Ultrasound induced cavitation and resonance amplification using adaptive feedback Control System

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Ultrasound induced cavitation and resonance amplification using adaptive feedback Control System

Master’s thesis

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Abstract

Acoustic cavitation in fluids using high powered ultrasound has been of great interest in industries and biomedical engineering. The need for high-intensity focused ultrasound (sound with frequencies between 20 kHz to 10 MHz) and modeling of such systems has drawn great attention in engineering. Ultrasound excitation has found recent application in terms of replacing the existing dynamic mechanical systems that use high energy with low levels of efficiency. The proposed thesis work focuses on an application of acoustic cavitation and on adaptive control of resonance amplification to be used in the paper pulp industry. The primary objective is to keep a system of coupled and tuned resonances stable, and by that obtain high cavitation intensity in a water filled beaker. The secondary aspect is to numerically model and experimentally evaluate a prototype beaker, where the adaptive control scheme is implemented to attain high and stable cavitation intensity. The characteristic control parameters (excitation frequency and amplitude) can be adjusted to the fluid condition in the beaker (reactor) by a feedback control from a pressure sensor inside the beaker. The aim of this feedback loop is to keep the resonance phenomena stable with respect to an adaptable frequency. In this application, the resonance amplification is mainly used to generate and control cavitation at a frequency that corresponds to a range of beaker natural frequencies. The results of the development process show that high cavitation intensity can be achieved by ultrasound induced power. The electric power input required to achieve high cavitation intensity is relatively low and resulted in high energy efficiency. The results of the study will be used for an application for fibrillation of cellulose fibers to further improve energy efficiency in paper pulp industry.

KEYWORDS: - Acoustic cavitation, optimization, FFT analysis, pure sine excitation, Sonotrode or ultrasonic horn, High intensity ultrasound, Sound pressure level(SPL) Acoustic pressure field, Feedback control.
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APPENDIX A

APPENDIX B
Outline of Thesis

The outline of the thesis is as following:

**Chapter 1**
Explanation of the overall outline of the thesis. It gives a basic understanding of system models and definitions.

**Chapter 2**
In depth theoretical background covering basic concepts and introducing system models

**Chapter 3**
Presentation of the design and physical simulation of the test reactor using FE modeling. It also explains the geometry, material properties and various modules used in the design process.

**Chapter 4**
Description of the experimental work, the proposed test reactor and excitation of the fluid using the Sonotrode.

**Chapter 5**
Validation of the experimental setup by designing the whole model using Simulink.

**Chapter 6**
Presents the experimental results, the simulated frequency response, and other outputs related to the system model. It also give an in-depth comparison of all the results obtained.

**Chapter 7**
Discussions and conclusions related to the whole methodology and simulation procedure. Outcomes and disadvantages related to the approach is briefly discussed

**Chapter 8**
Future work and ideas on further optimization of the developed methodology.
Chapter-1: Overview and outline

1.1. Background and Motivation:
The present project focuses on the application of high intensity ultrasound in liquids, which is a widespread technique for process intensification in industrial applications [1]. Ultrasound intensification is seen as a possible alternative method to a mechanical pulping process. One drawback of existing methods within the mechanical pulping process is that the energy consumption is very high. In 2012, the Energy Efficient Mechanical Pulping Initiative (E2MP-I) started research program on adapting ultrasound excitation and control of cavitation in the processing of mechanical pulp. The objective was to reduce overall energy usage in pulp production. Three types of objectives are considered of importance in the process.

- Improving energy efficiency of the existing methods.
- Implementation and optimization based on the existing technologies.
- Developed new processes based on breakthrough technologies.

To reach the required objectives, new methods and ideas were adapted. The motivating theory of this method of using ultrasound as a tool was first investigated by Johansson et al [2]. The idea is to use acoustic cavitation to induce high pressure variations inside a water filled beaker using an optimized Sonotrode driven by electric power. This process develops high pressure inside the beaker and the expected cavitation effect and fibrillation effect is observed. Experimental investigations have been performed with use of laboratory scale reactors to achieve optimum pressure. However, measuring sound pressure experimentally in the cavitation zone is basically complex and it is also necessary to estimate the magnitude of the loss factor incorporated during simulation. The interesting aspect arises when the acquired output is controlled and adapted to stabilize the resonance and thereby regulating sound pressure level (SPL). In the control process, pressure and frequency are considered to be the important parameters that change the system response drastically. Thus the combination of acoustic cavitation and control has a high influence to achieve high intensity and pressure.

1.2 Problem description:
The primary focus will be to achieve optimum resonance amplification in the beaker module and also to adapt to a specific resonant frequency of amplification in fluid. Acquiring the optimum resonance response of the experimental system is of important and is obtained by control of pressure response and
frequency. In the optimization process, reported problems and limitations can be summarized as a lack of detail when it comes to practical implementation, most likely due to difficulties to theoretically describe why a specific solution works. Problems often reported refer to lower energy efficiency than expected, material fatigue, and difficulties to increase the scale of operation. So there is a strong need to optimize the whole system [Mason 2003] Optimization relates to stable mode shapes both in the fluid and coupled structures, matching impedances and resonance frequencies. Mode shapes and natural frequencies depend on the acoustical properties of the Fluid, the material and geometrical properties of the beaker. Further problems associated with the system optimization are its internal loss factors and mismatched coupling between Sonotrode and beaker. To regulate and maximize the response and to overcome the critical parametric losses, the excitation frequency needs to be adaptive to stabilize the resonance phenomenon, which intern is sensitive to the temperature and the coupling between the natural vibration modes and frequencies [3]. So, experimental validation and modeling at different frequencies is required to develop the application for industrial use in effective influence of paper pulp processing.

1.3 Objectives:
The main objective of this thesis is to control the resonance and cavitation activity inside a prototype beaker. Main focus is to optimize acoustic cavitation on the basis of numerical modelling and experimentation evaluation to improve energy efficiency in a fibrillation process. The process of development can be categorized as follows:

- Physical modelling of the whole test prototype as a coupled FE-model in Comsol Multiphysics
- Experimentation with a realtime setup, to study critical parameters and control them.
- To identify natural frequencies and modes in the sonotrode and beaker.
- Optimization and control of the input frequency and power for high cavitation intensity.
- Further to adapt a new Interface design and adaptive control implemented in LabView.

1.4 Methodology:
This work focuses on the development of tools and methodologies for the use of adaptive control to achieve ultrasound induced pressure variations to generate high cavitation intensity, and ultimately to control the cavitation intensity under different conditions. The contributions of this work are:

1. Physical and numerical, models are developed to simulate the resonance phenomena, displacement, pressure study and the system control along with their effect on the system behaviour.
2. Design and experimental verification of a Sonotrode utilizing piezoelectric crystal, to maximize energy efficiency.

3. Development and evaluation of a Simulink model based on characteristic equations of a coupled mass-spring-damper system.

4. An experimental setup, designed and constructed for control and change of critical parameters (optimize frequency, displacement, pressure etc.). The system was assembled for validation in a sequential fashion as follows:

- The beaker system tuned to a piezoelectric Sonotrode whose resonance frequency is around 20 kHz.
- A Sonotrode model is designed by changing the rod or mass over piezo to generate maximum resonance at the specific frequency.
- Results based on changing parameters like height, position, temperature are collected to compare the optimum pressure of the system.

5. Cavitation intensity in the beaker is evaluated by FFT analysis of sound pressure variation.

6. Short presentation of a data acquisition and control model designed and implemented in LabVIEW.
Chapter 2: Basic Theory

What is sonoprocessing?

Sonoprocessing is a relatively new field of research with main focus on understanding the effect of ultrasound induced cavitation in fluid systems. Sonoprocessing refers to induction of ultrasound waves into a medium in the frequency range of (20 kHz–1 MHz); Sonoprocessing and its compound technologies are innovative methods that rely upon the acoustic cavitation activity and its outcome. An extensive theoretical background exists on the basis of acoustic cavitation in fluids. However, this thesis mainly concentrates on addressing the sonochemical process and its potential in industrial application regarding energy efficiency [2].

2.1 Ultrasonics

Acoustic wave propagation with frequencies above the limit of human hearing range as seen in figure 2-1 is referred to as ultrasound. Each wave type in a given homogeneous medium travels at a velocity that obeys a general wave equation and depends upon the properties of the medium. Ultrasound is reflected, refracted when going from one medium into another which effects velocity of sound. The ultrasonic wave equation is

\[ \nabla^2 \varphi = \frac{1}{v_0} \frac{\delta^2 \varphi}{\delta t^2} \]  \hspace{1cm} (1-1)

Here \( v_0 \) is the propagation velocity of sound and \( \varphi \) is the wave function. The term “wave propagation” in Ultrasonics is a condition that is transmitted and experienced at a distance depending on frequency, elastic properties of medium, velocity of sound, and density. Like all acoustic waves, ultrasonic waves can propagate either as longitudinal waves or transverse waves [4].

---

Figure 2-1. Representation of high frequency ultrasound range [4]
When the impedance difference produces a reflection that is everywhere in phase with an incident steady state wave, we can expect efficient energy storage within one element since the two waves reinforce each other to produce a standing wave. If two such systems are connected there will be an energy efficient energy transfer between them. For a system to be at resonance the driving frequency of the system should coincide with the natural or eigen frequency of the same system, which is important in some type of high-intensity applications [10]. At high intensities of ultrasound, the absorbed energy can produce cavitation which is strong enough to cause damage to the test prototype.

2.2 Cavitation:

Cavitation as already stated, is the formation and rapid collapse of small bubbles in a liquid medium. As discussed before; cavitation can be produced not only by intense acoustic pressure fields, but also by other means such as hydrodynamic cavitation, optics, Venturi tubes, etc. Cavitation occurs in a liquid medium when pressure is reduced to a certain critical value. Cavitation occurs when the vapour pressure in a liquid is exceeded by the instantaneous negative pressure during the rarefaction phase of an acoustic wave [4, 5].

There exists different type of devices that generate and transfer ultrasonic waves into fluids. A common concept is that a piezoelectric material as an electric exciter or crystal generates a standing wave in a resonant structure, typically a rod with dimensions in relation to the excitation frequency that allow the specific acoustic waves to propagate in a particular fashion. These devices are termed as ultrasound horns (or) Sonotrodes.

2.3 Acoustic Cavitation

Acoustic cavitation as seen in figure 2-2 is the inception and disruption of bubbles in liquid irradiated by exposure to high intensity ultrasound below the Sonotrode [6]. Applying ultrasound of a high intensity to fluid medium leads to a formation of repetitive cycles of compressions and rarefactions. Passage of this periodic disturbance through the liquid establishes a damped sinusoidal varying wave of acoustic pressure [1]. There are mainly two types of cavitation formations that describe the Cavitation activity.

- **Transient (inertial) cavitation** when there is a violent implosion in the medium and results in a shock wave at a specific temperature, occurs in the range of 20-350 kHz.

