Testing of a life saving device for scuba divers (Buddy Buzzer)

J.W.H. van Dordrecht

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Preface

This report, “Testing of a life saving device for Scuba divers (Buddy Buzzer)”, covers the short internship report study of the author, which has been performed within the division of Dynamics and Control of the faculty of Mechanical Engineering at the Eindhoven Technical University. The research was carried out within a project of 2M Engineering Ltd.

During this project I learned a lot of new things in mechanical vibration theory, behaviour of sound and data acquisition. I have met a lot of new people who made it possible for me to realize this project, and I would like to thank a few of them: first of all Henk Nijmeijer, Ines Lopez and Bert Roozen for giving me this assignment and support. Second of all I would like to thank Jan Mink and Gillian Mimnagh-Kelleher of 2M Engineering Ltd. for giving us the prototype of the Buddy Buzzer. Further I would like to thank Rens Kodde for the time, interest and help with the experimental set-up and Dik Hermes for the time and interest during the experiments in the Dommel. Finally I would like to thank Erwin van de Wiel for the good cooperation during our internship.

Eindhoven, March 2006
Summary

In the last years scuba diving has become more and more popular. But the increasing number of scuba divers has led to an increased number of fatal accidents worldwide. Therefore the company 2M Engineering Ltd. is developing a life saving device called the Buddy Buzzer. The goal of this traineeship is to test this prototype in the DCT lab and get a thorough understanding of the physical phenomena involved. Eventually this should lead to an improvement of the Buddy Buzzer design. The prototype consists of a piezoelectric element attached to a steel membrane and mounted in a casting.

Several frf measurements in air have been done in order to gain insight in the behavior and dynamics of the prototype of the buzzer. The resonance of the membrane in air occurs at 7250 Hz. The mechanical velocity at the resonance is 18 dB (ref 1 m/s/V). The mechanical velocity measured on the backside of the buzzer is -27 dB (ref 1 m/s/V) for a frequency of 7250 Hz. This is 45 dB lower than the mechanical velocity measured on the membrane. So the backside of the buzzer can be considered as fixed world.

In order to visualize the vibration shapes of the membrane, velocity measurement have been done in several points on the membrane. The first vibration shape occurs at 7250 Hz and the second vibration shape occurs at 16000 Hz.

In order to evaluate the results obtained by the tests, the test results are compared with the results from the FEM-model modelled by Erwin van der Wiel. The first and second natural frequencies match very well.

Frf measurements in water have been done in order to gain insight in the behavior and dynamics of the prototype of the buzzer in water. The resonance of the membrane in water occurs at 5300 Hz. The mechanical velocity at the resonance is 18 dB (ref 1 m/s/V). To check if the previous measurement in water is correct (the laser beam may refract in water), an extra accelerometer has been added for the new measurement. The resonance frequency has been lowered by 300 Hz. This decrease occurs due to the extra mass of the acceleration meter. The original velocity and the velocity obtained from the integration of the acceleration have a difference in amplitude of 2-3 dB.

In order to check if the behavior in water is the same as in air also an accelerometer has been added to the membrane in air. Now both transfers, input to velocity and input to acceleration, have been measured like in water. The resonance frequency has been lowered by 1550 Hz. This a relatively more than in water. The amplitude of the velocity and the amplitude of the velocity obtained from the integration of the acceleration exactly match. In order to avoid the effect of reflections, several measurements have been done in the Dommel. A resonance occurs at 5300 Hz. But at the 5750 Hz an anti-resonance occurs. After that, the amplitude increases slightly.

In order to understand why the amplitude is increasing for higher frequencies, an acoustic ra-
diation model has been analyzed. The amplitude of the Sound Pressure Level obtained from the transfer function from input to velocity is slightly increasing after the resonance. The amplitude of the Dommel measurement and the amplitude of the acoustic radiation model almost match. But after the resonance the amplitude of the measurement is increasing much more than the amplitude of the model. In the model no anti-resonance occurs.

