Variable frequency air coupled ultrasonic phased array sensors

by

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Abstract

The design and development of low cost variable frequency ultrasonic phased array is presented. The research outlines the working principles of a traditional piezo-electric ultrasonic range sensor and elaborates on the improvements in propagation and reception that can be achieved using a phased array approach. The phased array approach is extended to work with air-capacitive ultrasonic transducer, the design and development of which is outlined in the work detailed in the thesis

A simulation study of the excitation modal frequencies comparing the analytical approach and the numerical air-damped approach are presented. These modal frequencies are used to excite the transducer and study the effects of frequency with respect to range.

A circuit design to generate the phased array is developed based on the LM555 integrated circuit. The frequency control and resolution are determined using a digital potentiometer, which is controlled by a AT-Mega 328p microcontroller. Upon reception an amplifier and an eighth order multiple feedback band pass filter is designed to isolate the frequencies of interest.

The time of arrival (TOA) approach is used to extract the position of the target based on the time difference between propagation and detection of the wave. The TOA algorithm is used to determine the position of the target using an air-capacitive transducer and it was found that the maximum range of propagation and detection is limited to 55 cm with an angular resolution of 15 degrees.

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उठेंगे तो तूफ़ान बन कर , अभी उठने की ठानी नहीं है ।

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Nomenclature

A_ϕ	Amplitude of velocity potential function
D^*	Flexural rigidity
N_{loop}	Number of loops
R_*	Radius of Inductor
R^*	Reflection coefficient
R_0	Rayleigh distance
T^*	Transmission coefficient
U_a	Amplitude of surface normal velocity of breathing sphere
u_a	Surface normal velocity of breathing sphere
v_m	Spatial noise
y_m	Output signal
λ^*	Eigenvalues
τ_m	Time shift
ϵ_0	Permittivity of space
a	Radius
A^*	Area
B	Magnetic Field
$\mathcal{B}$	Beamforming function
C	Capacitance
c	Speed of sound

D	Directivity function
E	Young's modulus
h	Thickness
$h(r, t)$	Impulse response function
i	Current
I	Intensity
l_n	Bessels function of the second kind
j	$\sqrt{-1}$
J_n	Bessels function of the first kind
k	Wavenumber
L	Inductance
n	Noise
p	Pressure
P	Point in space
r	Radial dimension
S	Elemental area of baffle
SNR	Signal to noise ratio
'	Axial direction indicator
t	Time
T	Time dependent forcing harmonic function
V	Voltage
V	Volume

W	Spatial deflection function
x	Distance
y	Distance
z	Distance
Π	Sound power
G	Wave propagation functions
Z	Acoustic impedance
f	Frequency
u	Velocity
$\mathbf{C}$	Damping vector
$\mathbf{F}$	Forcing vector
$\mathbf{K}$	Stiffness vector
M	Gain magnitude
$\mathbf{M}$	Mass vector
$\mathbf{R}$	Coupling and interaction vector
$\mathbf{U}$	Displacement vector
δ	Dirac delta function
θ	Angle in x-z plane
κ	Relative Permittivity
λ	Wavelength
ξ	Vorticity
ρ	Density
σ	Elemental area

ψ	Angle in x-y plane
ω	Circular frequency
ϕ	Velocity potential function

Chapter 1

Introduction

As applications for unmanned aerial systems (UAS) increase, their environmental awareness for indoor applications is tremendously constrained by the sensors available onboard. Micro-air-vehicles (MAVs) rely primarily on global positioning system (GPS) for navigation in outdoor applications [1]. For low altitude and indoor application, the GPS is highly unreliable and other sensors are needed to perform guidance-navigation and control (GNC) [1].

Traditionally, ultrasonic range sensors are employed for collision avoidance as they are considered light weight and reliable [1,2]. However, as the weight of the MAVs is reducing significantly with advancement in material sciences, the weight of the sensor payload has increased proportionally. As shown in **Figure 1-1**, the weight of a modern MAV including payload is below 1 kg. Also, from **Figure 1-2**, it can be seen that the weight of the payload on an MAV accounts for less than 0.1% of its gross weight.

Figure 1-1: Gross mass vs Reynolds number for various flying platforms [2].

Figure 1-2: Weight of payload versus wingspan of the aerial platform [2].

A modern ultrasonic range sensor is shown in **Figure 1-3** and has a weight of 4.3 g. On an MAV platform, a number of these sensors are employed at strategic locations to increase situational awareness and object detection [3]. However, the weight of the sensor modules increases the payload weight significantly making the design infeasible for MAV application.

Figure 1-3: Ultrasonic range sensor for indoor applications LV-MaxSonar- EZ0 MB1000 [4]

In this thesis, an attempt is made towards improving the performance of these ultrasonic range sensors by using a phased array approach to steer the beam without the use of mechanical servos or actuators. The phased array approach allows for a reduction in the number of sensors employed by varying the angular control of a detection beam. The reduction in the sensor weight is accompanied by an improvement in the performance, inherent to a phased array system, thus offering a higher signal to noise ratio (SNR) [5].

1.1 Thesis Objectives.

The research presented focuses on development and design of a low cost air-coupled ultrasonic transducer that can be operated over a frequency range. Since most commercially available piezoelectric ultrasonic range sensors operate at 42 kHz, a variable frequency design is selected with an operation range between 30 kHz and 100 kHz.

The air-coupled ultrasonic transducer design is expanded to a phased array to study the effects of phased array transmission and reception. The phased array transducer design is compared to a piezoelectric transducer design to quantify the performance of the air-capacitive transducer.

To make the system efficient for a UAS application, a low power computational device is required, specifically a microcontroller, is required. This allows for the system to be embedded as a standalone unit on a UAS platform.

1.2 Thesis Organization

The thesis is organized into the following chapters:

Chapter 2: Commonly available range sensors are discussed with a brief insight into the physics involved. An overview of the Lead Zinc Titanate (PZT) based ultrasonic sensor is given, followed by a brief analysis of the air-capacitive design. The current limitation of the PZT are discussed along with the benefits of a phased array approach.

Chapter 3: An in-depth analysis into the physics of sound generation using an air-capacitive sensor is described using a single sensor. Using the single source propagation model, a single point receiver model is established. The single source and single receiver model is expanded to an array response for phased array propagation and reception modelling. Lastly, parameters to measure the performance of the sensor are described and the desired performance from the sensor array are established.

Chapter 4: The physical model outlined in Chapter 3 forms the basis of the analytical approach used to measure the theoretical performance. However, the lack of air coupling at the surface of the sensor is neglected by the analytical approach. A numerical method using Galerkin's approach is used to discretize the problem and allow for the inclusion of the air coupling mechanism. The results from the numerical and analytical approaches are then compared to visually and mathematically represent the effect of air-coupling at the surface of the sensor.

Chapter 5: The system design of the sensor array involving three sensors is described. The time of arrival (TOA) technique using a phased array approach is adapted to the three element array design. Similarly, a position and angle extraction algorithm is developed to estimate the position of the target.