- **Stable (non-inertial) Cavitation** is a process in which bubble in a fluid medium is forced to vibrate when some form of energy input is applied as an acoustic field. It occurs in the range of sub harmonic and ultra-harmonic frequencies of the main excitation frequency.
2.4 Piezoelectricity:

Piezoelectricity is the process of nature that makes it possible to change from one form of energy to other. The term “nature” describes the effect that happens naturally, (say for example that bats use ultrasound effect in navigation). Piezoelectricity is a basic process of electrical and mechanical interaction between two subsequently different systems combined or coupled together for a certain process. This coupling effect favors for energy conversion from mechanical fluctuation to charged potential. Piezoelectricity has the potential to act in both ways. The major advantage of piezoelectricity is the amplification factor which is applied in piezoelectric excitation for conferring pressure to a medium (Solids, Liquids and fluids) to create interaction between the electrical and mechanical variables. The electrical behavior of the material and a constitutive relation between mechanical and electrical variables in the stress charge and displacement is given below [7]. When we apply this electric field there is some displacement produced. There are four forms of piezoelectric constitutive equations, but by taking either two of the four field variables as the independent variables, Let say strain-displacement form are considered then the equations are given as following.

\[
\begin{aligned}
S_\lambda &= S_{\lambda\mu}T^\mu + d_{\lambda i} E^i \\
D_i &= d_{\mu i} T^\mu + \varepsilon_{i\mu} E^\mu
\end{aligned}
\]  

(2-4)
Basic Theory

\[
\begin{align*}
\text{stress-charge form:} \quad & \begin{cases} T = c_S S - \epsilon^i E^i \\ D = e S + \varepsilon_S E^i \end{cases} \\
\end{align*}
\] (2-5)

Where \( S \) is the mechanical compliance, \( d \) is the piezoelectric constant, \( \varepsilon \) is dielectric constant, \( E \) is electric field. The matrix form of the above constitutive equations is

\[
\begin{pmatrix} S_{\lambda} \\ D_{\lambda i} \end{pmatrix} = \begin{pmatrix} S_{\lambda\mu} & d_{\lambda i} \\ d_{\mu i} & \varepsilon_{i l} \end{pmatrix} \begin{pmatrix} T^\mu \\ E^l \end{pmatrix}
\] (2-6)

Typical scripts \( E \) and \( T \) denote respective constants which are evaluated further in the modelling part. Although stress charge form and strain charge form are mainly used in the modelling method, displacement also is considered important in the FE modeling.

2.5 Modelling of acoustic-piezoelectric interaction

The acoustic-piezoelectric domain in Comsol Multi-physics is a finite element modelling based interactive tool used to combine the pressure acoustics (frequency domain) and piezoelectric device interfaces. In the modelling procedure, both domains are put together to solve for the acoustic pressure variations in fluids and with the structural deformation or displacement in both solids and piezoelectric solid domains. The acoustic-piezo interface also includes features electrostatics to solve for the electric field in the piezoelectric material. It is widely used for modeling piezoelectric applications, for example, studying the improvement in impedance matching layers as well as the far-field radiation patterns of the transducer [7].

2.5.1 ACOUSTICS MODULE:

As described above, acoustics module physics interfaces like pressure acoustics, Acoustic solid interaction, aeroacoustics etc. In this part, we use pressure acoustics to model a complex system that exhibit reflection, radiation, transmission of sound. These are relevant to evaluation of acoustic interaction used in ultrasound and piezoelectric applications. We can also analyze the interaction between external flow and acoustic radiation in fluids volume.

2.5.2 PRESSURE ACOUSTICS

The pressure \( P \) represents the acoustic variations to the absolute or input pressure. Pressure acoustics module can generate boundary conditions like impedance, radiation, symmetry and periodic conditions.

\[
\frac{1}{\rho_0 c^2} \frac{\partial^2 p}{\partial t^2} + \nabla \left( -\frac{1}{\rho_0} (\nabla p - q) \right) = Q \quad [21]
\] (4-1)

The pressure is measured in Pascal (Pa). Where \( Q(1/s^2) \) and \( q(N/m^3) \) are possible acoustic dipole and monopole source terms. \( t \) is the time and \( \rho_0(Kg/m^3) \) is the density of fluid. This module also involves
-harmonic waves such as sinusoidal waves that are expressed as harmonic components via Fourier series. The wave equation in frequency domain will then be solved considering a single frequency at a time. Let say we have a simple harmonic wave as

\[ p_0 = p(x) \sin(\omega t) \]  

(4-2)

The complex representation of the equation is

\[ p_0 = p(x) e^{i\omega t} \]  

(4-3)

By substituting the above equation, the time dependent wave equation is further reduced to Helmholtz wave equation.

\[ \nabla \left( -\frac{1}{\rho_0} (\nabla p - q) - \frac{\omega^2}{\rho_0 c^2} p \right) = Q \]  

(4-4)

There are a few basic terms that we encounter during the modeling of the system. Terms like sound hard boundary, initial values, axial symmetry, zero charge, acoustic structure boundary etc. are used in the working process, some define the activity when dealing with fluid structure interaction and some define the acoustic structure behaviour. Short description of each function is given as following [8].

- **Sound Hard Boundary**, is one typical condition for by the pressure acoustics governed boundaries. It sets the normal acceleration on the boundary to zero, thus behaving as a wall. It is in general given as;

\[ -n \left( -\frac{1}{\rho_0} (\nabla p - q) \right) = 0 \]  

[21]  

(4-5)

- **Pressure source**, is a boundary condition which is assigned with a constant value to be maintained at the transmission end.it is given as \( p = p_0 \).

- **Free**, is a predefined boundary condition with no constraints and load acting on the boundary.

- **Acoustic structure boundary**, it is applied when we are dealing with acoustic-solid interaction with frequency domain interface.it is a default boundary condition applied on fluid and solid boundaries, it is given as [8].

\[ -n \left( -\frac{1}{\rho_0} (\nabla p - q) \right) = -nu_{tt} \]  

[21]  

(4-6)
2.6 Methodology of adaptive control

The method of evaluating feedback from sensor to adapt to a specific resonant frequency is an advantage when we are dealing with systems prone to change with time. In the simulation process, first part involves the experimental study and optimization of a Sonotrode to a specific resonant frequency (20 kHz). In the later part, the designed Sonotrode immersed in beaker is modeled and experimentally tested at particular excitation frequencies. Initially cavitation pressure fields under different conditions will be recorded at the position of a pressure transducer. This is followed by controlling and keeping the resonance phenomena stable at particular resonance frequency defined by a specific mode shape.

In the interactive methodology of control, the power input to the piezoelectric crystal (controller) is continuously adjusted based on the measurement data (sensor). In the amplification process modulating parameters like change in the speed of sound in the fluid, overheating of resonator, shift in frequency and overall intensity, and overload, are the primary causes that move away the system from reaching an optimum value of cavitational pressure [6]. Structural design of resonator is also a composite task because the desired frequency is directly proportional to the length and positioning of piezo. Without correct optimization of resonator, the resonance frequency of the Sonotrode does not tend to match with the excitation frequency which leads to lower amplitude levels and loss of energy. So, a specific methodology is adapted both as a real prototype test set up as well as a Simulink model (figure 2-3). The procedure starts with designing the test prototype physically and simulating it to a point at which optimum result is obtained.

This type of process comes in handy when we are dealing with a real test system that needs prior information about its behaviour. This reduces the risk of damage and increases the overall efficiency rate. Although Simulink data is close to the experimental data, we will notice that Comsol is a designed structure without losses so it largely differs with the values obtained experimentally (Due to many considerable varying situations, influencive parameters that are not considered in Comsol).
Figure 2-3. Flow chart of the whole simulation and test process
Chapter 3: FE modeling

3.1 FINITE ELEMENT MODELING

Finite element modeling is aimed to satisfy the need of physically model the system to have a clear understanding of the behaviour of the system. It gives a detailed study of how the test subject behaves at resonance and also to identify the displacement occurred due to the vibrations. On the whole FE modeling is used to design the system and analyse it with respect to varying eigenfrequency, Pressure and also the resulting displacement. In this chapter we will have a brief understanding about the simulation tool (COMSOL Multiphysics) used in the modeling, in section 3.1 and the preceding sections cover important simulation parameters, materials and their properties and corresponding values used in the research. An overview of the material parameters needed to define piezoelectric materials; elastic (non-piezoelectric) materials and fluids are given in Section 3.3

This chapter as seen in figure 3-1 deals with a detailed overview of the design process, geometry, material and the physics (Acoustics and piezoelectric interaction).

3.1.1 COMSOL MULTIPHYSICS

The FE modeling is performed using the latest version of the simulation tool called comsol® and the module is acoustics in fluids. A brief description about the theory is found in section 2.7. comsol® is a cad like design platform whose data structure can be imported as a Matlab code. Right from defining geometry to simulating results multiple assumptions are assigned to each single variable, allowing parametric simulations. Piezoelectric structure geometry is already available in the module. Additional structure can is developed and built using various points, areas and boundary conditions. This modeling offers the possibility of customizing the system to the desired state. The main advantage of using this software is that it has pre-set physical interfaces, which will be directly used including the preset governing equations. Modeling in detail will not be explained in this thesis due to its dynamic content which sometimes is unnecessary, so it mostly covers a detailed insight into the modeling procedure. The basic simulation parameters and construction steps are covered as following.
The geometry is designed according to the experimental setup and dimensions of the test subject in different domains are specified.

As the test involves both air and fluid domain, Material and its properties are selected that are governed by the physical interfaces.

Apply conditions to the specified domains and boundaries. In the fluid the longitudinal waves are used.

Assign solvers and studies to the selected domains. There are many solvers and study so we have to specific about selecting Eigen value study and frequency domain analysis.

Before proceeding to the next step meshing the model is where important where size and type of elements are set. Meshing can be either user defined or physics controlled.

Finally solvers are set to solve the study, through a selection of post-processing and visualization techniques.

3.1.2 GEOMETRY:

Geometry is the primary physical aspect that attributes to the dimensions of the test subject, which we have already seen in while experimenting and replicating the whole thing in a physical model.

![Geometry of the designed model with each part highlighted](image)
Above figure shows the geometry of the whole test object designed to meet the requirements of physical modelling. Geometry of the test subject is considered the main part of the whole FE modeling. Beaker and the Sonotrode as already defined in previous chapters are 2D axisymmetric shape designed and its domains are built from the basic shapes that already exist in the Comsol library.

### 3.1.3 PARAMETER DIMENSIONS:
Parameters define the physical values and the geometrical dimensions of the system. The geometry is now parameterized and by easily changing the value of a dimension we can update the geometry in the parameters list. These are the initial parameters that are declared to design the test subject; here the height and radius of the beaker and Sonotrode are specified as given in the box below.

