system planned for the IceCube Upgrade is a promising endeavour for the next generation. It’s inclusion will facilitate an independent geometry calibration and improvement in the current calibration accuracy.

In this thesis, a demonstrator for the acoustic modules for the Upgrade was developed and tested. The focus of the thesis was the functioning of the modules as acoustic emitters. The mechanical design presented in this work was adapted for laboratory tests, while keeping the considerations for inclusion in the Upgrade, in focus. Various electrical and acoustic measurements in air and water were performed for four different versions of the demonstrator. A comparison of the measured results to a commercial projector, Neptune D17, was also presented.

It has been shown with the results obtained in this work, that the demonstrator is competent in terms of acoustic output with the commercial counterpart. One of the versions has also been observed to be superior in directional output in comparison to the Neptune. This indicates that a competent, cost effective alternative to a commercial projector can be constructed for the acoustic modules. Additionally, the measured results have been verified with respect to a theoretical equivalent model to a reasonable understanding.

Work is required in order to improve the demonstrator for obtaining a prototype of the acoustic modules. The complex system cannot be characterised completely using the simplified equivalent circuit. Simulations and analysis based on mathematical models like finite element method, Matrix method etc. can be implemented in the future for a better understanding of the complex mechanical system. Furthermore, the system should be optimised for the operational requirements at the South Pole.
Appendix A

Technical Drawings
Figure A.1: Technical drawing of the End cap
Figure A.2: Technical drawing of the Head mass
Figure A.3: Technical drawing of the Pressure housing
Figure A.4: Technical drawing of the Tail mass
Appendix B

Impedance Measurement Results

The Impedance measurements plots for all versions are presented in this chapter. For each version first the results from the air measurements for both cases are presented followed by the water measurements.
B.1 V1:T1H1

B.1.1 Air Impedance Measurements

Figure B.1: Case: Without pressure housing; Top: Admittance magnitude as a function of frequency; Middle: Conductance as a function of frequency; Bottom: Closer view of the conductance peak.
Figure B.2: Case: With pressure housing; Top: Admittance magnitude as a function of frequency; Bottom: Conductance as a function of frequency.
B.1.2 Water Impedance Measurements

Figure B.3: Case: Without pressure housing; Top: Admittance magnitude as a function of frequency; Middle: Conductance as a function of frequency; Bottom: Closer view of the conductance peak.
Figure B.4: Case: With pressure housing; Top: Admittance magnitude as a function of frequency; Bottom: Conductance as a function of frequency.
B.2 V3:T1H2

B.2.1 Air Impedance Measurements

Figure B.5: Case: Without pressure housing; Top: Admittance magnitude as a function of frequency; Middle: Conductance as a function of frequency; Bottom: Closer view of the conductance peak.
Figure B.6: Case: With pressure housing; Top: Admittance magnitude as a function of frequency; Bottom: Conductance as a function of frequency.
B.2.2 Water Impedance Measurements

Figure B.7: Case: Without pressure housing; Top: Admittance magnitude as a function of frequency; Middle: Conductance as a function of frequency; Bottom: Closer view of the conductance peak
Figure B.8: Case: With pressure housing; Top: Admittance magnitude as a function of frequency; Bottom: Conductance as a function of frequency.
B.3 V4:T2H2

B.3.1 Air Impedance Measurements

Figure B.9: Case: Without pressure housing; Top: Admittance magnitude as a function of frequency; Middle: Conductance as a function of frequency; Bottom: Closer view of the conductance peak.
Figure B.10: Case: With pressure housing; Top: Admittance magnitude as a function of frequency; Bottom: Conductance as a function of frequency.
B.3.2 Water Impedance Measurements

Figure B.11: Case: Without pressure housing; Top: Admittance magnitude as a function of frequency; Middle: Conductance as a function of frequency; Bottom: Closer view of the conductance peak.
Figure B.12: Case: With pressure housing; Top: Admittance magnitude as a function of frequency; Bottom: Conductance as a function of frequency.
Appendix C

Acoustic Characterisation

The standard deviation for the peaks of the polar plots presented in Chapter 6 along with their error are presented in this section. Each peak was examined for various angles ranging from 0 to 180°. These peaks are a measure of the angular response of different versions of the demonstrator.