Chapter 6: The construction methodology using photolithography is described in detail. Also, A variety of other methods are discussed briefly and a repeatability test is performed on the photolithography technique to highlight the robustness and repeatability of the process.

Chapter 7: A component level digital design is detailed along with the circuit design. The system is divided into two main parts; propagation and reception model. The propagation model focuses on developing a focused beam at a specified angle and frequency. The reception model includes filtration, amplification and phase determination of the received signal. The outputs from the phased array system are forwarded to the user interface module.

Chapter 8: The results obtained using the modelling approach outlined in the aforementioned chapter are discussed. Two transducer design; PZT and air-capacitive, are used for the analysis. The performance of each sensor is discussed along with the effects of varying frequency, measurement range, phasing capabilities and target detection.

Chapter 9: Conclusions drawn from the research are presented along with recommendation for future work including improvements of the current design.

1.3 Summary of Contributions

In this research, a variable frequency air-capacitive ultrasonic phased array sensor is designed and developed. The air-coupled vibration modal frequency is determined using Ansys Workbench's fluid structure interaction simulation.

A printed circuit board manufacturing method was designed to test a PZT transducer array along with an air-coupled transducer array. To facilitate the testing of the phased array design, an anechoic chamber was also designed and constructed. The frequency and noise isolation response of the anechoic chamber was characterized for correction factor.

A novel circuit design involving a variable frequency design is implemented using a LM 555 timer. The variable frequency design is user controlled and forwards the frequency signal to a microcontroller for phasing. The AT-Mega 328p platform, is selected as the microcontroller as it has 3 on board timers that can be used for phasing the output beam to a specific angle. During the reception phase, the circuit design employs an eighth order multiple feedback bandpass filter for signal isolation and noise reduction. The time delay captured by the circuit design is used as an input to a time of arrival algorithm used to determine the target position in space.

Experiments are conducted to quantify the performance of the phased array air-capacitive ultrasonic sensor. The effects of phasing output and beamforming reception model are described. The phased array approach enhances the performance over an individual sensor by manipulating regions of signal amplification and nulls, thus producing a directional effect.

This thesis has contributed to the understanding of phased array ultrasonic sensor design, particularly in the application of obstacle detection. Furthermore, effects of variables in manufacturing and design of the transducer were studied and quantified to attain desired performance.

Chapter 2

Review of Range Finding Sensing Technologies

This chapter highlights the various methods of range sensing and divides the sensors according to their method of sensing. A comparison between the sensor types is performed and their feasibility for a MAV application are detailed. Based on the evaluation of each sensor's capability and its feasibility with the design requirements, a sensor design is selected and discussed.

2.1 Methods of range sensing

There is a multitude of methods to determine the range of a target, which includes optical, acoustic, inductive and capacitive methods. The optical and acoustic methods rely on the “pulse and echo” technique, where the range of a target is determined by the time of flight of the signal wave from the source (pulse) to the target and back to a receiver (echo) [6]. On the other hand, the inductive and capacitive transducers measure the change in electromagnetic and electrostatic field, respectively [7].

2.2 Capacitive range sensing

The capacitive sensor measures the change in capacitance induced by a target present in the field of the sensor. From equation 2.1, it can be seen that the measured capacitance depends directly on the composition of the target [7]

$$C = \frac{\kappa \epsilon_0 A^*}{x} \quad (2.1)$$

The excitation circuitry, which measures the change in the capacitance by measuring the capacitor's time constant, varies the current proportionally with respect to the changing capacitance to maintain a constant electric field [7]. **Figure 2-1**, highlights the change in the output signal, used to determine the change in capacitance.

Figure 2-1: Capacitive range sensor output signal with respect to change in target position

There will be a critical distance x_{max} , where the change in capacitance will result in an insignificant change in current measurement as shown by the following equation [8,9]:

$$i(t) = C \frac{dV(t)}{dt} \quad (2.2)$$

Table 2-1: Capacitive position sensors [10,11,12,13,14]

Capacitive Sensor	Maximum range (x_{max})
Balluff BCS0077/0078	30 mm
Omron E2K-C	25 mm
Rockwell 875C-M10NN30-A2/D4	30 mm
Eaton E53	35 mm
Average	30 mm

Table 2-1 shows the maximum range x_{max} of several commercially available capacitive sensors. Since the average maximum range is limited to a mere 30 mm, it is evident that the capacitive sensors do not present a feasible option for long range sensing for the current application.

2.3 Inductive range sensing

The inductive sensor works similar in principle to a capacitive sensor in that it measures the change in the field variable, which in this case is inductance. An alternating current is passed through the inductor as shown in **Figure 2-2**; this produces an alternating magnetic field. The relationship between the magnetic field and the current is given by equation 2.3 [8,9].

Figure 2-2: Inductive position sensor

$$B = N_{loop} \frac{\mu}{2} \frac{i(t)R_*^2}{(x^2 + R_*^2)^{\frac{3}{2}}} \quad (2.3)$$

The time-varying magnetic field induces a surface current on the target object, thus changing the magnitude of the magnetic field. The oscillator drive circuitry is designed to maintain a fixed magnetic field. Therefore, a change in the magnetic field produces a measurable change in alternating current [7,9].

An inductive sensor can only sense metallic objects since nonconductive materials do not have free electrons and cannot produce surface charges [7]. **Figure 2-2** and Equation 2.3 outline the highly nonlinear relationship between sensing distance and the magnetic flux. This non-linear relationship drastically reduces the measurement range, however by increasing the number of coil windings or current flow, a higher magnetic field can be produced, increasing the measurement range [9]. **Table 2-2** outlines the maximum sensing range of a few commercially available inductive sensors.

Table 2-2: Inductive position sensors [15,16,17,18]

inductive Sensor	Maximum range (x_{max})
Balluff BAW003L	60 mm
Omron E2Q5-N40ME1-M1	40 mm
Rockwell 872C	40 mm
Eaton E56CDL100UAE01	100 mm
Average	60 mm

As seen from **Table 2-2**, by increasing the magnetic field the range of the sensor is significantly higher than a capacitive sensor as seen in **Table 2-1**. The increased range of the inductive sensor is still well under a meter, and in comparison, to optical and acoustic methods does not present a feasible option for an MAV application.

2.4 Optical range sensing

The optical method of range sensing employs a light source such as a laser or infrared and a receiver to detect the reflected beam. The time delay between the projected and reflected beam is measured to determine the range of the target object. The infrared range sensors employ an infrared light emitting diode (IR-LED) that emits IR light with a fixed wavelength, typically between 0.9-1.7 μm [19]. Since, the emitted IR beam is of short wavelength, air molecules scatter the light. The relationship between the wavelength of light and the scattering is given by [20,21]:

$$I \propto \frac{1}{\lambda^4} \quad (2.4)$$

As the wavelength of light increases, the intensity decreases, this poses a severe limitation to the detection range, where a 10% increase in the wavelength can result in a 31.8% reduction in the intensity of light. Along with scattering, the range of an IR device decreases in the presence of a heat source and sunlight. **Table 2-3**, outlines the range sensing capabilities of a few IR range sensors.