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>(117/2)[mm]</td>
<td>Radius of the beaker</td>
</tr>
<tr>
<td>Height</td>
<td>106[mm]</td>
<td>Height of the beaker</td>
</tr>
<tr>
<td>h_sono</td>
<td>116.5[mm]</td>
<td>Height of the Sonotrode</td>
</tr>
<tr>
<td>t_wall</td>
<td>(148[mm] - 116[mm])/2</td>
<td>Inner dimensions of beaker</td>
</tr>
<tr>
<td>t_bottom</td>
<td>10[mm]</td>
<td>Inner dimensions of beaker</td>
</tr>
<tr>
<td>t_top1</td>
<td>10[mm]</td>
<td>Inner dimensions of beaker</td>
</tr>
<tr>
<td>t_top2</td>
<td>10[mm]</td>
<td>Inner dimensions of beaker</td>
</tr>
<tr>
<td>r_hole</td>
<td>35[mm]/2</td>
<td>Radius of the hole inside the beaker</td>
</tr>
<tr>
<td>Temp</td>
<td>23[degC]</td>
<td>Temperature of the fluid</td>
</tr>
</tbody>
</table>

**Table 3-1.** Parametric dimensions of the test object with description

### 3.1.4 MATERIAL AND PROPERTIES:
Material is the one that actually defines the physical aspect of the system. During experimentation we have extensively used a different setup in which each module is designed with some material like water, aluminum etc. Comsol holds a large database that already have predefined materials, the process of applying the material to a certain domain is quite easy and the governing equations and values are taken as per the material definitions. Some modules like piezoelectric interaction and acoustic module will require extra information related to the speed of sound $cS$, density $\rho$ of the material, thermal conductivity $K$, dynamic viscosity $\eta$. While shifting from one material to other we have to notice that the values get changed from one domain to other leading to error. Values of above specified properties vary with each material and as we are using a piezo material then we have governing equations and elasticity matrix $C^E$, relative permittivity related to stress and displacement.
3.1.4.1 Air

Air is modelled using the predefined values that are in the library, all the values are fixed except a little variation in speed of sound $c_s(T)$, dynamic viscosity $\eta(T)$, Heat capacity $C_p(T)$ and density. This material is pure air without any loss factors. The material properties and its corresponding plots are given below, see table 4-2 and figure 4-3.

<table>
<thead>
<tr>
<th>Property</th>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Property group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>$\rho$</td>
<td>$\rho(\text{pA}[\text{L}/\text{Pa}],[\text{L}])$</td>
<td>kg/m$^3$</td>
<td>Basic</td>
</tr>
<tr>
<td>Speed of sound</td>
<td>$c_s$</td>
<td>$c_s(T)[\text{L}/\text{K}],[\text{m/s}]$</td>
<td>m/s</td>
<td>Basic</td>
</tr>
<tr>
<td>Relative permeability</td>
<td>$\mu$</td>
<td>1</td>
<td>1</td>
<td>Basic</td>
</tr>
<tr>
<td>Relative permittivity</td>
<td>$\varepsilon$</td>
<td>1</td>
<td>1</td>
<td>Basic</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>$\mu$</td>
<td>$\eta(T)[\text{L}/\text{K}],[\text{Pa}]*[\text{s}]$</td>
<td>Pa*s</td>
<td>Basic</td>
</tr>
<tr>
<td>Ratio of specific heats</td>
<td>$\gamma$</td>
<td>1.4</td>
<td>1</td>
<td>Basic</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>$\sigma$</td>
<td>$0[\text{S/m}]$</td>
<td>S/m</td>
<td>Basic</td>
</tr>
<tr>
<td>Heat capacity at constant pressure</td>
<td>$C_p$</td>
<td>$C_p(T)[\text{L}/\text{K}],[\text{J}/\text{kg}]$</td>
<td>J/(kg*K)</td>
<td>Basic</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$k$</td>
<td>$k(T)[\text{L}/\text{K}],[\text{W/m}]*[\text{K}]$</td>
<td>W/(m*K)</td>
<td>Basic</td>
</tr>
<tr>
<td>Refractive index</td>
<td>$n$</td>
<td>1</td>
<td>1</td>
<td>Refractive index</td>
</tr>
<tr>
<td>Refractive index, imaginary part</td>
<td>$ki$</td>
<td>0</td>
<td>1</td>
<td>Refractive index</td>
</tr>
</tbody>
</table>

**Table 3-2. Material properties of the designed model (Air)**

![Dynamic viscosity, $\eta(T)$](image1)

![Heat capacity, $C_p(T)$](image2)

![Speed of sound, $c_s(T)$](image3)

**Figure 3-3.** Plots of varying (a) dynamic viscosity (b) heat constant pressure (C) speed of sound. These are results of changing parameters that attribute to change in behaviour of the material (air)
### 3.1.4.2 Water, liquid

Water is modelled using the predefined values that are in the library, all the values apart from a little variation in speed of sound $cS(T)$, dynamic viscosity $\eta(T)$, Heat capacity $C_p(T)$ and density. This change can be attributed to change in behaviour of material when simulated. This material is pure water with loss factors like bulk modulus etc. are ignored. The material properties and its corresponding plots are given below, see table 4-3 and figure 4-4.

<table>
<thead>
<tr>
<th>Property</th>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Property group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>rho</td>
<td>$\rho(T)[L/K][kg/...]$</td>
<td>kg/m$^3$</td>
<td>Basic</td>
</tr>
<tr>
<td>Speed of sound</td>
<td>$c$</td>
<td>$cS(T)[L/K][m/s]$</td>
<td>m/s</td>
<td>Basic</td>
</tr>
<tr>
<td>Dynamic viscosity</td>
<td>$\mu$</td>
<td>$\eta(T)[L/K][Pa*s]$</td>
<td>Pa s</td>
<td>Basic</td>
</tr>
<tr>
<td>Heat capacity at constant pressure</td>
<td>$C_p$</td>
<td>$C_p(T)[L/K][J/kg][K]$</td>
<td>J/(kg*K)</td>
<td>Basic</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$k$</td>
<td>$k(T)[L/K][W/(m*K)]$</td>
<td>W/(m*K)</td>
<td>Basic</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>$E$</td>
<td>0</td>
<td>Pa</td>
<td>Basic</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>$\nu$</td>
<td>0</td>
<td>1</td>
<td>Basic</td>
</tr>
</tbody>
</table>

#### Table 3-3. Material properties of the designed model (Water)

#### Figure 3-4. Plots of varying (a) dynamic viscosity (b) heat constant pressure (c) Density (d) speed of sound. These are results of changing parameters that attribute to change in behaviour of the material (Water)
3.1.4.3 Aluminum

Out of all metals, the most frequently used metal is aluminum. Although there are many metals that could be replaced with the existing one, aluminium is quite suitable option for efficient transfer of energy between two different mediums. Its properties can be seen in table 4-4.

<table>
<thead>
<tr>
<th>Property</th>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Property group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>rho</td>
<td>2700[kg/m^3]</td>
<td>kg/m^3</td>
<td></td>
</tr>
<tr>
<td>Young's modulus</td>
<td>E</td>
<td>70e9[Pa]</td>
<td>Pa</td>
<td>Young's modulus and Poisson's ratio</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>nu</td>
<td>0.33</td>
<td>1</td>
<td>Young's modulus and Poisson's ratio</td>
</tr>
<tr>
<td>Relative permeability</td>
<td>mu</td>
<td>1</td>
<td>1</td>
<td>Basic</td>
</tr>
<tr>
<td>Heat capacity at constant pressure</td>
<td>Cp</td>
<td>900[J/(kg*K)]</td>
<td>J/(kg*K)</td>
<td>Basic</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>k</td>
<td>2.28[W/(m*K)]</td>
<td>W/(m-K)</td>
<td>Basic</td>
</tr>
<tr>
<td>Electrical conductivity</td>
<td>sigma</td>
<td>3.77e2[S/m]</td>
<td>S/m</td>
<td>Basic</td>
</tr>
<tr>
<td>Relative permittivity</td>
<td>epsilonr</td>
<td>1</td>
<td>1</td>
<td>Basic</td>
</tr>
<tr>
<td>Coefficient of thermal expansion</td>
<td>alpha</td>
<td>23e-6[1/K]</td>
<td>1/K</td>
<td>Basic</td>
</tr>
<tr>
<td>Speed of sound</td>
<td>c</td>
<td>346.13</td>
<td>m/s</td>
<td>Basic</td>
</tr>
<tr>
<td>Murnaghan third-order elastic modulus</td>
<td>l</td>
<td>-2.5e11[Pa]</td>
<td>N/m^2</td>
<td>Murnaghan</td>
</tr>
<tr>
<td>Murnaghan third-order elastic modulus</td>
<td>m</td>
<td>-3.3e11[Pa]</td>
<td>N/m^2</td>
<td>Murnaghan</td>
</tr>
<tr>
<td>Murnaghan third-order elastic modulus</td>
<td>n</td>
<td>3.5e11[Pa]</td>
<td>N/m^2</td>
<td>Murnaghan</td>
</tr>
<tr>
<td>Lame parameter λ</td>
<td>lam1lam1</td>
<td>3.1e10[Pa]</td>
<td>N/m^2</td>
<td>Lame parameters</td>
</tr>
<tr>
<td>Lame parameter μ</td>
<td>mu1mu1</td>
<td>2.6e10[Pa]</td>
<td>N/m^2</td>
<td>Lame parameters</td>
</tr>
</tbody>
</table>

Table 3-4. Material properties of the designed model (Aluminum)

3.1.4.4 Lead Zirconate Titanate (PZT5)

In this project work, Lead Zirconate Titanate (PZT5) was chosen for the design of piezoelectric material. PZT5 is the most common piezoelectric ceramic in use today, which exhibits a high coupling coefficient and high levels of efficiency in energy transmission. The governing equations that solve the piezoelectric properties are already given before and its matrices can be seen in table 4-5.

<table>
<thead>
<tr>
<th>Property</th>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
<th>Property group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>rho</td>
<td>7750[kg/m^3]</td>
<td>kg/m^3</td>
<td></td>
</tr>
<tr>
<td>Elasticity matrix (Ordering: xx, yy, zz, xy, xz, yx)</td>
<td>cE</td>
<td>[1.20346e+01][Pa]</td>
<td>Pa</td>
<td>Stress-charge form</td>
</tr>
<tr>
<td>Coupling matrix</td>
<td>cES</td>
<td>[0][C/m^2]</td>
<td>C/m^2</td>
<td>Stress-charge form</td>
</tr>
<tr>
<td>Relative permittivity</td>
<td>epsilonS</td>
<td>[21.91, 919.1, 826...</td>
<td>1</td>
<td>Stress-charge form</td>
</tr>
<tr>
<td>Loss factor for elasticity matrix cE</td>
<td>eta_cE</td>
<td>0</td>
<td>1</td>
<td>Stress-charge form</td>
</tr>
<tr>
<td>Loss factor for coupling matrix e</td>
<td>eta_ES</td>
<td>[0, 0, 0, 0, 0, 0, 0,...</td>
<td>1</td>
<td>Stress-charge form</td>
</tr>
<tr>
<td>Loss factor for electrical permittivity εS</td>
<td>eta_epsilonS</td>
<td>0</td>
<td>1</td>
<td>Stress-charge form</td>
</tr>
<tr>
<td>Compliance matrix (ordering: xx, yy, zz, xz, yx, yx)</td>
<td>sE</td>
<td>[1.64e+01][Pa]</td>
<td>1/Pa</td>
<td>Strain-charge form</td>
</tr>
<tr>
<td>Coupling matrix (ordering: xx, yy, zz, xz, yx, yx)</td>
<td>dE</td>
<td>[0][C/N]</td>
<td>C/N</td>
<td>Strain-charge form</td>
</tr>
<tr>
<td>Relative permittivity</td>
<td>epsilonT</td>
<td>[1730, 1730, 1700]</td>
<td>1</td>
<td>Strain-charge form</td>
</tr>
<tr>
<td>Loss factor for compliance matrix sE</td>
<td>eta_sE</td>
<td>0</td>
<td>1</td>
<td>Strain-charge form</td>
</tr>
<tr>
<td>Loss factor for coupling matrix d</td>
<td>eta_dE</td>
<td>[0, 0, 0, 0, 0, 0, 0,...</td>
<td>1</td>
<td>Strain-charge form</td>
</tr>
<tr>
<td>Loss factor for electrical permittivity εT</td>
<td>eta_epsilonT</td>
<td>0</td>
<td>1</td>
<td>Strain-charge form</td>
</tr>
</tbody>
</table>

Table 3-5. Material properties of the designed model (Piezoelectric disk, PZT5)
3.1.7 STUDY AND SOLVER CONFIGURATION
The numerical solver study is the final step in modeling where each study differs with their characteristics; most frequently used studies are frequency domain study and eigenfrequency study. Brief description of the studies is given as following.