<table>
<thead>
<tr>
<th>Angle</th>
<th>Peak 1 (V)</th>
<th>Peak 2 (V)</th>
<th>Peak 3 (V)</th>
<th>Peak 4 (V)</th>
<th>Peak 5 (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.190 ± 0.026</td>
<td>0.278 ± 0.026</td>
<td>0.247 ± 0.026</td>
<td>0.564 ± 0.026</td>
<td>0.160 ± 0.026</td>
</tr>
<tr>
<td>30.0</td>
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<td>0.407 ± 0.017</td>
<td>0.133 ± 0.017</td>
</tr>
<tr>
<td>35.0</td>
<td>0.161 ± 0.022</td>
<td>0.184 ± 0.022</td>
<td>0.158 ± 0.022</td>
<td>0.247 ± 0.022</td>
<td>0.092 ± 0.022</td>
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<td>40.0</td>
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<td>0.160 ± 0.027</td>
<td>0.233 ± 0.027</td>
<td>0.078 ± 0.027</td>
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<td>45.0</td>
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<td>0.253 ± 0.031</td>
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<td>0.130 ± 0.029</td>
<td>0.057 ± 0.029</td>
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<td>55.0</td>
<td>0.151 ± 0.022</td>
<td>0.207 ± 0.022</td>
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<td>90.0</td>
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<td>0.105 ± 0.013</td>
<td>0.048 ± 0.013</td>
<td>0.160 ± 0.013</td>
<td>0.052 ± 0.013</td>
</tr>
<tr>
<td>120.0</td>
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<td>0.395 ± 0.019</td>
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<td>135.0</td>
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<td>0.320 ± 0.024</td>
<td>0.123 ± 0.024</td>
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<td>160.0</td>
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<td>0.211 ± 0.016</td>
<td>0.097 ± 0.016</td>
<td>0.231 ± 0.016</td>
<td>0.052 ± 0.016</td>
</tr>
</tbody>
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Table C.1: The peak height as obtained for V1 along with uncertainties
APPENDIX C. ACOUSTIC CHARACTERISATION

<table>
<thead>
<tr>
<th>Angle</th>
<th>Peak 1 (V)</th>
<th>Peak 2 (V)</th>
<th>Peak 3 (V)</th>
<th>Peak 4 (V)</th>
<th>Peak 5 (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.250 ± 0.023</td>
<td>0.590 ± 0.023</td>
<td>0.441 ± 0.023</td>
<td>0.263 ± 0.023</td>
<td>0.125 ± 0.023</td>
</tr>
<tr>
<td>22.5</td>
<td>0.203 ± 0.023</td>
<td>0.462 ± 0.023</td>
<td>0.366 ± 0.023</td>
<td>0.181 ± 0.023</td>
<td>0.105 ± 0.023</td>
</tr>
<tr>
<td>45.0</td>
<td>0.139 ± 0.021</td>
<td>0.441 ± 0.021</td>
<td>0.385 ± 0.021</td>
<td>0.182 ± 0.021</td>
<td>0.105 ± 0.021</td>
</tr>
<tr>
<td>67.5</td>
<td>0.161 ± 0.023</td>
<td>0.119 ± 0.023</td>
<td>0.148 ± 0.023</td>
<td>0.055 ± 0.023</td>
<td>0.065 ± 0.023</td>
</tr>
<tr>
<td>90.0</td>
<td>0.147 ± 0.016</td>
<td>0.115 ± 0.016</td>
<td>0.143 ± 0.016</td>
<td>0.063 ± 0.016</td>
<td>0.041 ± 0.016</td>
</tr>
<tr>
<td>112.5</td>
<td>0.081 ± 0.012</td>
<td>0.276 ± 0.012</td>
<td>0.236 ± 0.012</td>
<td>0.131 ± 0.012</td>
<td>0.050 ± 0.012</td>
</tr>
<tr>
<td>135.0</td>
<td>0.224 ± 0.014</td>
<td>0.253 ± 0.014</td>
<td>0.160 ± 0.014</td>
<td>0.123 ± 0.014</td>
<td>0.045 ± 0.014</td>
</tr>
<tr>
<td>157.5</td>
<td>0.223 ± 0.016</td>
<td>0.435 ± 0.016</td>
<td>0.384 ± 0.016</td>
<td>0.191 ± 0.016</td>
<td>0.105 ± 0.016</td>
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<tr>
<td>180.0</td>
<td>0.223 ± 0.018</td>
<td>0.435 ± 0.018</td>
<td>0.370 ± 0.018</td>
<td>0.194 ± 0.018</td>
<td>0.105 ± 0.018</td>
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Table C.2: The peak height as obtained for V2 along with uncertainties