Table 2-3: Infrared position sensors [22,23,24,25]

Infrared Sensor	Maximum range (x_{max})
Sharp GP2Y0A21YK0F	80 cm
Sharp GP2Y0A710K0F	350 cm
Sharp GP2Y0A02YK0F	150 cm
Sharp GP2Y0A60SZ0F	150 cm
Average	182.5 cm

The shortcomings of the IR-based sensors are mitigated by replacing the non-collimated LED source with a collimated laser source. A laser range sensor has a longer distance measurement range than an LED sensor due to the monochromatic and collimated nature of the light being emitted [26,21]. The beam of light emitted by an IR-LED is a broader spectrum as compared to a laser light source, requiring the receiver to be of a wider bandwidth thus reducing the probability of signal detection [19,26].

The optical method of range sensing significantly improves the range sensing capability of the sensor; however, the limitations restrict their use. Laser and IR sensors are unable to detect optically transparent materials such as glass and clear plastics. Their performance is further degraded by the presence of smoke (increased diffraction) and non-reflective or light-absorbing materials. In the case of IR, the temperature of the target alone can degrade the range perception of the sensor severely [19,21].

2.5 Acoustic range sensing

Non-contact acoustic range measurement employs the echo location technique to locate targets in the field of the sensor. The methodology is similar to the optical methods discussed previously, where the time of flight of an acoustic wave from the emitter to the object and back again is measured by the sensor circuitry to determine the range of the target [27].

This acoustic range sensing system involves a transmitter and a receiver, in some modern sensors a transceiver, to determine the range of the target [28]. **Figure 2-3**, highlights the two common types of ultrasonic range sensors used in range sensing applications. **Figure 2-3 a**, shows an ultrasonic sensor with a transceiver design while **Figure 2-3 b**, employs a separate transmitter and receiver. The transceiver design offers weight reduction by combining the transmitter and the

receiver. However, this weight reduction is achieved at the expense of a fixed maximum range, as the sensor has to switch between propagation and reception mode. **Table 2-4** outlines the performance of a few ultrasonic range sensors along with their weight.

a) Transceiver design

b) Separate transmitter and receiver design

Figure 2-3: Types of ultrasonic range detection sensors [29,30]

Table 2-4: Ultrasonic position sensors [31,32,33]

Ultrasonic Range Sensor	Range	Weight
Maxbotics LV-MaxSonar -EZ 0	600 cm	4.3 g
Maxbotics X L-MaxSonar -WR 1	1000 cm	50 g
Parallax Ping Sensor	300 cm	9 g
Average	633.3cm	

The transducers are typically made from piezo-ceramics, most commonly involving the lead zirconium titanate (PZT) [34]. The piezo-ceramic used in ultrasonic range finders involves

the 1-3 configuration, where the parallel PZT fibers are embedded in and supported by a polymer matrix as shown in **Figure 2-4** [34,35,36].

Figure 2-4: PZT transducer composite structure, adapted from [34]

Upon application of an alternating electrical potential, the piezo-ceramic fibers contract and elongate due to the piezoelectric effect, inducing an internal vibration of the composite structure. Exciting the PZT at resonant frequencies produces greater sound pressure, thus increasing the measurement range of the sensor [34].

The disadvantage of piezo-ceramic transducers is the inefficiency in air-coupled application due to the acoustic impedance mismatch that occurs on the surface boundary of the transducer during oscillation. The energy transmission and reflections coefficients is given by the following equation [27,37]

$$T^* = \frac{4Z_1Z_2}{(Z_1 + Z_2)^2} \quad (2.5)$$

$$R^* = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2} \right)^2 \quad (2.6)$$

Where Z_1 and Z_2 are specific acoustic impedances of the two medium given by

$$Z_1 = \rho_1 c_1 \quad (2.7)$$

$$Z_2 = \rho_2 c_2 \quad (2.8)$$

The transmission coefficient highlights the transfer of acoustic energy from the sensor to the medium at the interface. On the other hand, the reflection coefficient accounts for the reflected energy within that reverberates within the sensor's structure. **Table 2-5** outlines the transmission coefficient of some common piezoelectric materials.

Table 2-5: Transmission coefficients of various piezoelectric materials [38]

Material	Density	Speed of sound	Acoustic Impedance	T_{air}
Quartz SiO_2	2650	5760	15.3×10^6	10.8×10^{-5}
Zirconate piezoceramic PZT-5	7750	3880	30×10^6	5.5×10^{-5}
Lead-niobate Piezoceramic $PbNb_2O_6$	5800	2800	16×10^6	10.3×10^{-5}
Piezopolymer PVDF	1780	2260	4.6×10^6	35.9×10^{-5}

In order to overcome the transmission losses due to impedance mismatching, an ultrasonic focusing aperture is used with a PZT transducer as shown in **Figure 2-5**. The aperture axially focuses the ultrasonic beam in order to provide directionality to the ultrasonic energy being transmitted while simultaneously reducing scattering [27,34].

Figure 2-5: Internal components of a disassembled PZT range sensor.

While the impedance mismatch highlights the transmission losses between the medium and the transducer, the PZT also requires large amounts of power to drive the oscillating sensor. Since the dynamic behavior of a PZT is very complex, its dynamic behavior is given by the equivalent circuit shown in **Figure 2-6**. It can be seen that in order to oscillate the sensor at high frequencies, the drive circuitry must be capable of providing high current at high voltages. Additionally, the resonance frequency of the PZT is entirely dependent on the geometry and the internal capacitance of the PZT transducer.

$$f = \frac{1}{2\pi} \sqrt{\frac{C + C_s}{LC C_s}} \quad (2.9)$$

Figure 2-6: Equivalent circuit for a PZT transducer, adapted from [27,39]

Electrostatic coupled or air-capacitive sensors, improve on the bandwidth of the acoustic sensors versus PZT devices. While being driven at lower voltages, these sensors are purely capacitive in nature and have lower internal electrical capacitance as compared to PZT transducers. This reduces the time constant that allows the circuit to be excited at very high frequencies ranging from 10 kHz-10 MHz [27].

While ultrasonic range sensors improve upon the issues related to indoor flight, when compare to the aforementioned optical methods, the acoustic methods of range sensing are accompanied with their own set of limitations. The acoustic sensors are very sensitive to ambient noise especially if the noise present in the environment is within the operating frequency of the sensor (e.g. ultrasonic room occupant sensors). Target acoustic absorption is another factor that deteriorates the acoustic range sensor's detection capability as the target absorbs the sound wave and the reflected amplitude is significantly reduced. However, for MAV application, an ultrasonic sensor is favorable over an optical sensor due to lower power consumption. A typical ultrasonic range sensor operates between 3 V to 5 V and requires between 3 to 5 mA of current, while the most advanced and compact laser range finder consumes 100 mA at 5 V.