3.1.7.1 Eigen frequency
The eigenfrequency study is used to compute eigenmodes and eigenfrequencies of a linear or linearized model. For example, in acoustics, the eigenfrequencies correspond to the resonant frequencies and the eigenmodes correspond to the normalized acoustic field at the specific resonant frequencies. We then use this solver to study and determine an eigenvalue problem within a set of resonant modes and associated resonant frequencies [16].

3.1.7.2 Frequency Domain
The frequency domain study is used to compute the response of a linear or linearized model subjected to harmonic excitation for one or several frequencies. A frequency domain study accounts for the effects of all eigenmodes that are properly resolved by the mesh and how they couple with the applied loads or excitations. The output of a frequency domain study is typically displayed as a transfer function, for example, magnitude or phase of deformation, sound pressure, impedance, or scattering parameters versus frequency. This chapter contributes results related to eigenfrequencies and mode shapes of the pressure distributed inside the beaker. We also calculate the maximum Sound pressure level, displacement, intensity, velocity [16].
Chapter 4: Experimentation

4.1 EXPERIMENTAL SETUP AND MEASUREMENT METHODS

The experimental analysis includes testing a piezoelectric Sonotrode immersed in a prototype beaker system. Experiments were conducted to determine transfer functions, resonance frequency, pressure, and cavitation intensity inside the beaker. The main goals of experimental work were:

- Determination and analysis of the system frequency response by FFT measurements
- Definition of the resonant frequencies and resonant modes
- Check for loss factors that affect the system.

All of these aspects were controlled and recorded at various excitation frequencies, under the controlled conditions of input power and calibrated sensors. Simulations were also performed in parallel under these varying conditions in an attempt to associate the obtained results with the experimental data. Finally, tests were done with aluminium foil material in order to validate the changes in cavitation effects by the system.

4.1.2 Experimental setup

A schematic representation of the measurement setup is shown in figure 4.1. The measurement setup is primarily based on a prototype developed by Johansson et al, 2013 [2]. The experimental setup includes a fluid filled beaker and a fibre material container which is placed in the centre of beaker. The experimental beaker is made up of solid aluminum and it is manufactured by the SCA mechanical workshop in Sundsvall. The geometry of the beaker has a fixed diameter of 116mm and a water level (between bottom and top end) that is adjustable between 106-111mm. It also has a lid (or) a solid cover circular metal structure which is used to close the beaker and also to rigidly hold the Sonotrode in position. Sonotrode is a combination of “piezoelectric converter+horn”. The piezoelectric material is denoted PZT27, which according to the numerical simulations satisfied the need of high pressure variations in the beaker (also at the pressure sensor position).

The setup used can be seen in Figure 4-2. Initial operation includes a signal transmitted from the device 1 to the sound amplifier 2 which further transmits the input at the piezoelectric converter or Sonotrode. Here the electrical input is converted to acoustical vibration induced into the beaker volume creating
-pressure inside it. The ultrasound signal is measured by the pressure transducer “4” placed at the bottom of the beaker. The calibration of transducer is monitored using the conditioning amplifier. A secondary transducer “5” is also used to compute the live transfer function and also to individually compute the Sonotrode resonant frequency.

Figure 4-1. Schematic representation of the experimental setup

During the experiment, the Sonotrode power output was adjusted by the Clio interface (computer controlled signal generator) and amplifier setup specially developed for the used Sonotrode. The generated acoustic pressure is measured by a pressure transducer (Dytran 2200V1) which was mounted in the center of the beaker bottom layer. The pressure transducer is connected to the FFT-based measurement and analysis system (CLIO) via a B&K conditioning amplifier (used to monitor the transducer setup and also to keep the overload on check).
The Sonotrode, used to induce vibrations, was manufactured at “LTU - mechanical workshop”, and assembled in the laboratory. The actual element consists of a 217.1[mm] in length and 44[mm] diameter, 90.6[mm] long aluminum rod fixed on the top and 35[mm] diameter, 116.5[mm] long aluminum rod placed in the bottom of the piezoelectric element to achieve reliable conditions. The piezo is ordered from Ferroperm A/S, Denmark. The height position of the sonotrode tip was adjusted to flush inside the top lid. Initially some critical parameters were subjected to change and tested accordingly.

4.1.2.1 Segment A and B:
Measurement, control and recording of the output from the sensors are carried by the segment A and B. Segment A is the primary controller of the entire setup. Segment B acts as interface to perform the actions of transmission and reception. Features range from generating an input test wave form, performing the FFT- analysis of the pressure output. It also monitors the overload problem, if observed at the sensor. A signal is generated by the Clio measurement system (PC-based software and hardware).
The signal is transmitted to the Clio interface; it is connected to the laptop by an IEEE-1394 standard link giving the possibility of maximum performances; Coaxial cables with a characteristic impedance of 50Ω are used to connect the instruments. The connections can be seen in the Figure 4-3. The sampling frequency is set to 192 kHz. Channel A and B input peak meters can be user controlled based on the load applied to the sensors.

**4.1.2.2 Segment D and E:**

The segment D and E on the whole is a single system used as a test prototype in the experiment process. It consist a beaker module with pressure sensor fixed inside the bottom of the beaker. The sensor is manufactured by Dytran model 2200V1 and is a probe style miniature IEPE pressure sensor. A fiber material container as seen in figure 4-4(b) is also placed in the center of the beaker giving the feasibility of varying the test samples. Sonotrode is used as the transmitting transducer. There is also another accelerometer which is placed below the piezoelectric crystal and is used to test for calibration of the equipment. Sonotrode is mounted rigidly on to the top of the beaker in a way that the water touches the bottom end tip. The whole setup can be seen in figure 4-4 and figure 4-5.

**Figure 4-3.** Working image of the segment (a) Clio operated system (b) Clio user interface
Figure 4-4. Design of the prototype test beaker showing (a) dismantled beaker and the pressure sensor indicated (b) Container that’s placed inside the beaker
Figure 4-5. Test system showing Sonotrode dipped inside the beaker and input probes connected to piezoelectric crystal
4.1.2.3 Segment C and G:

Segment “c” is an audio power amplifier, which amplifies the input signal to specific amplitude based on the input specified and application used. Here the audio amplifier intensifies the low power input signal that is acquired from the Clio system to a level of higher amplitudes which is suitable for driving the piezoelectric disk. The parametric aspects in the use of amplifier are gain, frequency response and test sound signal. Sinusoidal signal generated from the Clio is transferred to the amplifier where in the signal is acquired at section no.5 as an analog signal. The output and input impedance specifications and sensitivity of the amplifier are 150mV/47KΩ.

A Brüel & Kjær, Nexus conditioning amplifier is used to determine excessive drive overload for the sensors, thereby indicating overload that is a very difficult problem unless detected by the amplifier. It has multiple input/output channels and different filter options which can be adjusted to the user’s convenience. In the experimental process we have used first two input and output channels with Dytran pressure sensor, Brüel & Kjær accelerometer connected to input channels. All the operations are performed according to the IEEE 1451.4. Accurate gain control is used in nexus amplifiers [17]. For all the tests done on sensors and transducers there is an automatic gain adjustment. This is evaluated and stored during the testing and calibration. The overall gain is automatically calculated as:

\[
\text{Gain} = \frac{\text{output sensitivity}}{\text{Transducer sensitivity}}
\]

Where output sensitivity, transducer sensitivity are set according to users interest.

4.2 Ultrasonic Horn/Sonotrode:

Ultrasonic horn is an element operating in a longitudinal mode used for the efficient transfer of ultrasonic energy from a source element (transducer). Generally, the electromechanical transducer acts as the source of mechanical oscillations in all manufacturing systems using ultrasonic vibrations, which is used to transform the electrical power received from the generator into mechanical vibrations. The electromechanical transducers are based on the principle utilizing magnetostrictive or piezoelectric effects. The electromechanical ultrasonic transducers generate the vibration at resonant frequency \( \approx 20 \) kHz or more. The amplifying wave guided elements of the ultrasonic machining equipment’s are connected to the electromechanical transducer enabling to achieve the necessary size of amplitude.
Ultrasonic horn transfers the longitudinal ultrasonic waves from the top end to the bottom end, inserted in the beaker. The input vibrations are amplified so that the amplitude at the output end is considered adequate to perform required excitation process.

The general horn equation is given as

\[
\frac{1}{c^2} \frac{\partial^2 \varepsilon}{\partial t^2} - \frac{1}{S} \frac{\partial \varepsilon}{\partial x} \frac{\partial \varepsilon}{\partial x} - \frac{\partial^2 \varepsilon}{\partial x^2} = 0 \quad [14]
\] (4-1)

Where \( \varepsilon \) is the displacement, \( S \) is the cross sectional area at a distance \( x \) and \( c \) is the speed of sound in the material of horn. The above equation can be written in terms of particle velocity as

\[
\frac{\partial^2 v}{\partial x^2} - \frac{1}{S} \frac{\partial s v}{\partial x} - \frac{\omega^2}{c^2} v = 0 \quad [14]
\] (4-2)

Where \( \omega \) is the angular frequency, \( 2\pi f \).

The performance of ultrasound induced vibrations inside the beaker primarily depends on the design pattern of the Sonotrode [14].

**Experimental Setup**

Ultrasonic horn transfers the longitudinal ultrasonic waves from the top end to the bottom end, inserted in the beaker. The input vibrations are amplified so that the amplitude at the output end is considered adequate to perform required excitation process.

The general horn equation is given as

\[
\frac{1}{c^2} \frac{\partial^2 \varepsilon}{\partial t^2} - \frac{1}{S} \frac{\partial \varepsilon}{\partial x} \frac{\partial \varepsilon}{\partial x} - \frac{\partial^2 \varepsilon}{\partial x^2} = 0 \quad [14]
\] (4-1)

Where \( \varepsilon \) is the displacement, \( S \) is the cross sectional area at a distance \( x \) and \( c \) is the speed of sound in the material of horn. The above equation can be written in terms of particle velocity as

\[
\frac{\partial^2 v}{\partial x^2} - \frac{1}{S} \frac{\partial s v}{\partial x} - \frac{\omega^2}{c^2} v = 0 \quad [14]
\] (4-2)

Where \( \omega \) is the angular frequency, \( 2\pi f \).