Finally one can conclude that the first resonance in air occurs at 7250 Hz, with an amplitude of 18 dB (ref 1 m/s/V). At this frequency the first vibration shape \((i= 0, j= 0)\) is excited. The second resonance occurs at 16000 Hz. At this frequency the second vibration shape \((i= 1, j= 0)\) is excited. In theory the piezoelectric element will not excite this vibration shape because of the symmetry of the piezoelectric element. This vibration shape is excited because the piezoelectric element is not perfectly attached to the center of the membrane. The first resonance in water occurs at 5300 Hz, with also an amplitude of 18 dB (ref 1 m/s/V). Measured with an hydrophone the amplitude is 76 dB (ref 1e-6 Pa/V).

For future frf measurements the transfer \(\text{out} / \text{in} \) to velocity should be measured in stead of the transfer input to velocity. That way only the dynamics of the system will be considered without the electronics. The 3 dB difference in velocity and velocity obtained from the integration of the acceleration can be further examined. Also the dip in the resonance peak that occurs in the measurements of the velocity and acceleration in water, with the added accelerometer should be further examined. The difference in the Sound Pressure Level measurements in the Dommel and the results of the acoustic radiation model should be further examined. Also the anti-resonance that occurs in measurements that were done in the Dommel should be further examined.
Contents

Preface iii

Summary v

1 Introduction 1
  1.1 Problem formulation ............................................. 1
  1.2 Outline of the report ............................................ 2

2 Buddy Buzzer prototype 3

3 Measurements in air 5
  3.1 Frf measurements in air .......................................... 5
  3.2 Vibration shapes .................................................. 8
  3.3 Comparison of testresults and FEM-model results in air .......... 12

4 Frf Measurements in water 13
  4.1 Velocity and acceleration measurement in water .................. 14
  4.2 Velocity and acceleration measurement in air .................... 15
  4.3 Measurements with hydrophone ................................... 17
  4.4 Acoustic radiation model ......................................... 18

5 Conclusions and Recommendations 21
  5.1 Conclusions ....................................................... 21
  5.2 Recommendations ................................................ 21

A Material properties membrane 23

B Nodal lines for a circular plate 25
Chapter 1

Introduction

In the last years scuba diving has become more and more popular. But the increasing number of scuba divers has led to an increased number of fatal accidents worldwide. The main cause for these accidents is that the victim panics, cannot warn his buddy and tries to get out of the water as soon as possible, which is a terrible mistake.

The company 2M Engineering Ltd. is developing a life saving device called the Buddy Buzzer. The goals of this device are:

- Divers will feel more confident when wearing such a device
- It will allow divers to warn their buddy if they are in trouble
- It will help the rescue teams find the missing diver quicker

The Buddy Buzzer should be a compact device able to produce loud noise levels and a strong light during 1 hour and keep on sending light signals during 24 hours. It should work down to 100 meter depth and be energy efficient and easy to use.

The Dynamics and Control group will focus on the noise generation and propagation aspects. What is the most efficient way to generate high levels of noise underwater? How does the sound propagate from the source to the receiver? At the moment 2M is working on a prototype consisting of a piezoelectric element attached to a steel membrane and mounted in a casting.

1.1 Problem formulation

The goal of this traineeship is to test this prototype in the DCT lab and get a thorough understanding of the physical phenomena involved. Eventually this should lead to an improvement of the Buddy Buzzer design. The first step will be to test the system in air and compare the results to a FEM model built by Erwin van der Wiel in a twin traineeship. Next the interaction of the prototype with the water will be tested. To this end, a suitable test set-up has to be developed in the lab. The effect of reflections not present in the real life situation should be compensated for. The results from the underwater tests will also be compared to the FEM results in order to gain insight into the behavior of the system.
1.2 Outline of the report

This report is organized as follows. In chapter 2, the Buddy Buzzer is introduced. Here, the several elements which the prototype consists of are being discussed. In chapter 3, frequency response measurements in air and the vibration shapes of the membrane will be discussed. Also the results in air of both the tests and the FEM model are being discussed. Next in chapter 4 frequency response measurements in water will be discussed. Finally, in chapter 5 conclusions and recommendations are given.
Chapter 2