2.6 Research Objectives

Conventional PZT-based ultrasonic range sensors are employed in a variety of UAS platforms including but not limited to fixed wing, rotorcraft and multirotor systems. Most of the aforementioned systems also employ Global Navigation Satellite System (GNSS) receivers that cannot be used for indoor MAV flight and navigation. The GNSS-based navigation approach is also impractical for outdoor MAV applications due to platforms' limited power and payload capacity [40,41].

The PZT-based ultrasonic sensors are capable of providing short range situational awareness when placed at specific locations, their weight and accompanying control system renders them heavy enough to be neglected for MAV applications [38]. **Figure 2-7** shows an early attempt by a prior student made towards incorporating a coupled array of PZT ultrasonic range sensors to enhance the system's sensing capability from 1-D to 2-D. However, the increase in weight and size, outweighs the benefits in sense and avoid application [42]. While there are mechanical methods to physically rotate the sensor perpendicular to its measurement axis, these methods also add extra weight to the aircraft and draw increased power.

Figure 2-7: Phased array PZT range sensor on Parrot AR Drone.

A phased array approach involving multiple sensors can allow the outbound ultrasonic signal beam to be steered, similar to mechanical actuation or actively scanned radar systems. The phasing approach eliminates the extra weight and power required by the mechanical system. This phased array air coupled capacitive ultrasonic range determination technique will be the focus of the thesis. The following chapters elaborate on the principles, design and construction of this novel sensor system.

Chapter 3

Background Theory of Acoustics and Sound Propagation

Sound being a pressure wave travels through a medium by transferring energy from one particle to another. In order for the wave to propagate through the medium, it must possess the physical properties of inertia and elasticity. Such a vibratory motion is termed as sound when the medium of wave transfer is a liquid such as air [33,44].

The problem of acoustic analysis can be resolved by three approaches - wave acoustics, ray acoustics and energy acoustics [45]. The classical analysis of sound generation and propagation focuses on the wave acoustics approach, due to its fundamental nature. Therefore, in the following analysis the wave acoustics approach is adopted for modelling of the transducer [44,45].

3.1 Acoustic Wave Model

A sound wave is the transfer of information from a point in space to another through the vibratory motion of waves. The important parameters that allow the measurement of the transportation of this information in space are pressure (P), velocity (u) and density (ρ) [44,45].

3.2 Dispersion Relationship

The parameters, pressure, velocity and density are all time and spatially interdependent functions. The mathematical relationship describing the interdependency is given by the *Dispersion relationship* [45,27,46]:

$$\lambda = \frac{c}{f} \quad (3.1)$$

Where λ is the wavelength, containing the spatial component and f is the frequency, containing the time domain component. The interdependency between time and space is related by the wave propagation speed of the medium, c [45,27]. The interdependencies shown by the dispersion relationship form the basis of physical acoustic analysis.

3.3 Conservation of Mass and Momentum (velocity and density relationship)

A one dimensional mass flow through an elemental control volume dV is illustrated in **Figure 3-1**. Where u_x represents the velocity along the x-axis.

Figure 3-1: Mass and momentum balance, adapted from [44,45]

From the principle of conservation of mass [44]:

$$\frac{\partial(\rho A dx)}{\partial t} = (\rho u A)_x - (\rho u A)_{x+dx} \quad (3.2)$$

Using Taylor-series expansion [44]:

$$\frac{\partial(\rho A dx)}{\partial t} = \left\{ (\rho u A)_x - (\rho u A)_x - \frac{\partial(\rho u A)_x}{\partial x} dx \right\} \quad (3.3)$$

Equation (3.2) can be simplified to the following expression:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_x)}{\partial x} = 0 \quad (3.4)$$

Expanding the equation from one dimension to all three dimensions leads to the following expression:

$$\frac{\partial \rho}{\partial t} + \rho \vec{\nabla} \cdot \vec{u} = 0 \quad (3.5)$$

Where the Nabla operator defines the divergence of the velocity in all three axes.

It is important to note that the term $\frac{\partial \rho}{\partial t}$ takes into the account the fluctuation of the density with respect to time and therefore varies with position and time [27]. On the other hand, the density model associated with the velocity is time independent and only has spatial components determining its value [44,45]. Therefore, equation (3.5) defines the direct relationship between velocity and density.

3.4 Conservation of momentum (pressure and velocity relationship)

The equation of conservation of momentum can also be obtained using a similar approach by balancing the forces around the elemental volume dV in one dimension. From **Figure 3-1** the elemental force balance is shown as follows.

$$\frac{\partial(\rho u_x A) dx}{\partial t} = (\rho u^2 A)_x - (\rho u^2 A)_{x+dx} + (P A)_x - (P A)_{x+dx} \quad (3.6)$$

By performing a Taylor series expansion, the above expression simplifies to:

$$\frac{\partial(\rho u_x)}{\partial t} = \frac{\partial(\rho u_x^2)}{\partial x} - \frac{\partial P}{\partial x} \quad (3.7)$$

Representing the equation in three dimensions yields:

$$\rho \left\{ \frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \vec{\nabla}) \vec{u} \right\} + \vec{\nabla} P = 0 \quad (3.8)$$

The equation is the famous Euler equation and is also known as the nonlinear, inviscid momentum equation [44,46]. For the wave propagation model, the nonlinearities of Euler's equation can be simplified using linearization where by the higher order convection terms in the function are neglected [45,46] thus producing the following expression known as the linear inviscid force equation encompassing the conservation of momentum in three dimensions or the *linearized Euler's Equation* [46].

$$\rho \frac{\partial \vec{u}}{\partial t} + \vec{\nabla} p = 0 \quad (3.9)$$

Therefore, the *linearized Euler's Equation*, fully describes the relationship between excess pressure and velocity [45].

Finally, the relationship between density and pressure can be established by employing the state equation as described by [47,48] as:

$$\frac{\partial P}{\partial \rho} = c^2 \quad (3.10)$$

3.5 Velocity Potential Function

In a velocity field, the curl of the velocity is equal to the vorticity, however for an irrotational flow, the vorticity is 0 at every point [48,49].

$$\xi = \vec{\nabla} \times \vec{u} = 0 \quad (3.11)$$

Consider a scalar ϕ , which defines the *velocity potential* such that [49]:

$$\vec{u} = \vec{\nabla} \phi \quad (3.12)$$

Then $\partial \phi$ by definition is given as [50,51]:

$$\partial \phi = u_x \partial x + u_y \partial y + u_z \partial z \quad (3.13)$$

The velocity potential holds great significance in the field of acoustics and sparks an obvious interest into the physical interpretation of the function itself. To understand the function, the Euler equation is integrated with respect to the time domain [46]:

$$\int -\frac{1}{\rho} \frac{\partial p}{\partial x} dt = \int \frac{du_x}{dt} dt = u_x + u_0 \quad (3.14)$$

To develop a linear model, the nonlinearity introduced by $\frac{du}{dt}$ an instantaneous motion of an infinitely short interval is assumed. The impulsive force ϕ per unit mass can be described by the following equation [48,49]:

$$\phi = \int \frac{p}{\rho} dt \quad (3.15)$$

Thus, producing the x-axis partial differential of equation (3.2):

$$u_x = -\frac{\partial \phi}{\partial x} \quad (3.16)$$

Therefore, “the velocity potential function is identical with the impulsive response force per unit mass of fluid that would generate the motion described by it from rest” [46].