The performance of ultrasound induced vibrations inside the beaker primarily depends on the design pattern of the Sonotrode [14].

**Figure 4-6.** (a) Piezoelectric crystal. (b) Sonotrode with varied lengths. (c) Sonotrode design with piezoelectric material on top
The Sonotrode is the primary part of the system for ultrasonically induced system which is unique to each process. They are used in various shapes and sizes, according to the application, but should be resonant at the operating frequency. The Sonotrode material designed and used is in between the needs of the ultrasound requirement and the application (aluminum is used in this project). There are many extensive shapes that can be used in a Sonotrode application; in this project we use cylindrical rods in the Sonotrode making process. To achieve optimal performance of ultrasonic system, it is necessary to take into account all relevant effects and parameters that affect the dynamics of the system [6]. The selection of a suitable shape and corresponding dimensions of Sonotrode are usually determined by numerical simulations and finite element method [1, 10, 11, 12 and 13]. The effect of relevant Sonotrode dimensions on natural frequencies and mode shapes and for complicated geometrical shapes are analysed by finite element method (Comsol Multiphysics). Generally, the Sonotrodes are made of metals that have high fatigue strengths and low acoustic losses.

The most important aspect of Sonotrode design is the determination of the correct Sonotrode resonant wavelength. The wavelength should be usually integer multiple of the half wavelength of the Sonotrode. The resonant frequency of Sonotrode, which has simple geometrical shape can by determined analytically (cylindrical shape). For complicated geometrical shape, the resonant frequency is usually determined numerically using lumped parametric approach (RLC representation) and finite element method. The Piezoelectric crystal used in the making of this Sonotrode is denoted PZT27. Figure 4-6 show the Sonotrode design that was used in the experimental process. Its dimensions are fixed to specific values. A Sonotrode structure with correct dimensions and optimization will presumably have a better coupling factor, sensitivity and bandwidth compared to other converter elements. The Sonotrode used in this work are made for excitation of resonant mode of the water volume of a beaker (coupled structure). The piezoelectric disk has the dimensions of 40 mm in diameter and 10 mm in length with resonant frequency approximately at 40 kHz. The main aim of this design is to bring down the resonant frequency as low as around to 20 kHz (this is the better frequency range for the transient cavitation to occur, as obtained from the previous research).
The basic principles of the Sonotrode/transducer construction in this work are modeled in Comsol before testing it experimentally. The main components are a piezoelectric element and two metal cylinders coupled all together with epoxy glue. A schematic drawing of the designed Sonotrode is shown in figure 4-8 with dimensions indicated. The dimensions of the metal cylinders were varied from nominal values during the optimization process. Below table shows a range of change in resonance frequencies and pressure levels at that particular height (when coupled to the beaker).

<table>
<thead>
<tr>
<th>Height of the Sonotrode(mm)</th>
<th>Maximum Peaks-SPL(dB)</th>
<th>Frequency(Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>90.6</td>
<td>267(optimum)</td>
<td>20850</td>
</tr>
<tr>
<td>91.6</td>
<td>220</td>
<td>19625</td>
</tr>
<tr>
<td>91</td>
<td>214.5</td>
<td>18825</td>
</tr>
<tr>
<td>91.6</td>
<td>217.0</td>
<td>19600</td>
</tr>
<tr>
<td>93.5</td>
<td>208</td>
<td>20675</td>
</tr>
<tr>
<td>94.6</td>
<td>248.5</td>
<td>20575</td>
</tr>
<tr>
<td>95</td>
<td>206.5</td>
<td>18800</td>
</tr>
</tbody>
</table>

Table 4-2 Optimum values of SPL with change in height and frequency

4.2.1 Placement of Piezoelectric Material in Sonotrode
A part from optimizing the Sonotrode to a particular frequency is also important to position the piezoelectric material within Sonotrode structure. The position has an effect on Sonotrode performance both on the dynamic stress distribution and magnitude. Detailed literature exists on the placement methods where focus was on to tune the system to resonance and also to have larger displacement values. This topic about matching-impedances based on two different placements is illustrated in
-acoustical point of view. Assume that the Sonotrode to be a full wave length system, with two possible nodal lines regarding displacement variations in axial direction. Two piezo positions are considered, one at $1/2$ the wavelength and the other at $1/4$ the wavelength. In the first case, the piezoelectric material is placed in exact center of the Sonotrode. Picture 4-9 shows the piezo placement along with the corresponding displacement (Red), stress graph (Blue). We can see that at the mid position of Sonotrode the displacements are large and stress is at very low level.

![Figure 4-9. Sketch of the assembled Sonotrode, considering case number 1 i.e. when piezoelectric crystal placed in 1/2 wave length](image)

To fit the piezo to a resonant rod (half or one wavelength), the assumption of quarter wave length resonance in the piezo material is the best choice, since the free-free resonance (half wavelength) is determined to be around 40 kHz. If one side of the element is attached to a totally rigid surface, it results in a quarter wavelength resonance. The quarter wavelength resonance will occur at around 20 kHz. From the impedance plot (Figure 4-10), we can see that the impedance at nodal lines is expected to be very large. In the mid position, it has zero impedance with larger displacement. We can observe the relative stress and displacement on piezo in figure 4-10.

![Figure 4-10. Impedance plot showing larger impedance values when considered in parallel with the Sonotrode](image)
In the case when the piezoelectric material is placed in between 1/8th and 1/4th position (Picture 4-11), we expect to have best results. The good result is obtained since the piezo is in close proximities of a nodal line (rigid side), and the impedance matching between piezo material and Sonotrode material is good on the other side. However, the displacement obtained close to a nodal line is lower and conditions in this position may lead to piezoelectric damage. The problem of failure happens due to contact stress being very high at the point and also due to bad coupling.

The major advantage of updating the previous design is its ability to draw larger displacements at the tip end of Sonotrode. Tensile stress is higher but we can observe much preferable impedance match between the piezoelectrical and mechanical parts. The differences between the cases can be explained by simulated displacement values in figure 4-12.

However Sonotrode design where piezo is placed in mid position is used as it better matches with the modes of the water volume of the beaker structure.
4.3 Data Acquisition

The computer based Clio software is a measurement and analysis system used for different communication instrument interfaces; the measurement is initiated by applying a signal at the input end. These vibrations are induced into the fluid filled beaker and the pressure inside it is measured by the pressure sensor. The pressure level measured at the pressure sensor end is given as input to the amplifier which transfers the value to the Clio interface and further it is displayed as the plot. The resonance spectrum is determined by the regular FFT analysis. By alternatively running white noise, varying frequencies are absorbed and they are further used in measuring pressure. The whole process is performed for a multiple times to record the better optimum values of pressures. The experimental process is conducted for the eigenfrequency analysis and frequency response measurements. The received signal from test object is windowed and transformed into the frequency domain utilizing FFT and there by searching for the prominent resonant frequency spectrum.
Chapter 5: Simulink

5.1 SIMULINK MODELING

This chapter aims to present the practical implementation of the reference method. Modeling this system is done in three stages where in each stage is linked to the background discussed in chapter 2. Simulink is used to design the system and Matlab R2012a is used to assign equations and values to the workspace. Figure 5.1 shows a piezoelectric circuit element with load. It is a block representation of the individual blocks and their functionality in terms of the process adapted.

![Piezoelectric model with load indicating sinusoidal power input](a) Piezoelectric block (b) Voltage level converter (c) Load

The RLC circuit design without load was already described in the Sonotrode design section and the equation derived will be used in this model. The main objective is to measure the output voltage and current with respect to the signal and frequency applied. The data derived from the model is aimed to give a clear understanding of the comparison between input and output. We already know that a piezoelectric disk or device is different from a typical power source wherein, its impedance is capacitive besides being inductive, which is further driven with a certain power signal producing mechanical vibrations with respect to amplitude and frequency.

![RLC circuit diagram taken from chapter 3 and implemented in Matlab](a) 5th Harm. Filter (b) Current Measurement (c) Scope
The RLC circuit shown above is designed and implemented in Simulink. It is a basic trial design of a Sonotrode to test its impedance and phase plot with respect to change in input power.

**Figure 5-3.** Example of impedance plot to frequency

**Figure 5-4.** Example of the phase plot describing the above system

### 5.2 Circuit Modeling of Sonotrode:

There are many possibilities of presenting and analysing equivalent models of piezoelectric converters or horns. The subject presented in this chapter includes modeling of high power piezoelectric horns or Sonotrode; optimization of ultrasonic power supply includes delivery of maximum power supplied to the load. For inducing such maximum power efficiency in the ultrasound horns, simple and practical representations of the existing model are satisfied by initially representing it in an electrical equivalent. Parameters like voltages, current, resistance and capacitance of the system can be used to qualitatively differentiate the components that exhibit electrical and mechanical or acoustical nature. The Butterworth-van Dyke (BVD) model approach is used to represent a typical piezoelectric converter or Sonotrode. Wide spread literature exists on Sonotrode modeling that used different parametric methods (parametric or Mason models) to represent equivalent circuits; each of them has their own topological-
In order to understand the detail depiction of the modeling scenario, it would be interesting to explain how model of a Sonotrode behaves with load. Sonotrode in general is a combined structure that comprises a piezoelectric element and a horn or mechanical element attached to the top and bottom of it. The RLC design of this structure slightly differs with the usual modeling techniques due to the fact that Sonotrode is an assembled structure, we should know the basic concept of placing two more equivalent circuit models representing horns [6]. Previous background states that added horns also exhibit certain kind of resonance structure and so it is easy to replace them with a mechanical equivalent circuit [9].

The step by step modeling of what means “horn+piezoelectric converter+horn” can be shown in figure 5-5. Sonotrode with complex shapes can create new resonant frequencies, so here we limit the observations only to couple of series resonances. The process in the figure 5-5 is that by adding horns to a piezoelectric transducer will create higher order electrical and mechanical circuits with new optimum resonant frequency. The internal losses of the system cannot be neglected as the resonant frequency is strongly dependent on the coupling factor of the entire system. This defines that mechanical resonant circuit (Sonotrode) should be strongly coupled in a way that creates high quality factor [9]. Piezoelectric coupling with a horn (or) rod or in terms of whole system, a well-designed Sonotrode will have a high quality factor. Here we see that $L_{pz}$ and $c_{pz}$ is the primary transformer section and $C_s$, $L_s$, $C_{s1}$, $L_{s1}$ are secondary transfer sections. The above circuit in series can be modified as following.
Starting from dual circuit model, it is important to underline that “horn+Converter+horn” [9] combinations are strongly coupled. The above circuit can be simplified to final circuit as following.