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<th>Peak 4 (V)</th>
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<tbody>
<tr>
<td>0.0</td>
<td>0.273 ± 0.019</td>
<td>0.556 ± 0.019</td>
<td>0.469 ± 0.019</td>
<td>0.962 ± 0.019</td>
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<tr>
<td>22.5</td>
<td>0.263 ± 0.013</td>
<td>0.424 ± 0.013</td>
<td>0.445 ± 0.013</td>
<td>0.781 ± 0.013</td>
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<tr>
<td>45.0</td>
<td>0.160 ± 0.012</td>
<td>0.324 ± 0.012</td>
<td>0.274 ± 0.012</td>
<td>0.243 ± 0.012</td>
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<td>67.5</td>
<td>0.118 ± 0.012</td>
<td>0.170 ± 0.012</td>
<td>0.129 ± 0.012</td>
<td>0.089 ± 0.012</td>
</tr>
<tr>
<td>90.0</td>
<td>0.079 ± 0.013</td>
<td>0.113 ± 0.013</td>
<td>0.071 ± 0.013</td>
<td>0.091 ± 0.013</td>
</tr>
<tr>
<td>112.5</td>
<td>0.036 ± 0.015</td>
<td>0.134 ± 0.015</td>
<td>0.148 ± 0.015</td>
<td>0.082 ± 0.015</td>
</tr>
<tr>
<td>135.0</td>
<td>0.113 ± 0.015</td>
<td>0.131 ± 0.015</td>
<td>0.163 ± 0.015</td>
<td>0.180 ± 0.015</td>
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<tr>
<td>157.5</td>
<td>0.142 ± 0.016</td>
<td>0.089 ± 0.016</td>
<td>0.046 ± 0.016</td>
<td>0.186 ± 0.016</td>
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<tr>
<td>167.5</td>
<td>0.141 ± 0.019</td>
<td>0.117 ± 0.019</td>
<td>0.042 ± 0.019</td>
<td>0.036 ± 0.019</td>
</tr>
<tr>
<td>180.0</td>
<td>0.173 ± 0.017</td>
<td>0.145 ± 0.017</td>
<td>0.062 ± 0.017</td>
<td>0.143 ± 0.017</td>
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Table C.3: The peak height as obtained for V3 along with uncertainties

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<tr>
<th>Angle</th>
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<th>Peak 3 (V)</th>
<th>Peak 4 (V)</th>
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<td>0.0</td>
<td>0.258 ± 0.014</td>
<td>0.742 ± 0.014</td>
<td>1.130 ± 0.014</td>
<td>0.266 ± 0.014</td>
</tr>
<tr>
<td>22.5</td>
<td>0.172 ± 0.019</td>
<td>0.383 ± 0.019</td>
<td>0.655 ± 0.019</td>
<td>0.194 ± 0.019</td>
</tr>
<tr>
<td>45.0</td>
<td>0.099 ± 0.018</td>
<td>0.278 ± 0.018</td>
<td>0.489 ± 0.018</td>
<td>0.105 ± 0.018</td>
</tr>
<tr>
<td>67.5</td>
<td>0.123 ± 0.014</td>
<td>0.098 ± 0.014</td>
<td>0.227 ± 0.014</td>
<td>0.037 ± 0.014</td>
</tr>
<tr>
<td>90.0</td>
<td>0.114 ± 0.016</td>
<td>0.149 ± 0.016</td>
<td>0.081 ± 0.016</td>
<td>0.045 ± 0.016</td>
</tr>
<tr>
<td>135.0</td>
<td>0.074 ± 0.010</td>
<td>0.169 ± 0.010</td>
<td>0.373 ± 0.010</td>
<td>0.069 ± 0.010</td>
</tr>
<tr>
<td>157.5</td>
<td>0.172 ± 0.014</td>
<td>0.146 ± 0.014</td>
<td>0.064 ± 0.014</td>
<td>0.030 ± 0.014</td>
</tr>
<tr>
<td>180.0</td>
<td>0.194 ± 0.012</td>
<td>0.191 ± 0.012</td>
<td>0.134 ± 0.012</td>
<td>0.048 ± 0.012</td>
</tr>
</tbody>
</table>

Table C.4: The peak height as obtained for V4 along with uncertainties

The swimming pool measurement setup facilitated the angular emission measurement for two opposite angles at the same time. An acoustic measurement for a frequency range of 0 to 35 kHz in steps of 100 Hz was performed for 0° angle. The transfer curve for direct and back end emission are presented for comparison in Fig. C.1. The emitter has a forward boosted emission. The peaks in the transfer curve observed for the direct measurement decrease significantly for 180° angle.
Figure C.1: Representation of direct signal acoustic measurement for V4 versus the backend emission at 180° in the swimming pool test.
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