3.6 Modelling spherical sound waves emitting from a point source transducer

To develop the wave propagation model, the first approximation is made by assuming the transmitter to be a point source. Since the point source will be emitting the sound waves in all three dimensions, a spherical geometry is selected to simplify the model. The geometry is then used to determine the wave equation in spherical coordinates.

Since sound waves propagate radially out from the source, therefore the spherical coordinate system model reduces from a three dimensional model to a one dimensional model with radial distance (r) as the variable. The resulting wave equation is:

$$\frac{\partial^2(r\phi(r,t))}{\partial r^2} - \frac{1}{c^2} \frac{\partial^2(r\phi(r,t))}{\partial t^2} = 0 \quad (3.17)$$

Where ϕ, c and r represent the velocity potential, speed of sound in air and radial distance, respectively.

From the principles of harmonic motion, the solution to the velocity potential can be approximated using the general solution of harmonic systems [52]:

$$\phi(r, t) = \frac{G_1\left(t - \frac{r}{c}\right)}{r} + \frac{G_2\left(t + \frac{r}{c}\right)}{r} \quad (3.18)$$

From harmonic motion analysis, it is known that G_1 and G_2 are any arbitrary functions defining the direction of wave propagation. The function G_1 defines the waves propagation radially outwards and the function G_2 defining the propagation from the boundary defined by the radius back towards the source [44,52]. Since the focus of the analysis is on waves propagating away from the source, the function G_2 is neglected. On the other hand, the solution to G_1 is assumed to be a complex harmonic solution and is shown to be [44]:

$$\phi(r, t) = \frac{A_\phi}{r} e^{j(\omega t - kr)} \quad (3.19)$$

Where A_ϕ is a constant determined by boundary condition at the surface of the point source and k is the wave number.

Now, by extrapolating from the model of a breathing sphere of radius a , and a surface normal velocity solution given by [44]:

$$u_a = U_a e^{j\omega t} \quad (3.20)$$

Substituting equation (3.19) into (3.20) given that the relation is described by the expression $\frac{\partial \phi}{\partial r} = u_r$, results in the solution of the scalar constant A_ϕ as a solution with respect to the normal surface velocity and is given as [44]:

$$A_\phi = -U_a \left\{ \frac{a^2}{1 + jka} \right\} e^{jka} \quad (3.21)$$

By substituting the scalar A_ϕ into the velocity potential function produces the following expressions [27]:

$$\phi(r, t) = -\frac{U_a}{r} \left\{ \frac{a^2}{1 + jka} \right\} e^{i(\omega t - k(r-a))} \quad (3.22)$$

By introducing the concept of source strength $Q(t)$, defined as the surface area multiplied by the surface velocity produces the expression [44,27]:

$$Q(t) = 4\pi a^2 U_a e^{j\omega t} = Q_p e^{j\omega t} \quad (3.23)$$

The expression for the velocity potential can then be rewritten as [45]:

$$\phi(r, t) = -\frac{Q(t)}{4\pi r} \left\{ \frac{1}{1+jka} \right\} e^{-jk(r-a)} \quad (3.24)$$

Similarly, pressure (p) , velocity (u) , acoustic impedance (Z_a), intensity (I) and sound power (Π) can be evaluated and are given as follows [44]:

$$p(r, t) = -\rho \left\{ \frac{\partial \phi}{\partial t} \right\} = -jk\rho c \phi(r, t) = \frac{Q_p}{4\pi r} \left\{ \frac{jk\rho c}{1+jka} \right\} e^{j\omega t - k(r-a)} \quad (3.25)$$

$$u(r, t) = \frac{\partial \phi}{\partial r} = -\left\{ \frac{1+jkr}{r} \right\} \phi(r, t) = \frac{Q_p}{4\pi r} \left\{ \frac{1+jkr}{1+jka} \right\} e^{j\omega t - k(r-a)} \quad (3.26)$$

$$Z_a = \rho c \left\{ \frac{k^2 r^2}{1+k^2 r^2} + j \frac{kr}{1+k^2 r^2} \right\} \quad (3.27)$$

$$I(r) = \frac{Q_p^2 k^2 \rho c}{32\pi^2 r^2 (1+k^2 a^2)} \quad (3.28)$$

$$\Pi = \int_S \vec{I} \cdot d\vec{S} = 4\pi r^2 I(r) = q = \frac{Q_{rms}^2 k^2 \rho c}{4\pi(1+k^2 a^2)} \quad (3.29)$$

From equation (3.27) it can be seen that the acoustic impedance has a reactive and resistive component represented by their imaginary and real parts, respectively. When the acoustic impedance is dictated only by the real component, the sound pressure fluctuations and the velocity are in phase. This case only happens when the value of $kr \gg 1$ and allows for sound power to propagated outwards from the source. On the other hand, when the acoustic impedance is reactive

or complex and $kr \ll 1$, then the pressure fluctuations are out of phase with the velocity therefore producing no sound power as shown in **Figure 3-2**.

Figure 3-2: Effect on impedance components with changing wavelength ratio

3.7 Radiation from a Circular Piston

The expansion of the point source radiating waves spherically can now be extrapolated to model sources that have a definite surface geometry. In order to model the system, it is assumed that the circular piston is mounted on an infinite baffle, such that sound it radiated only in the forward direction. It is also assumed that the surface of the transducer is excited with a uniform surface velocity (u_n) across its face [27,44-46,51].

Figure 3-3 shows the resulting geometry, where the radiating circular piston is located in the x - y plane. Assuming an infinitesimal area, on the radiating piston $\overrightarrow{dA}$ produces the differential pressure dp at a point P in the axial direction of the piston with a distance r' is given by [44,53]:

$$dp = j \frac{\rho c k}{2\pi r'} (u_n dA) e^{j(\omega t - kr')} \quad (3.30)$$

Figure 3-3: Geometry and parameters of a circular piston. Adapted from [53]

Where r' from geometry in **Figure 3-3** is defined as:

$$r' = (r^2 + \sigma^2 - 2r\sigma \sin(\theta) \cos(\psi))^{\frac{1}{2}} \quad (3.31)$$

Eq. (3.21) can be used to obtain the velocity potential function(ϕ), since velocity function and pressure can be related using Eq. (3.25) [53]:

$$p(r', t) = -\rho \left\{ \frac{\partial \phi(r', t)}{\partial t} \right\} = -jk\rho c \phi(r', t) \quad (3.32)$$

The velocity potential (ϕ) at a point P can be described by the velocity potential function as follows [53] :

$$\phi(r', t) = \int_S \frac{u_n(r', t - \frac{R}{c})}{2\pi R} dS \quad (3.33)$$

Where u_n is the piston's axial velocity in the z direction.