Buddy Buzzer prototype

To see which elements the prototype of the Buddy Buzzer consists of, the prototype has been unscrewed. The different elements which the prototype consists of are shown in figure 2.1. The prototype consists of a piezoelectric element (no. 7) attached (by glue) to a steel membrane. This membrane is a part of the front casting (no. 4) and mounted in a back casting (no. 1). The casting consists of an o-ring (no. 3) which makes sure that the prototype is waterproof. The cable (no. 8) guides the power through a brass element (no. 2) to an other brass element (no. 6). Then the power is guided through a wire (no. 5) to one side of the piezoelectric element. To make use of the piezoelectric properties the other electrode is connected to the housing. The glue between the piezoelectric element and the membrane is thinned, so there is electrical contact.

![Figure 2.1: The Buddy Buzzer unscrewed](image)

Piezoelectricity is the ability of certain crystals to generate a voltage in response to applied mechanical stress. The piezoelectric effect is reversible in that piezoelectric crystals when subjected to an externally applied voltage, can change shape by a small amount. The latter is applied in the buzzer. This is called the converse effect [3]. In figure 2.2 the deformation as a result of the piezoelectricity is shown.
Figure 2.2: Asymmetric configuration
Chapter 3

Measurements in air

In this chapter several frf measurements in air have been done in order to gain insight in the behavior and dynamics of the prototype of the buzzer. After that velocity measurements have been done in several points on the membrane to visualize the vibration shapes of the membrane. The test results are finally compared with the results from the FEM-model.

3.1 Frf measurements in air

Frf- measurements have been done on several parts of the system. The measuring scheme is shown in figure 3.1. A chirp signal has been used as an input signal. Chirp signals contain a single frequency component that shifts from low-to-high frequency as a function of time. All measurements with the laservibrometer were done with Siglab. The prototype of the buzzer was hung freely. With the laservibrometer the velocity of the membrane as a function of the input voltage could be measured.

The following three transfers have been measured:

- input to velocity = total
- out\_\text{100} to velocity = dynamics
- input to out\_\text{100} = electronics

The first frf that has been measured is the one of the membrane. That’s the transfer of the velocity to the input voltage of the amplifier. The results are shown in figure 3.2.
3.1 Frf measurements in air

The system is a 1 DOF system. For a 1 DOF system where the membrane is force excited and the displacement is measured, the frequency response function is given by \( \frac{F}{T} \). The frequency response function has a 0 slope in the beginning and after the resonance peak the slope becomes -2. But the velocity is measured instead of the displacement, so the amplitude is given by \( \frac{v}{F} \). Because velocity is given by: \( v = x \cdot i \omega \), the whole frf can be multiplied by +1. As can be seen in figure 3.2 the amplitude starts with a +1 slope. After the resonance peak the slope becomes -1. The corresponding phase with the +1 slope is 90° and shifts to -90° at the resonance frequency. After that the phase will decrease slightly. The coherence of this measurement is very good except in the low frequencies, but that’s not in the area of interest. The resonance of the membrane in air occurs at 7250 Hz. The mechanical velocity at the resonance is 18 dB (ref 1 m/s/V).

Figure 3.2: Transfer function from input to velocity in air
In figure 3.3 can be seen that the transfer input to velocity = transfer \( \text{out} \) to velocity + input to \( \text{out} \). The transfer of \( \text{out} \) to velocity has the same behavior as the one shown in figure 3.2 except the phase is not decreasing after it’s -180° shift. Interesting is the behavior of the transfer of input to \( \text{out} \). In the beginning the slope of the amplitude is 0 with it’s corresponding phase of 0°. In stead of a resonance peak a resonance and anti-resonance peak occurs. The corresponding phase decreases at the resonance peak and increases at the anti-resonance peak. After that the phase will slightly decrease to 180° and the amplitude will slightly increase. This measurement also includes the electric impedance of the transducer. In both measurements the coherence is very good, except for very low frequencies.