Here $c_{op}$ is the model parameter capacitance $R_{op}$ is the model parameter resistance, “A” is the surface area of Sonotrode and “d” is the distance. While testing for resonance, it is necessary to select one single converters operating mode to select a frequency window which captures the mode of interest and let resonance analyzer to perform resonance measurements by producing sweeping or sine or white or
multi frequency signal in the selected frequency interval and also to measure the voltage and current passing on the Sonotrode connected to the FFT analyzer. This gives a clear idea to get numerical values of all the electrical components relevant for selected frequency range and this method has been the most effective for optimizing ultrasonic power supplies, realizing optimal resonant frequency and output power. Piezoelectric modeling also works on material characteristics depending on the direction of applied field, displacement, stress and strain derived from piezoelectric governing equations [9]. The piezoelectric governing equation is once again specified for the user to clearly understand basic concept of piezo. The piezo stack represents the strain charge form and displacement form of the electrical and force characteristics of a piezoelectric material.

\[ S = s^E T + dE \]  
\[ D = dT + \varepsilon^T E \]  
\[ (5-7) \]
\[ (5-8) \]

Where S is the strain tensor, T is the stress tensor, E is the electric field, D is the electric displacement vector, \( s^E \) is the elastic compliance matrix, d is the piezoelectric constant matrix, \( \varepsilon^T \) is the permittivity measured at constant stress. The Simulink model of the piezostack and other parts of the design are shown. The need for simulating whole system is to compare different simulations with the experimental results and optimize all the results individually. Various designs are modelled using the piezo stack but due to the lack of supporting subsystems and due to the complexity of the whole system we tried to keep it to simple design with keeping it to minimal assumptions.

**Figure 5-8.** Sub-block of the model indicating piezostack and other sub-blocks
In order to clearly understand the functionality of the model logic, each subsystem will be described and its example output plot will be presented. Sensors monitors the power generated during the simulation test, this are used to optimize the values based on the pressure generated. The pressure transducer block models a generic pressure generated at the output end of piezoelectric stack. It turns the voltage into the pressure. The output pressure is proportional to the voltage and vice versa. This part is where the signal from sensor is transmitted to the FFT block which computes the Fourier transform of the acquired signal. It performs the transform (FFT) for each row of the sample based on the stress and displacement matrix for 1-p input vector. The equation for FFT is given as following

$$Y = \text{fft} \ (u, P)$$  \hspace{1cm} (5-9)

The block uses number of samples and over a frequency range specified by the user. The transformed signal is then connected to the window block; the window block computes the window and applies it to the passing signal. Generally, there are many window blocks but as we are dealing with peak pressure levels of pure sine component, flattop window as seen in figure 5-9 is the best option for windowing. The input can be a matrix or an n-dimensional array. The pressure at the other end is sensed by the pressure sensor and it is displayed as sound pressure level in dB. Below first diagram shows the FFT block and the window, later shows the mass block with the input values indicated as discussed before. Below shows an example simulations of the transformed output signal

**Figure 5-9.** Block diagram showing fft and the window function with spl conversion

Above block is the logarithmic measure of sound pressure $p_{rms}$ to a reference value $p_{ref}$, called sound pressure level (SPL). This pressure is plotted as a spectrum.
Figure 5-10. Block diagram of the whole system with all the above specified subsystems included with in the design
Chapter 6: Results

Results and discussions

This chapter gives the detailed data analysis of experimentation and simulated results collected from the prototype test system. The optimization process and results are described step by step as follows:-

- Experimental and simulated results related to optimization of sonotrode in free air
- Simulated results of displacement and pressure when the sonotrode is coupled to beaker
- Results of optimization of beaker pressure, Sonotrode displacement and mode shapes
- Results of experimental verification of the prototype test system
- Comparison of sound pressure and cavitation effect
- Adaptive control of resonance frequency and input power.

6.1 Parameters effecting cavitation:

There are a multiple parameters that affect the cavitational activity in a liquid medium by application of high power ultrasound. Although there are many critical factors that affect the functionality of the experimental setup, the detailed discussions are limited to:

- Geometry properties
- Sonotrode design
- Water temperature
- Static pressure
- Input power
- Input frequency

6.1.1 Effect of geometry and temperature of water volume:

Every real-time setup has loss factors that cannot be ignored. Loss factors range from simple correctable to complex that needs to be handled. Simple errors on contrary are the sonotrode position inside the beaker, temperature and height of the beaker. These factors have a great influence on the performance of the whole test prototype. To overcome these errors the prototype is optimized by changing the height of the beaker, and adjusting the sonotrode position and also by changing the temperature from room temperature to 50°C. The height of beaker is adjusted by a thin “ring” in the range of “1mm-3mm”. The Sonotrode position is adjusted to obtain a maximum value at specific resonance frequency. Figure 6-1 shows the sound pressure amplitude inside the beaker when changing temperature.
The frequency range 18600-21000Hz was excited by pure tones or white noise. From the results we can see that there is an effect of uncertainty on the natural frequency and SPL. To attain optimum results in the experimental process, fluid temperature was maintained at room temperature. The height of the beaker was modified by using the rings and as shown in figure 6-2, 1mm height, showed highest response.

**Figure 6-1.** Resonance frequency versus temperature in relation to maximum pressure level. Temperatures in the range of 23-25.5 gives maximum response at 20800 Hz. Temperatures above 25.5 are ignored due to random change in frequency and low pressure levels.

**Figure 6-2.** Resonance frequency versus change in height shows dominant pressure level at 1mm. This optimum height was later used in all the experimental evaluations.
Results and discussions

We observed that as frequency increases, formation of cavitation bubbles gradually decreases, and at one point no cavitation was recorded. This happens due to the misalignment between excitation frequency and input power. Higher acoustic pressure can be obtained by increasing the intensity and by choosing the desired resonance frequency.

6.2 Evaluation of Parameters that influence the sonotrode behaviour:

The sonotrode is a combination of piezoelectric transducer and an Al-rod that can be operated at different frequencies. We have already seen that the sonotrode exhibits an optimum response at the total length of 217.1mm. However, optimizing the sonotrode to one particular frequency is essential to meet the need of having a maximum cavitation output inside the beaker. Obtaining a good cavitation factor is dependent on the way sonotrode responds to a specific natural frequency coupled to beaker resonance.

6.2.1 Simulated natural frequencies and mode shapes of the coupled model

The natural frequencies for the sonotrode are calculated based on dimensions and material properties. The natural frequencies are calculated in the frequency range of 20 kHz-23.5 kHz but only favourable results are presented. The maximum sound pressure level, displacement, intensity and admittance of the coupled model were detected at 20.8 kHz.

Figure 6-3. (a) Sound pressure level of the sonotrode indicating resonance around 20.5-21 kHz (b) Total displacement in the sonotrode (c) Intensity at the bottom of sonotrode (d) Admittance showing maximum peak around 20.5-21 kHz
6.2.2 Numerical modelling of sonotrode response:

The longitudinal displacement amplitude the sonotrode is calculated at three positions (top, centre, and bottom) in the frequency range 18 kHz-50 kHz. This frequency range is chosen considering that the resonant frequency of the piezo crystal is 40 kHz, to check for matching standing wave patterns. The piezo resonance may not be the same frequency as the sonotrode resonant mode shape. But for maximum output, resonances are supposed to match. Displacement plot and 2d mode shapes related to the optimization are shown in figure 6-4. The resonant frequency is near to satisfy the experimental resonant frequency, but there is a noticeable displacement at multiple frequencies (18250Hz, 21150Hz, 34750Hz and 42725Hz). The presence of multiple frequencies is not surprising because of local phenomena inside the sonotrode and beaker. The resonance peak between 20 and 21 kHz is expected to be the perfect coupling frequency. Amplitude peaks at lower or higher frequency than that will be present due to interaction between multiple systems (beaker, sonotrode etc.).

Figure 6-4. Shows the response in a case when piezo and structure response are mismatched

This result will be compared with the experimental result to find the perfect match between the models. Evaluation of the whole model was made to optimize pressure level in the water filled beaker to attain cavitation at one particular frequency of interest. First objective was to optimize the acoustic behaviour of sonotrode within the ultrasound frequency range (20 kHz-23.5 kHz). The plots of pressure, intensity and admittance are shown in the figure 6-3.
6.2.3 Displacement mode shapes:

Figure 6-5. (a) Individual Displacement mode shapes plotted considering the peaks obtained in the figure 6-5 at (a) mode shape around 20-21 kHz (b) mode shape around 40-43 kHz

Figure 6-5 shows the mode shape at frequencies around 20-21 kHz and 40 kHz. Other frequencies around 18 kHz and 33 kHz are ignored due to very low levels of displacements or deformed structural behaviour. In figure 6.5 the harmonics correspond to the resonant mode resulted in sonotrode coupling. Each harmonic frequency relates to a particular mode shape which gives information about the-
-convenience of the standing wave pattern. Below we can see different mode shapes at corresponding resonance frequencies. The mode shapes clearly exhibit a resonant behaviour of sonotrode but the modeshapes differ with respect to displacement. We can apparently notice the difference in the mode shapes. Figure 6-4 indicates a resonance at 18 kHz which is too far from the natural frequency range of interest. The mode shape at 18 kHz shows high displacement at the bottom (indicated in red) and very low displacement in the remaining parts of the sonotrode which is not desired. The expected standing wave pattern should have high displacement in the top, centre, bottom of sonotrode. However, the frequencies in the range of 20-21 kHz have modeshapes showing close resemblance to the expected standing wave pattern. The mode shapes at 34750 Hz and 42725 Hz are not considered due to inefficient standing wave pattern. In this sonotrode optimization process we conclude that we will have the best response in the range of 20.5 kHz. This needs to justify experimentally.

6.2.4 Experimental evaluation of sonotrode in free field:

The Sonotrode in free field acts without load and can be represented equivalent to the FE model. However, there is a difference in response due to loss factors associated with a real application. The FFT spectrum recorded at the pressure sensor (figure 6-6), due to pure tone excitation, indicates resonant peaks at three different harmonic frequencies. However, maximum response is detected at the excitation frequency. In the case below we have a maximum response at 20530Hz. We also have resonance peaks at other frequencies higher than the piezoelectric resonance frequency of 40 kHz, but they are ignored since no cavitation occurs at these frequencies. In the optimization process to obtain cavitation indications, input power has been kept constant over the frequency range. To verify the accuracy of the sonotrode simulations a comparison is made with experimental results.

![Figure 6-6](image-url)
6.2.4.1 Variation in coupling effect:

Figure 6.7 shows frequencies higher than 20 kHz i.e. (figure 6-7(b) and figure 6-7(c)) we can observe harmonics and the response is much higher at 40 kHz.

Figure 6-7. White noise excitation (a) peak at 20850 Hz (b) peak at 24 kHz (c) peak at 41960 Hz. Figure a specifies a perfect coupling between the sonotrode. Figure b indicates bad coupling due to multiple distortions. Figure c shows dominating peaks below 20 kHz which indicates imperfect coupling of sonotrode.
The goal is to search for a resonant frequency that matches with the simulated results and gives a high pressure response and indications of cavitation. The optimization of the sonotrode in free air gave best result in the range of 20 kHz-21 kHz.

6.2.5 Results of numerical modeling of pressure response

Generating transient cavitation inside the beaker is a non-stationary process and the bubbles formed inside the beaker are only to some extent detected by pressure sensor. To make an accurate computation of acoustics and vibration of the fluid behaviour at resonance and cavitation require an adaptive control system. Based on the findings from the physical and numerical simulation, the Fourier analysis in real time (eigenfrequency, pressure distribution, displacement) is used to support the theory. Although it looked promising with the simulations, problems popped up during experimental testing of the beaker. From the step by step optimization, on the basis of Fourier analysis, an estimate has been made on the power input given to the pressure generated in the beaker unit.
Figure 6-8 shows the sound pressure and velocity value are measured in different positions of the test subject. Primary positions considered are in the centre of the beaker (container position) and bottom (Transducer position).