The pressure field model expressed in equation (3.32) when integrated over the surface of the piston can only be approximated on the z axis and is given by the following expression:

$$p(r, t) = \rho c u_n \left(e^{-jk\sqrt{r^2 + \sigma^2}} - e^{-jkr} \right) \quad (3.34)$$

As shown by multiple authors [43-46,51,53,27] due to the analytical complexity associated with equation (3.30), only axial solutions are available for the nearfield solution given by equation (3.34). However, in the far-field the wave behaves like a spherical wave propagating from a point source [27,44-46].

3.8 Impulse Response Method

Since Eq. (3.30) is not directly integrable, it only provides axial analytical solutions. The impulse response method aims at providing the exact solution of the pressure field in the near and far field at any point in space, irrespective of its axial position. The impulse response method relies on the spatial impulse response function $h(r, t)$ and the source velocity waveform $u(t)$. Harris [54] outlines the relationship between velocity potential function (ϕ) as convolution of the velocity waveform and the spatial response:

$$\phi(r', t) = u(t) * h(r', t) \quad (3.35)$$

The relationship between pressure (p) and velocity potential is defined by Equation (3.32):

$$p(r', t) = -\rho \left\{ \frac{\partial \phi(r', t)}{\partial t} \right\} \quad (3.36)$$

Thus pressure is defined as [54,55]:

$$p(r', t) = \rho \frac{\partial [u(t) * h(r', t)]}{\partial t} \quad (3.37)$$

3.9 Spatial impulse response function $h(r', t)$

The spatial impulse response function defines the velocity potential at a point P , in the z direction, resulting due to the impulsive velocity excitation of the piston. From **Figure 3-4** it can be seen that infinitesimal area dS , when treated as a point source, produces a spherical wave.

The impulse response at point P is the result of the impulse generated by the infinitesimal area dS , produced at time t . Since the wave is travelling spherically from the elemental area dS , the time it takes to reach point P can be determined by $\frac{R}{c}$, where R is the radial distance of point

P , from the source. Thus the impulse, represented by the Dirac delta function occurred at $\delta(t - \frac{R}{c})$.

Figure 3-4: Projection of the impulse on the source. Adapted from [55,56]

This impulse response observed at point P , is the sum of all the points that lie on the source (baffle) and are at a distance R away from point P , as shown in **Figure 3-5**.

Figure 3-5: Planar projection of point P on the source. Adapted from [55,56]

Therefore, the spatial impulse response function $h(r', t)$ can be written as [53-56]:

$$h(r', t) = \int_{R1}^{R2} \int_0^{\theta_1(R)} \frac{\delta\left(t - \frac{R}{c}\right)}{2\pi} d\theta dR \quad (3.38)$$

Since there are two possible scenarios for the projection of point P , one where the projection of P given by P' lies on the surface of the source and another scenario where P' is outside the bounds of the arbitrary source surface S . **Figure 3-6** shows the two cases

Figure 3-6 : Two projections of point P on surface of the transducer. Adapted from [54]

From the geometry, defining $\Omega(r)$ as the half angle subtended by the arc in the x - y plane, centered at point P' . The elemental area source is, in accordance with **Figure 3-5** can be defined as [54,56] :

$$dS = \Omega(R) r dr \quad (3.39)$$

By substituting back into Equation (3.38) and integrating from the surface of the source to infinity produces the following equation:

$$h(r', t) = \int_0^\infty \frac{\delta\left(t - \frac{R}{c}\right) \Omega(r', R)}{2\pi} dR \quad (3.40)$$

by substituting $\tau = \frac{R}{c}$ into Equation (3.40)

$$h(r', t) = \int_0^\infty \frac{\delta(t - \tau) \Omega(r', \tau)}{2\pi} d\tau \quad (3.41)$$

using the sifting property of the Dirac Delta function, Equation (3.41) can be reduced to :

$$h(r', t) = c \frac{\Omega(r', t)}{2\pi} \quad (3.42)$$

The above equation is quite an important solution to the time limited impulse response model development as it directly implies that the instantaneous spatial impulse response function $h(r't)$, is directly related to the geometry.

Equation (3.40) outlines only the generic solution of the spatial impulse response function, a shape specific numerical model has been established for circular [53-56] and rectangular sources [58,59,60].

3.10 Near-Field and Far-Field

Far-field can be described from the geometry outlined in **Figure 3-3**, it can be seen that as $r \gg a$, the expression for r' in Eq (3.21) reduces to [53]:

$$r' = r - \sigma \sin(\theta) \cos(\psi) \quad (3.43)$$

By using the small angle approximation at long distances, the approximation $r' \approx r$ can be made and the pressure (p) can be defined as:

$$p(r, \theta, t) = j \frac{\rho c k a^2 U_p}{2r} e^{i(\omega t - kr)} \left[\frac{2J_1(ka \sin(\theta))}{ka \sin(\theta)} \right] \quad (3.44)$$

The term inside the square brackets is termed as the directivity function and is used to define the pressure in the direction.

$$D(\theta) = \frac{2J_1(ka \sin(\theta))}{ka \sin(\theta)} \quad (3.45)$$

From the above derivation it can be seen that far field is the region along the z axis where the particle velocity is in phase with the pressure, therefore allowing for the energy to be transported through sound waves.

As the point p is brought closer to the source, this results in the opposite effect where $r \ll a$. Since analytical solutions are only available for point along the axis of the piston, this results in the expression for r' to be simplified to:

$$r' = (r^2 + \sigma^2)^{\frac{1}{2}} \quad (3.46)$$

By substituting Equation (3.46) into Equation (3.30):

$$dp = j \frac{\rho c k}{2\pi} U_p \frac{e^{j\left(\omega t - k(r^2 + \sigma^2)^{\frac{1}{2}}\right)}}{(r^2 + \sigma^2)^{\frac{1}{2}}} \quad (3.47)$$

By integrating the above expressions, the pressure p is defined for the nearfield as:

$$p = \rho c U_p e^{j\omega t} \left(e^{-j\left(k(r^2 + \sigma^2)^{\frac{1}{2}}\right)} - e^{-jkr} \right) dA \quad (3.48)$$

In the case of nearfield, the velocity is generally out of phase with respect to the pressure thus having small contribution in terms of the power of the source [42]. Also, as the frequency increases, the wave number (k) increases, therefore reducing the pressure contribution.

Equation (3.48) also sheds light on the geometric contributions to the pressure. It is quite evident from the geometry that the first term inside the brackets is the pressure contribution from the center and the second term is the direct contribution of the edge of the oscillator. Therefore, it is important to note that these pressure waves have an interfering pressure field produced by each component, which at times, cancels. This cancellation of pressure is the most dominant result when the distance from the center in the z axis is large compared to the wavelength λ .