For future frf measurements the transfer \( \text{out} \) to velocity as shown in figure 3.3 should be measured in stead of the transfer input to velocity. That way only the dynamics of the system will be considered without the electronics.
The mechanical velocity measured on the backside of the buzzer is -27 dB (ref 1 m/s/V) for a frequency of 7250 Hz. This is 45 dB (ref 1 m/s/V) lower than the mechanical velocity measured on the membrane. So the backside of the buzzer can be considered as fixed world. The frf of the backside of the buzzer is shown in figure 3.4. Not only a resonance occurs, but at 8650 Hz also an anti-resonance occurs. The coherence at 7250 Hz is very good, but the coherence at 8650 Hz is almost 0, due to a bad signal/noise ratio at this frequency. In the beginning the phase is 90°. At the resonance and anti-resonance the phase jumps from 90° to -90° and back to 90°. After that the phase slightly decreases to -90°, due to the amplifier. This corresponds with the slopes of the amplitude.

![Graph showing frequency response and coherence](image)

**Figure 3.4:** Transfer function from input to velocity of the backside of the buzzer in air

### 3.2 Vibration shapes

In order to visualize the vibration shapes of the membrane, velocity measurements have been done in several points on the membrane. A 5 x 5 grid has been used see figure 3.5. This gives 25 measuring points. The velocity can be converted to displacement by dividing by $2\pi f$. This is the result when $\sin(2\pi ft)$ is integrated.
The first resonance occurs at 7250 Hz. In figure 3.6 an example of a velocity measurement of node 6 is shown. In figure 3.7 the first vibration shape has been visualized.

Figure 3.5: Grid

Figure 3.6: Transfer function from input to velocity of node 6 in air
The second vibration shape occurs at 16000 Hz and is shown in 3.8.

The third and higher order vibration shapes occur above the 20 kHz. This frequency cannot be obtained because the measurement range of siglab is limited to 20 kHz. But at 16000 Hz a resonance and anti-resonance occurs. At this frequency, in practice, the second vibration shape occurs. This vibration shape occurs for $i = 1$ and $j = 0$ [1]. In theory it is assumed that the piezoelectric element is mounted perfect symmetrically, which implies that the second vibration shape can not be
excited. However, in practice the piezoelectric element isn’t mounted perfect symmetrically to the membrane. This implies that in practice the second vibration shape will be excited. In appendix B the nodal lines and the belonging mode shapes and natural frequencies of a circular plate are given.

The natural frequency \( f_{ij} \) for a circular membrane can be calculated \([1]\) by:

\[
f_{ij} = \frac{\lambda_{ij}^2}{2\pi a^2} \left[ \frac{Eh^3}{12\gamma(1-\nu^2)} \right]^{1/2}; \quad i = 0, 1, 2 \ldots; j = 0, 1, 2 \ldots
\]  

(3.1)

where

\( \lambda_{ij} = \) non-dimensional frequency parameter;
\( a = r = \) radius of the plate;
\( h = \) thickness of plate;
\( i = \) number of nodal diameters;
\( j = \) number of nodal circles, not counting the boundary;
\( E = \) modulus of elasticity;
\( \gamma = \) mass per unit area of plate;
\( \nu = \) Poisson’s ratio.

The material properties of the membrane are given in appendix A. The boundary condition of the membrane can be considered as clamped. For the first mode shape \((i=0, j=0)\) the non-dimensional frequency parameter \(\lambda_{ij}^2 = 10.22\). For the second mode shape \((i=0, j=1)\), \(\lambda_{ij}^2 = 39.77\).

for

- \( i = 0, j = 0 \rightarrow f_{ij} = 5838 \text{ Hz.} \)
- \( i = 0, j = 1 \rightarrow f_{ij} = 22717 \text{ Hz.} \)

The natural frequencies, 5838 Hz and 22717 Hz, calculated by formula 3.1 differ a lot compared to the measured natural frequencies 7250 Hz and 16000 Hz. This difference can be explained by that Blevins [1] uses the assumption that the thickness of the plate is less than about \(\frac{1}{10}\) the minimum lateral plate dimension. In reality the piezoelectric element and the glue also influence the natural frequencies. This influence is examined by van de Wiel [4].