6.3 Optimization of system response when sonotrode inside the beaker

The optimization effect of the test model structure using the excitation frequency of sonotrode are presented first, followed by measurements of displacement, \( D \), sound pressure level (SPL), \( I_p \) and comparison of mode shapes. Experimentally recorded Fourier analysis and cavitation plots recorded at the pressure sensor are discussed. The comparison between the simulated results and experimental results are displayed in the end.

6.3.1 Simulation of displacement when sonotrode is coupled to beaker:

The coupled mode shape of the water volume and structure of the beaker are simulated at different resonant frequencies. The goal is to define single resonant modes considered to produce the optimum pressure distribution inside the beaker. As seen in the figure 6-9 the desired maximum SPL is obtained at 20875 Hz, but we can also see other peaks around the frequency range. The maximum amplitude of the peak is much higher than the adjacent peaks; the difference can be attributed to the higher Q-factor and efficiency at that particular frequency. Other factor that does not apply is the losses in the designed model. FE models have in general results in very high pressures at resonant frequencies. The pressure is reduced when deviated to other frequencies.

![Figure 6-9. Displacement of the sonotrode when it is placed in beaker. Maximum displacement obtained around 20850 Hz resonant frequency.](image-url)
Despite the fact that there is much difference in pressure at different frequencies, there is also a difference the peak pressure compared to experimental results. In figure 6-9 the SPL is calculated at different positions inside the beaker; (marked in numbers). To determine the best maximum frequency the pressure distribution inside the beaker are calculated. The mode shapes are determined at different frequencies indicating the whole structure behaviour with respect to different excitation frequencies. The mode behaviour of the sonotrode in free air and when placed in beaker are studied. The objective is to find if the desired mode structure at that expected resonance frequency.

6.3.2 Analysis of displacement modes: Shapes

The displacement mode shapes were evaluated in the frequency range 18 kHz-22 kHz. The expectation is to have less or no displacement in beaker where the sonotrode exhibits the same standing wave pattern when it is coupled in the beaker. Figures 6-10, is an example of a mode shape at which there is a resonance displayed in the beaker wall. Low output pressure or very high displacements in the beaker are not desirable. Although Figure 6-11 mode shape is very near to the expected result but the sonotrode has distorted structure that creates unwanted results. Mode shapes at 30-40 kHz are not useful due to low pressures in the centre of the beaker. The strongest response in terms of pressure and displacement is found near to the expected resonant frequency previously obtained, i.e. 20850 Hz. Figures 6-11 shows the desired-
-mode shapes with sonotrode acting according to the standing wave pattern and with less displacement noted inside the beaker module. As we go higher in the frequency above 40 kHz, the behaviour of sonotrode the efficiency rate goes down and the pressure output that is to be induced inside the Beaker reduces dramatically.

**Figure 6-11.** Desired mode shape (low displacement in beaker structure and high in sonotrode) obtained in the resonant frequency 20850Hz

### 6.3.3 Sound pressure level distribution inside the beaker:

The FE simulation is made as a coupled system of the piezoelectric material (PZT) sonotrode structure and the beaker structure water volume. Figure 6-12 shows the maximum sound pressure level response of the system at 20850 Hz. There was a change in frequency with difference of 300Hz and change in amplitude level of pressure. The measured pressure at amplitude 20875 Hz is 267dB. Firstly, can clearly understand that the resonant frequency which was assumed to be around 20 kHz is justified and it matches with the previously obtained results. The 3d mode shapes of the whole setup gives a clear picture of pressure distribution inside the simulated setup. Useful mode shape has to have maximum pressure in the centre and bottom where as other boundaries of the whole test system should have lower pressure. Mode shapes are evaluated for each peak in the specific frequency range to decide which one useful.
Results and discussions

**Figure 6-12.** Sound Pressure Level mode shape displaying pressure distribution in test subject at frequency **20875 Hz**, desirable mode shape with higher pressure levels.

**Figure 6-13.** Sound Pressure Level mode shape displaying uneven pressure distribution in test subject at frequency **20900 Hz**, example mode shape explaining the pressure behavior beyond the eigenfrequency mode.
6.3.4 Comparison of SPL and verification of numerical models

Comparison of SPL between FE modelling and experimental output will give a better picture of which frequency better matches the requirement. In figure 6-14, we can notice that two frequencies are of interest (better amplification). One is in the range of 20.5 kHz and the other at >40. Although we expect a better pressure ratio at 40-50 kHz, the maximum cavitation effect was below the assumed level. We also observe low level of displacement at that frequency and so the frequencies greater than 40 kHz are not of interest. The high frequency might be of interest in case of multiple pure sine excitation.

![Figure 6-14. Sonotrode sound pressure level comparison between FE modeling and experimental results](image)

6.4 Experimental evaluation of Cavitation after optimization

Optimization of the whole system is done to verify that the cavitation effect can be observed or not. The beaker was tested several times with different input power combinations. Since we already know that there are many internal loss factors, we do not expect a perfect cavitation index, but sure to reach the level required for the fluid to cavitate. Cavitation threshold values for driven waveform are calculated, the set of waveforms consists of pure tone, white noise and dual frequency modes. White noise was used to obtain the resonance frequencies. A sinusoidal signal at a specific resonance frequency was used as excitation signal and by the cavitation activity was detected. One advantage of this process is that, we can notice the difference between a cavitating signal and non-cavitation signal by looking at the output. If the output is a pure sine it indicates that there is no cavitation activity generated inside the beaker and if the sin wave is distorted then we can conclude that there is cavitation. The value of the pressure amplitude ratio \( p(1.5f_{us})/p(f_{us}) \) reaches a maximum when there is high cavitation activity.
The cavitation intensity depends on the power induced and coupling between vibrating sonotrode and beaker water volume. It was already discussed that the expected pressure has to be higher in the centre than at the transducer boundary. In that case, a Sonotrode has to generate a useful pressure mode inside the beaker. Trial test was done with fluid inside the beaker and sonotrode placed on top as specified. Figure 6-14 represents examples on SPL vs Frequency corresponding to pressure signals recorded by the pressure sensor. These plots are used as examples to show that, in both the cases we have a strong resonance at one specific frequency but if we simultaneously look at the output data, we can clearly notice a cavitating and non-cavitating activity in test Beaker.

6.4.1 Example plot of non-cavitating and cavitating signal.

![Example plots of FFT and its corresponding (a) non-cavitating (Pure sin) (b) cavitating signal (nonlinear distorted pattern indicating of cavitation)](image)

6.5.2 Parameters influence the cavitation intensity inside the test beaker

To determine cavitation activity inside the test beaker, the FFT spectrum is analysed at different levels of input power to the sonotrode. Pressure ranges from 20 kPa-140kPa (note that 1Pa=94dB) are recorded.
Only values showing cavitation signature (heavily distorted sinusoidal signal) are considered. Sometimes the problem is a loss of finding optimum values at the desired frequencies. This is due to errors during testing (note that the results in figure 6-14 are obtained at the same frequency). Following findings are considered important to have an optimum pressure for the cavitation to be recorded.

- Sonotrode calibration and optimization
- Pressure sensor calibration (sensitivity)
- Water level inside the beaker (making sure to touch the base of sonotrode)
- Overload problem in the pre amplifiers

To analyse differences in cavitation pressure, waveforms at different frequencies are evaluated. The goal is to increase the cavitation intensity relative to given stable power input. To do so, we adapted the simulation results and evaluated the cavitation intensity at the pressure sensor position. From previous simulations we know that the suitable eigenfrequency for this simulation is around 20.5 kHz. The maximum cavitation intensity is also observed experimentally around the frequencies of 20.5 kHz (i.e. a few Hz less than or a few Hz more than the original eigenfrequency). We have also seen another resonance peak in the range of 40-50 kHz but the results show that the cavitation rounds to zero.

All resonances in the frequency range of 20-21 kHz are tested experimentally at constant input power signal. The aim is to satisfy the need of obtaining the maximum pressure and cavitation intensity at low input power as possible but still keep the required activity. Peak pressures greater than 100kpa is desired to meet the expected result. In the initial stages of evaluation, The Sound pressure levels were too low for the cavitation effect to be registered. Problems include frequency mismatch and overheat of the piezo material. After simultaneous testing of sonotrode in free air and within the beaker, the optimization point was reached at which the initial signatures of cavitation are recorded. Although we had good resonance effect the cavitation effect was still low.
6.5.3 Optimum cavitation intensity measured with change in power and excitation frequency.

First test is performed with the same setup and specifications but there is a slight shift in the resonant frequency. The input power to the sonotrode was set a little higher (5.110 Watts) than the last run and the test scenario is evaluated based on the pressure level reached and cavitation intensity obtained. In this test the sound pressure level was 182 dB which is higher than the previous result, but lower than the required limit. The cavitation effect is also considered to be weak as we can observe in figure 6.15 (pure sine with very little distortion). Expected effects of cavitation are a completely distorted signal with sharp peaks in the positive end and rather clamped signal at the negative side. If we could attain clamped signals on both sides with very high deformation of the sin signal then it is considered as a good indication of transient cavitational intensity. The final test consists of simulations performed at different power inputs and at frequencies intervals finally reaching the cavitation in with the desired frequency range of natural frequencies.

Figure 6-15.(1) Sound pressure level vs frequency at 20220 Hz with input power of 7.11 Watts
(2) linear distorted time signal showing cavitation signatures where the peak pressure is 111868 Pa pressure frequency (20220 Hz)
Results and discussions

Figure 6-16. (1) Sound pressure level vs frequency at 20220 Hz with input power of 7.83 Watts (2) linear distorted time signal showing cavitation signatures where the peak pressure is 135974 Pa pressure frequency (20220 Hz)
It is evident that the frequency of excitation dominates, but harmonic peaks are also visible. The difference between the resonant frequency obtained in both Comsol and experimentation is also noted. This happened due to the local phenomenon inside the sonotrode which results in multiple peaks. The test beaker is not a stable system since assembly is repeated for every new test. The system is prone to change the results whenever there is change in few parameters. Reason for low cavitation is related to decrease in water level or dislocation of resonator, but most important is that a considerable ratio of input power and output power has to be maintained to have maximum pressure in the second simulation of an alternative design of the same process. Sound pressure and cavitation levels were improved. We could also consider the driving power of the piezoelectric device as it gives great improvements of output from the resonator. During the course of simulation, considerable improvement was gained in either of the cases. When we reached the optimum values of pressure, the maximum excitation power was lower than initially used.

Figure 6-17. (1) Sound pressure level vs. frequency at 20297 Hz with input power of 10 Watts (2) linear distorted time signal showing cavitation signatures where the peak pressure is 148950 Pa pressure frequency (20297 Hz)
6.5.4 Cavitation effect when piezoelectric material placed near 1/4\textsuperscript{th} wave length position

The title indicates that piezo placement near 1/4\textsuperscript{th} wave length yields better cavitation effect although this topic is not studied extensively. Figure 6-18 illustrate that the FFT spectrum gives multiple peak output and the time domain signal is rather highly distorted. This indicates that the piezo placed in 1/4\textsuperscript{th} position has the ability to give larger values when optimized correctly. The comparison between the two different placements with respect to various levels are shown in Appendix B.