The transition point between near field and far-field is defined by the Rayleigh distance given by the following expression [42,43,53]:

$$R_0 \equiv \frac{S}{\lambda} \quad (3.49)$$

Where S is the piston's surface area, in the case of circular piston this is given by [42,43,53]:

$$R_0 = \frac{S}{\lambda} = \frac{ka^2}{2} \quad (3.50)$$

The Equation (3.42) can now be written as:

$$p = \frac{jR_0 P_0}{r} e^{[\omega t - k(r - R_0)]} \quad ; P_0 = \rho c u_n \quad (3.51)$$

Equation (3.51) illustrates that in the near field region, the pressure can be approximated by using plane wave impedance relationship. As the distance is increased beyond R_0 the beam spreads by dispersing pressure in spherical manner as shown in **Figure 3-7** [42]. This concludes that in the far-field the piston behaves as a monopole source.

Figure 3-7: Near-field plane wave dispersing into far field spherical wave; adapter from [42]

3.11 Directivity function, sensor size and wavelength relationship

There is an important relationship between the size of the sensor and the excitation frequency as shown in the *directivity function*:

$$D_{element}(\theta) = \frac{2J_1(ka \sin(\theta))}{ka \sin(\theta)} \quad (3.52)$$

As the sensor size decreases for a specific frequency, the source behaves like a monopole with a spherical wave front. On the other hand, when the sensor size is increased, side lobes and dead zones start appearing which indicated the directional nature of the sound produced by the transducer [42]. As shown in **Figure 3-8** the main lobe is a highly directed beam in the center containing the sound.

Figure3-8: Angular representation of half power angle [42]

An important performance parameter of an acoustic transducer is its half power beam width and is defined as the angle between the half power points on the major lobe. The half power angle, defining a 3dB loss in sound pressure level (SPL), is given by the following expression [42]:

$$2\theta_{HP} = 2 \sin^{-1} \left(\frac{1.616}{ka} \right) \quad (3.53)$$

3.12 Phased Array Propagation Model

The pressure generated at a point P in the far field is the sum of contributions of all the elements in the array. Since all the elements of the array lie on the same plane, by approximating each element as a point source, the pressure contribution can be evaluated.

The position of point P here, represents the position along the polar coordinates where the amplitude of the pressure is maximum. By varying the phase of the propagated wave emitting from each element, a constructive and destructive pattern can be established such that the position of point P can be varied as shown in **Figure 3-9**.

Figure 3-9: Constructive and destructive pattern using time delays

From Eq (3.51), it can be shown that by approximating a variable A to be defined as

$$A_p = j\rho ck A_\phi \quad (3.54)$$

The pressure at a point P by a single element can be written as [42,53] :

$$p(r, t) = p_0 = \frac{A}{r} e^{j(\omega t - kr)} \quad (3.55)$$

Figure 3-10 shows an array with an odd number of N elements, with the distance d between them.

Figure 3-10: Array pressure contribution

The pressure contribution of individual sources towards the left of the central element are given by [42,53]:

$$p_{+1} = \frac{A}{r} e^{j[\omega t - k(r + d \sin(\theta))]} = p_0 e^{-j2\phi} \quad (3.56)$$

Here ϕ represents the angle and not the velocity potential function.

Therefore, the pressure contribution of elements to the right and left of the array are given by the following functions [46,53]:

$$p_{+n} = p_0 e^{-j2n\phi} \quad (3.57)$$

$$p_{-n} = p_0 e^{j2n\phi} \quad (3.58)$$

By summation of pressures produced by both sides of the array,

$$p = p_0 [\dots + e^{-j4\phi} + e^{-j2\phi} + 1 + e^{j2\phi} + e^{j4\phi} + \dots] \quad (3.59)$$

The right hand side of the equation (3.59) represents a geometric series that can be simplified to produce the following results [46]:

$$p = p_0 \frac{\sin(N\phi)}{\sin(\phi)} \quad (3.60)$$

Therefore, the directivity function can be written as [42,62] :

$$D_{Point Array}(\phi) = \frac{\sin(N\phi)}{N \sin(\phi)} \quad (3.61)$$

Where $D_{point array}(\phi)$ represents the directivity function of the entire array

The directivity of point array and the geometry of the source can be related to provide the directivity of the phased array as follows [42, 62]:

$$D(\theta) = D_{element}(\theta) D_{Point Array}(\phi) \quad (3.62)$$

Therefore, it can be concluded that $D_{element}(\theta)$ is a modulation function that relates the point array directivity function to the phased array.

3.13 Phased array Reception Model

Since the focus of the application is to evaluate distance with limited computational resources and power, the impulse response and other computationally intensive approaches are neglected. The focus is shifted towards an approach that is the inverse of the point source model.

The model assumes that the sound is emitted from the target, as if it were the source and is then captured by the reception array as shown in **Figure 3-11**.

Figure 3-11: Phased array reception model.

The pressure produced by source s^n can be related to the transmitter's pressure by using the pressure equation (3.55). The amplitude reduction from the transmitted wave can be related to the reflected wave at the source point s^n by the following expression:

$$p_r(x, z, t) = \underline{R} p(x, y, t) \quad (3.63)$$

Where $\underline{R}$ denotes the complex reflection factor, and is related to the impedance and surface absorption [64,65]. However, to simplify the model, it is assumed that the $\underline{R}=1$, implying a *specular reflection*.

With the simplified model, it is evident that the pressure observed by the receiver is simply due to the effect of attenuation. In order to account for attenuation, the expressions for the wave number is expanded into complex angular wave number given by:

$$\underline{k} = k - j \frac{m}{2} = \frac{\omega}{c} - j \frac{m}{2} \quad (3.64)$$

Where m represents the attenuation constant of the medium. **Figure 3-12** show the attenuation per unit length for 50 kHz and 100 kHz measured at a variety of humidity levels and temperature.

Figure 3-12: Attenuation of ultrasonic waves in air [64]

By assuming standard temperature and pressure with the relative humidity selected at 40%, the attenuation in air is approximated to be 1.6 dB/m [64]. Since the desired range for the sensor is selected to be 10 m, the observed attenuation of the signal upon reception is expected to be reduced by 32 dB or more.

As the waves propagate from the source s^n as spherical waves, the radius of the wave increases as it is reflected back from the target. Since the sensor array's width is small as

compared to the reflected wave front, it is essentially perceived as a plane wave when the signal is received.