Blevins [1] also uses the following assumptions:

- The plates are flat and have constant thickness.
- The plates are composed of a homogeneous, linear elastic, isotropic material.
- The plates deform through flexural deformation. The deformations are small in comparison with the thickness of the plate. Rotary inertia and shear deformation are neglected.
- The in-plane load on the plate is zero.
### 3.3 Comparison of test results and FEM-model results in air

The test results are compared with the results from the FEM-model modelled by van de Wiel [4]. The results are shown in Table 3.1.

**Table 3.1: Comparison test results and FEM-results**

<table>
<thead>
<tr>
<th>Mode shape</th>
<th>Natural frequency measured [Hz]</th>
<th>Natural frequency FEM model [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7250</td>
<td>7500</td>
</tr>
<tr>
<td>2</td>
<td>16000</td>
<td>16400</td>
</tr>
<tr>
<td>3</td>
<td>out of range</td>
<td>27500</td>
</tr>
<tr>
<td>4</td>
<td>out of range</td>
<td>32300</td>
</tr>
</tbody>
</table>

In this table can be seen that the natural frequencies obtained from the measurements and the FEM-model match very well. The measurement range of Siglab is limited to 20 kHz. The third and fourth natural frequencies lie above this frequency and therefore cannot be measured. In theory the piezoelectric element will only excite the first and the fourth mode shapes because of the symmetry of the piezoelectric element. The second mode shape is excited because the piezoelectric element is not perfect symmetrically attached to the center of the membrane. In the FEM model all modes shapes can be obtained from the eigenvalue calculation.
Chapter 4

Frf Measurements in water

Now that the measurements in air give some useful information about the behavior and dynamics of the prototype of the buzzer, measurements have been done in water. At first a similar test as the first one in air has been done to gain insight in the dynamics of the buzzer in water.

The resonance of the membrane in water occurs at 5300 Hz. So the resonance frequency is about 2000 Hz lower than in air. This can be explained because the density of water is much larger than the density of air resulting in a significant fluid-loading. For estimating the natural frequencies of fluid-loaded structures \( f'_m \) equation 4.1 can be used [2]. The relationship is restricted to frequencies below the critical frequency. It is

\[
f'_m = f_m \left(1 + \frac{\rho_0}{\rho_s k_m}\right)^{-1/2}
\]  

(4.1)

where

- \( f'_m \) = the fluid-loaded natural frequency (Hz);
- \( f_m \) = in vacuo natural frequency associated with fluid loading = 7250 Hz;
- \( \rho_0 \) = the fluid density = 998 kgm\(^{-3}\);
- \( \rho_s \) = the surface mass per unit area of the structure = 5.46 kgm\(^{-2}\);
- \( k_m \) = the primary structural wavenumber component = \( \omega/c = 2\pi/\lambda = \frac{2\pi}{240.02} \) m\(^{-1}\).

As the wavenumber increases, the fluid loading has a smaller effect on the structural natural frequencies.

If we work out equation 4.1, we get

\[
f'_m = 0.68 f_m \approx 5000 \text{ Hz}
\]

For an estimation of the natural frequency of a fluid-loaded structure this is a reasonably good result.
4.1 Velocity and acceleration measurement in water

The mechanical velocity at the resonance is 18 dB (ref 1 m/s/V), the same as in air. This is shown in figure 4.1. The shape of the frf in water is the same as the frf in air see figure 3.2.

To check if the previous measurement in water is correct (the laser beam may refract in water), an extra accelerometer has been added for the new measurement. Now the speed and acceleration are measured. The results are shown in respectively figure 4.2 and figure 4.3.

Because velocity and acceleration cannot be compared with each other, the acceleration has been integrated. Figure 4.4 shows the original velocity and the velocity obtained from the integration of the acceleration. In this figure is shown that by adding an accelerometer, the resonance frequency has been lowered by 300 Hz. This decrease occurs due to the extra mass of the acceleration meter, which results in a lower natural frequency. Interesting is the fact that the difference in amplitude is approximately 2-3 dB with a crossover frequency at 18000 Hz. This is probably a measuring problem. Possibly due to differences in propagation speed of the laser beam in air and water. By adding an accelerometer a leap just before the resonance occurs at 4000 Hz. This still has to be investigated.