![FFT Spectrum](image)

**Figure 6-18.** (1) Sound pressure level vs frequency at 20609 Hz (2) where the peak pressure is 97267 Pa pressure frequencies (20609 Hz)

6.6 Comparison of experimental results after optimization.

During the initial stages of experimentation the amplitude levels were lower than the required level. The problem is that the resonator didn’t match with the test object and the misconfiguration of the sonotrode was also detected. In the optimization process, we redesigned the resonator with replacing the Magnetostrictive material with piezoelectric material and Figure 6-19 proves the basic principle of optimization. Redesigning the sonotrode by matched impedances of the test beaker results in higher-
Results and discussions

-pressures. Quickly varying parameters like frequency, intensity are also monitored and more stable conditions are recorded compared to previous test.

6.6.1 Comparison of sound pressure levels:
In case of optimum cavitation intensity, we expect high amplitudes to be generated at the sensor position. The effect is not always the same as in simulation. In the experimental simulations we have seen that the maximum obtained is 191dB, In Comsol the maximum pressure reached up to 235dB and in Simulink it is 187dB. The difference in pressure levels can be attributed to the difference in simulation settings. As already specified, Comsol model is a designed system without coupling loss factors and results is unrealistically high amplitude levels. 191dB in experimentation is considered be a result that generates cavitation intensity (a non-linear response). Slight shift in the frequency apparently resulted in peaks lower than expectation. The difference between the lower levels and optimum level is due to the influence of the varying parameters, like the effect of the mode shape properties in the beaker. Sound pressure is evaluated initially using the designed models and later compared with the experimental results. Previously we have seen that at resonance frequency, we have high pressure output, but before coming to a conclusion, amplitude values at different frequencies near to resonant frequency are measured. Noting down the expected peak amplitude along with the second, third and fourth harmonics that are seen in the plot.

![Figure 6-19. Comparison of Experimental evaluation of pressure before and after optimization](image-url)
Cavitation effect was clearly observed in the optimization process, but it needs to be justified by aluminium foil erosion test. This test focuses on how the foil surface reacts to the pressure generated inside the test object. The same setup was used, but this time an aluminium foil was placed inside container. A reference foil was also used to compare the cavitation produced. Cavitation effects were measured at three different pressures applied on 3 different samples. Figure 6-20 shows the followed test procedure, Sonotrode and test subject are indicated in colour, “1” is the test sample foil which is placed inside the container in the centre of beaker, and “0” is the reference foil place just adjacent to the pressure sensor area. The whole test setup process is focused on the outcome of foil erosion and scale of the cavitational. Tests are conducted at regular intervals of pressure within the range of 40kpa-100kpa. Time period of each sample exposed to ultrasound is varied in the range of 1-5 minutes. Each sample is tested at a specific exposure time and pressure. Results are further published as images acquired from observing samples under a microscope. The measure range is 5mm; the aluminium foil are circular shaped and has a diameter of 3cm. Position of foil and transducer are shown in figure 6-21 and figure 6-22. The reference foil is the one which is not exposed to ultrasound in fluid and is kept as a comparison with the ultrasonically exposed foil.

**6.7 Aluminium Foil Test**

![Figure 6-20. Comparison of simulated and experimental sound pressure Levels](image)

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Figure 6-21. Sketch Diagram of the setup highlighting positions of test sample and reference sample. 
Figure 6-22. Geometrical representation of the same setup with highlighted positions of test and reference samples.
6.8 Results of LabVIEW implementation

In the adaptive feedback control process, main emphasis was given to stabilize the response of the test beaker to a specific resonant frequency. The presence of random disturbances make the adaptation process complicated and for that reasons standard techniques are not considered effective. So a combination of peak identification and Amplitude locked loop method is used. This algorithm (Appendix A) is very similar to that of Phase Locked loop (PLL) and real time identification of nonlinear systems. In this case, first the Fourier transform of the data from the sensor is calculated and natural frequencies are evaluated. If the peak found is prominent for the next number of samples, then the existing frequency is retained and this can be determined without adaptive control. If the resonant frequency is shifted, then the output from FFT is fed as input to the control algorithm. The output of the algorithm identifies the new resonant frequency. In the figure 6-24 we can notice that the frequency is around 20 kHz and amplitude is 192dB. If we consider that the excitation frequency and resonant-
-frequency doesn’t match, the system is excited again with adaptive controller. In the initial simulation case the reference frequency counters with the frequency in figure 6-24 and if the frequency is not optimum, the algorithm re-simulates till the frequency matches with the optimum value. This control algorithm works for n number of samples which is either specified by user or can be system generated. According to the length n of data, different outputs are obtained. Once the whole system is started, control process corresponding to the sampling rate of 192 kHz is applied. The advantage of adaptive control is it has better tracking capability. The test results showed better adaptation of frequency, but as the system is not fully adaptive its accuracy drops after 10 iterations so the system needs further optimization to make the algorithm to run over larger sample periods.

Figure 6-22 Sound pressure level vs frequency at 20800 Hz
Chapter 7: Final overview

Conclusions

The thesis addresses a methodology using FE-modelling and experimental validation to design and resonances in order to optimise pressure and acoustic cavitation. Main effort, however, has been to establish a novel concept for product development and optimization. The thesis work is based on a beaker and Sonotrode design initiated by Johansson, et al [31]. Design aspect was first FE modelled in Comsol and tested experimentally. The prototype was further optimized in order to implement the complete experimental setup in Comsol, including a piezo-electric exciter. Parallel to the Comsol modelling, a Simulink model based on experimental results was developed. Favourable results are obtained in three different cases with a good match in excitation and natural frequency but there was a difference between obtained Pressure levels in each of the three cases. This can be explained as a problem of loss factors that are expected in a real application. The built models only include internal loss factors of material. However, the greatest losses are due to coupling loss factors which are neglected in the initial design. This means that the obtained FE modelling results are considerably higher than the experimentally based. The main problem is the coupling of a Sonotrode to a specific resonator frequency of a fluid filled beaker. This problem can be approached by redesigning the resonator to a new length and by positioning the piezo crystal in line with the wavelength of the resonator. Another aspect is to optimize the positioning of the piezo-crystal with respect to the longitudinal wavelength of the Sonotrode structure.

Simulink and LabVIEW models could be further developed into a full model with control algorithm more suited for real time applications. As mentioned in results, experimentally maximum pressure was <130kPa and SPL of 191dB, better results can be obtained with redesign of the test beaker and by replacing the piezo with a more powerful exciter. It is clear that the present prototype system is a good illustrative example of study on stabilizing the eigenmodes and frequencies around which the cavitation effect is expected to happen. The prototype beaker structure used in this experiment is rather a compact structure, which has many loss factors. Optimization of one parameter at a time is not sufficient and may lead to errors. In the final results, we could observe that the required pressure for transient cavitation is reached and the optimum frequency of excitation was considered to be around 20.5-21 kHz. Regarding the energy efficiency factor we have had substantial reduction in the total power used for the excitation process.
Chapter 8: Future

Future work

This project is a stepping stone for basic prototype experimentation and simulation, besides it is also surrounded by limitations and draw backs that make it restrained to some extent. This present system on the whole can be improved and optimized for new results and for future consideration. The further approach would be to totally replace the existing design with a new design that comprises a longitudinal tube with two ends open and piezoelectric excitors on the outside. This model is a further update on the existing prototype and is designed to give resonance amplification and ultrasound induced cavitation inside a continuous fluid flowing tube.

Further studies on cavitation effect will consider experimenting with different fiber samples placed in the water. It gives a detailed understanding of the fluid properties and variations in physical properties of the material.

Adaptive control algorithm:

In case of adaptive control, it is a basic approach and there is huge scope in further implementing it fully in LabVIEW. Specific control methods like Amplitude Locked Loop (ALL) can be a major advantage for implementation. The amplitude loop method is required when dealing with fluid systems and resonators. More specifically, in this type of applications amplifying feedback loop is a major advantage in which the resonator excitation is realized by an amplified input signal. The whole test environment is further designed by using LabVIEW graphical programming tool and virtual environment which configured is using a Computer that is equipped with the data acquisition device (DAQ).
Bibliography


Bibliography


Appendix A:

Experimental Results

Geometry of sonotrode 1

![Geometry of sonotrode 1](image)

figure 1.1: Sonotrode when piezo placed at 1/4 position

Vibration measurement on Sonotrode 1 in free field

![Vibration measurement on Sonotrode 1 in free field](image)

Figure 1.2: Acceleration spectrum due to white noise excitation at 21237 Hz

Sine in free field of sonotrode 1

![Sine in free field of sonotrode 1](image)

Figure 1.3: Acceleration spectrum due to sine excitation at 21237 Hz

Geometry of sonotrode 2

![Geometry of sonotrode 2](image)

figure 2.1: Sonotrode when piezo placed at 1/4 position

Vibration measurement on Sonotrode 2 in free field

![Vibration measurement on Sonotrode 2 in free field](image)

Figure 2.2: Acceleration spectrum due to white noise excitation at 20457 Hz

Sine in free field of sonotrode 2

![Sine in free field of sonotrode 2](image)

Figure 2.3: Acceleration spectrum due to sine excitation at 20457 Hz
**Appendix**

**White noise excitation of Snotrode 1 when placed in beaker**

![Graph](image1)

Figure 1.4: Sound pressure level spectrum at 21438 Hz of maximum level 153 dB

**Sin of sonotrode 1 when placed in beaker**

![Graph](image2)

Figure 1.5: (a) Frequency spectrum with maximum value 190dB at 21355 Hz (b) Time signal with peak value of 133387 Pa

**White noise excitation of Snotrode 2 when placed in beaker**

![Graph](image3)

Figure 2.4: Sound pressure level spectrum at 20446 Hz of maximum level 148 dB

**Sin of sonotrode 2 when placed in beaker**

![Graph](image4)

Figure 2.5: (a) Frequency spectrum with maximum value 186dB at 20192 Hz (b) Time signal with peak value of 133484 Pa
COMSOL RESULTS

Geometry of sonotrode 1

Frequency response of pressure inside beaker generated by Sonotrode 1

Displacement modeshape of sonotrode 1 in beaker

Figure 1.1: Sonotrode when piezo placed at 1/2 position

Figure 1.2: Frequency spectrum amplitude of 250dB at 20800Hz

Figure 1.3: Desired mode shape obtained at 20800Hz

Geometry of sonotrode 2

Frequency response of pressure inside beaker generated by Sonotrode 2

Displacement modeshape of sonotrode 2 in free field

Figure 2.1: Sonotrode when piezo placed at 1/4 position

Figure 2.2: Frequency spectrum amplitude of 245dB at 20875Hz

Figure 2.3: Desired mode shape obtained at 20875Hz
**Sound pressure inside the beaker**

**Figure 1.4:** Pressure mode shape at 20800 Hz of pressure level 239 dB

**Figure 2.4:** Pressure mode shape at 20875 Hz of pressure level 245 dB