Figure 4.1: Transfer function from input to velocity in water
4.2 Velocity and acceleration measurement in air

In order to check if the behavior in water is the same as in air a similar measurement with the accelerometer has been done in air. The results are shown in figure 4.5 and in figure 4.6.
Figure 4.5: Transfer function from input to velocity in air including accelerometer

Figure 4.6: Transfer function from input to acceleration in air

Figure 4.7 shows the original velocity and the velocity obtained from the integration of the acceleration. In this figure is shown that by adding an accelerometer, the resonance frequency has been lowered by 1550 Hz. This decrease is relatively more than in water. In figure 4.7 is shown that the amplitude of the velocity and the amplitude of the velocity obtained from the integration of the acceleration exactly match. The leap in the resonance peak that occurs in the measurement in water does not occur in the measurement in air.

Figure 4.7: Transfer function from input to velocity in air including accelerometer + velocity obtained from transfer function from input to acceleration
4.3 Measurements with hydrophone

In figure 4.8 the Sound Pressure Level has been measured with a hydrophone. This measurement has been done in a bucket (distance 0.20 meter from source) with foam on the inner side to absorb the vibrations. In this figure also the resonance occurs at 5300 Hz with a Sound Pressure Level of 67 dB (ref 1e-6 Pa/V). Another resonance occurs at 12000 Hz with a SPL of 78 dB (ref 1e-6 Pa/V) and a resonance occurs at approximately 16900 Hz with a SPL of 71 dB (ref 1e-6 Pa/V).

Figure 4.8: Frf of the membrane in water (hydrophone)
The former measurement with the hydrophone had been done to quickly get some results. In order to avoid the effect of reflections, several measurements have been done in the Dommel, a river near the campus. An example of a measurement is shown 4.9. The distance of the hydrophone was 1.5 meter.

In this figure a small resonance can be seen at also 5300 Hz. But at the 5750 Hz an anti-resonance occurs. After that, the amplitude increases slightly. The coherence of this measurement is very good except for the low frequencies. If we look at the phase, a small dip occurs at the resonance and anti-resonance area. After that the phase decreases.

4.4 Acoustic radiation model

In order to understand why the amplitude is increasing for higher frequencies, an acoustic radiation model has been analyzed. The radiated mean-square acoustic pressure fluctuations can be calculated by [2]:

\[ p_{rms}^2 = \frac{Q_{rms}^2 k^2 (\rho_0 c)^2}{16 \pi^4 r^2 (1 + k^2 a_r^2)} = I(r) \rho_0 c. \] (4.2)

The root-mean-square source strength \( Q_{rms} \) is given by

\[ Q_{rms} = v_{laser} A_{eff} \] (4.3)

where

\[ c = \text{speed of sound} = 1500 \text{ m/s} \]
\( \rho_{0\text{ water}} = \text{density of water} = 0,998 \cdot 10^3 \text{ kg/m}^3 \)

\( k = \text{wavenumbers} = \omega/c \)

\( a_r = \text{radius of source} = 17,5 \cdot 10^{-3} \text{ m} \)

\( r = \text{radial distance} = 1,5 \cdot \text{ m} \)

Hereby the effective surface area \( A_{\text{eff}} \) is:

\[ A_{\text{eff}} = \int_{-b/2}^{b/2} \int_{-a/2}^{a/2} 0.5 (\cos\left(\frac{2\pi x}{b}\right) + 1) \cdot 0.5 (\cos\left(\frac{2\pi y}{a}\right) + 1) \, dx \, dy \quad (4.4) \]

If we work out equation 4.4, we get

\[ A_{\text{eff}} = \int_{-b/2}^{b/2} \left[ \frac{1}{8} \left( \cos \left( \frac{2\pi y}{a} \right) + 1 \right) \left( b \sin \left( \frac{2\pi x}{b} \right) + 2 x \pi \right) \pi^{-1} \right]_{-a/2}^{a/2} \, dy \]

\[ A_{\text{eff}} = \int_{-b/2}^{b/2} 0.5 \cdot b \cdot \cos \left( \frac{\pi y}{a} \right)^2 \, dy \]

\[ A_{\text{eff}} = \left[ \frac{1}{8} \left( b \sin \left( \frac{\pi y}{a} \right) a + 2 \pi y b \right) \pi^{-1} \right]_{-b/2}^{b/2} \]

Eventually we find

\[ A_{\text{eff}} = \frac{1}{4} ab \]

For the effective surface area \( a = b = \text{diameter of the membrane} \).

The radiated acoustic pressure fluctuations have been plotted against the frequency. This is shown in figure 4.10. In this figure also the Sound Pressure Level measured in the Dommel and the transfer function from input to velocity in water are shown.
In figure 4.10 is shown that the amplitude of the Sound Pressure Level obtained from the transfer function from input to velocity is slightly increasing after the resonance. The amplitude of the Dommel measurement and the amplitude of the acoustic radiation model almost match. But after the resonance the amplitude of the measurement is increasing much more than the amplitude of the model. In the model no anti-resonance occurs.
Chapter 5

Conclusions and Recommendations

5.1 Conclusions

The first resonance in air occurs at 7250 Hz, with an amplitude of 18 dB (ref 1 m/s/V). At this frequency the first vibration shape \((i=0, j=0)\) is excited. The second resonance occurs at 16000 Hz. At this frequency the second vibration shape \((i=1, j=0)\) is excited. In theory the piezoelectric element will not excite this vibration shape because of the symmetry of the piezoelectric element. In practice this vibration shape is excited because the piezoelectric element is not perfect symmetrically attached to the membrane.

The first resonance in water occurs at 5300 Hz, with also an amplitude of 18 dB (ref 1 m/s/V). Measured with an hydrophone the amplitude is 76 dB (ref 1e-6 Pa/V).

5.2 Recommendations

For future frf measurements the transfer \(\text{out}_{100}\) to velocity as shown in figure 3.3 should be measured instead of the transfer input to velocity. That way only the dynamics of the system will be considered without the electronics.

The 3 dB difference in velocity and velocity obtained from the integration of the acceleration can be further examined. Also the dip in the resonance peak that occurs in the measurements of the velocity and acceleration in water, with the added accelerometer should be further examined.

The difference in the Sound Pressure Level measurements in the Dommel and the results of the acoustic radiation model should be further examined. Also the anti-resonance that occurs in measurements that were done in the Dommel should be further examined.
# Appendix A

## Material properties membrane

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Description</th>
<th>Value</th>
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<td>$\rho$</td>
<td>density</td>
<td>$7.8 \cdot 10^3 \text{ kgm}^{-3}$</td>
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<tr>
<td>$E$</td>
<td>E - modulus</td>
<td>$210 \cdot 10^9 \text{ Nm}^{-2}$</td>
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<tr>
<td>$\nu$</td>
<td>Poisson’s ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>$r$</td>
<td>radius</td>
<td>$17.5 \cdot 10^{-3} \text{ m}$</td>
</tr>
<tr>
<td>$h$</td>
<td>thickness</td>
<td>$0.7 \cdot 10^{-3} \text{ m}$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>mass per unit area of plate</td>
<td>$5.46 \text{ kgm}^{-2}$</td>
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## Appendix B

### Nodal lines for a circular plate

<table>
<thead>
<tr>
<th>Eigenmode</th>
<th>Mode shape</th>
<th>Cross-section</th>
<th>$f_{ij}$ [Hz]</th>
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<td>1</td>
<td>$i = 0, j = 0$</td>
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<td>5838</td>
</tr>
<tr>
<td>2</td>
<td>$i = 1, j = 0$</td>
<td><img src="image2" alt="Cross-section" /></td>
<td>12144</td>
</tr>
<tr>
<td>3</td>
<td>$i = 2, j = 0$</td>
<td><img src="image3" alt="Cross-section" /></td>
<td>19924</td>
</tr>
<tr>
<td>4</td>
<td>$i = 0, j = 1$</td>
<td><img src="image4" alt="Cross-section" /></td>
<td>22717</td>
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Bibliography