3.14 Signal Reception Signal Processing

Since the signals received are continuous in time domain however are dependent on the discrete time domain of the chipset processing the received signal. It is assumed that each incoming signal is occurring at a discrete time index k . The output from m sensors can now be characterized as [63]:

$$y_m(k) = x_m(k) + v_m(k) \quad (3.65)$$

Where y_m is the discrete time output, x_m is the received signal and v_m is the spatial noise added to the system. Referring to **Figure 3-11**, as the wave propagates over the sensor, the time delay between reception can be attributed directly to the spatial position of the sensors such that the output signal can be written as [63]:

$$y_m(k) = x(k - t - \tau_m) + v_m(k) \quad (3.66)$$

Where

$$\tau_m = \frac{(m - 1) d \cos(\theta)}{c}$$

By converting the signal into frequency domain equation (3.66) becomes:

$$Y_m(\omega) = X_m(\omega)e^{-j\omega(t+\tau_m)} + V_m(\omega) \quad (3.67)$$

By employing the *Delay and Sum* (DS) beamforming technique, the output of the beamformer can be defined as

$$Z(\omega) = X(\omega)e^{-j\omega t} + \frac{1}{M} \sum_{m=1}^M V_m(\omega)e^{j\omega(\tau_m)} \quad (3.68)$$

The effectiveness of the DS beamformer becomes quite obvious when the input signal-to-noise ratio (*iSNR*) given by equation (3.69) is compared to the output signal-to-noise ratio (*oSNR*) given by equation (3.70) :

$$iSNR(\omega) = \frac{E[|X(\omega)|^2]}{E[|V_1(\omega)|^2]} \quad (3.69)$$

$$oSNR(\omega) = \frac{E[|X(\omega)|^2]}{\frac{1}{M} E[|\sum_{m=1}^M V_m(\omega)e^{j\omega(\tau_m)}|^2]} \quad (3.70)$$

The output gain can now be evaluated by taking the ratio of the output and input SNRs :

$$\mathcal{G}(\omega) = \frac{oSNR(\omega)}{iSNR(\omega)} = M \quad (3.71)$$

Therefore, the improved performance of the DS beamformer is by a factor of M . The reception beam pattern can now be defined as a magnitude of the transfer function between the input and output signal [63,61]. By substituting the equation (3.69) and (3.70) into equation (3.71) the beamformer output is defined as:

$$\mathcal{B}(\omega, \theta) = \left| \frac{Z(\omega)}{X(\omega)} \right| = \left| \frac{\sin \left[\frac{M\omega d}{2c} (\cos \theta - \cos \theta_s) \right]}{M \sin \left[\frac{\omega d}{2c} (\cos \theta - \cos \theta_s) \right]} \right| \quad (3.72)$$

Where θ_s is the expected direction of the source and θ is incidence angle of the plane wave with respect to the sensor. **Figure 3-13** to **3-17** shows the beamformer gain output for a three element sensor that is excited at 30kHz, 50kHz and 100kHz. **Figure 3-18** highlights the interference pattern as the frequency is increased.

Figure 3-13: Array factor response of a phased array sensor with 3 sensor elements with 6mm diameter placed 4 mm apart at a) 100 kHz b) 50 kHz and c) 30 kHz.

Figure 3-14: Reception beamforming gain with respect to incidence angle represented in linear and polar plot at 30 kHz

Figure 3-15: Reception beamforming gain with respect to incidence angle represented in linear and polar plot at 50 kHz.

Figure 3-16: Reception beamforming gain with respect to incidence angle represented in linear and polar plot at 100 kHz

a) 30 kHz Beam pattern

b) 50 kHz Beam pattern

c) 100 kHz Beam pattern

Figure 3-17: Qualitative 3D visualization of the gain patterns at 30 kHz, 50 kHz and 100 kHz

Figure 3-18: Beam patterns produced by a 3 transducer linear array as a function of frequency.

3.15 Sensor Size and Modelling Methodology.

Since the sensors under consideration are to be modelled for range sensing applications, the nearfield model of the sensor is neglected. In the far field, the mathematical model of a baffled piston reduces to that of a monopole excited at given frequency. Therefore, equations predicting the pressure, intensity, impedance and particle velocity for a monopole are used for the modelling and performance evaluation.

The transducer design under consideration is driven at frequencies ranging from 30 kHz to 100 KHz, this results in wavelengths between 11.43 mm to 4.29 mm. From literature [42,46,53,66] it is suggested that by reducing the sensor radius compared to the wavelength ($ka \gg 1$), the reactive impedance can be reduced. Therefore, the sensor size of 3 mm in radius is selected, which produces ka values ranging between 1.65 to 5.50 ,and is used in the work described in the later chapters for the design and construction of the phased array.

Chapter 4

Spatial Positioning

The acoustic model for transmission and reflection in the previous chapters needs to be related to the source's position. This chapter will present the mathematical and signal processing model that is implemented to extract the position information of the source based on the response generated by a phased array transducer [6].

Four techniques of source localization were considered namely; time of arrival (TOA), time difference of arrival (TDOA), received signal strength (RSS) and direction of arrival (DOA) [6]. **Table 4-1** outlines the advantages and the information that can be obtained from each methodologies.

Table 4-1: Comparison of various localization methodologies [6]

Model	Information	Advantages	Disadvantages	Time Synchronization
TOA	Range	Accuracy is high	Line of sight operation	Yes
TDOA	Range difference	Accuracy is high	Line of sight operation	No
RSS	Range	Simple and inexpensive	Low accuracy	No
DOA	Bearing	At least two sensors are required	Significant post processing required	No

From **Table 4-1**, the TOA technique has very high accuracy, but requires synchronization of the source and receivers [6]. Since the transducer functions as the transmitter and the receiver over time, the system is time synchronous by default and is therefore selected as the reception processing model. The TOA technique only provides the position information and can be used to extrapolate angular position by evaluating the time delay. In the analysis, it is assumed that the sensors position is static and does not change during the position acquisition stage.

Letting the position of the target from each sensor be represented by following equation:

$$\mathbf{r} = \mathbf{f}(\mathbf{x}) + \mathbf{n} \quad (4.1)$$

Where $\mathbf{r}$ is the position measurement vector obtained from the sensors directly, $\mathbf{n}$ is the additive zero mean noise and $\mathbf{x}$ is the position vector of the target [6].

The time of pulse emission is known, along with the time at which the pulse is received, this can be used to evaluate the time from target to receiver to be written as

$$t_l = \frac{d_l}{c}, \quad l = 1, 2, \dots, L \quad (4.2)$$

Therefore, the model described in spatial domain by equation (4-1) is as follows:

$$\mathbf{r} = [r_1 \quad r_2 \quad r_3] \quad (4.3)$$

$$\mathbf{n} = [n_1 \quad n_2 \quad n_3] \quad (4.4)$$

$$\mathbf{f}(\mathbf{x}) = \begin{bmatrix} \sqrt{(x - x_1)^2 + (y - y_1)^2} \\ \sqrt{(x - x_2)^2 + (y - y_2)^2} \\ \sqrt{(x - x_3)^2 + (y - y_3)^2} \end{bmatrix} \quad (4.5)$$

From the equation it can be seen that the parameters of the target positions are a function of the sensor position vector. Also it is evident that the approximation of the position target shown by equation (4.5) is non-linear. Thus by using a linear least square localization approach to evaluating the position, the nonlinearity can be simplified to a linear model given by [6]:

$$\mathbf{Ax} + \mathbf{q} = \mathbf{b} \quad (4.6)$$

Where $\mathbf{q}$ has the noise terms embedded in it. By assuming $\mathbf{q}$ to be very small such that the noise term can be neglected, the model can be simplified further to be a linear system of equation defined by the only the parameters $\mathbf{A}$ and $\mathbf{b}$:

$$\mathbf{Ax} = \mathbf{b} \quad (4.7)$$

$$\mathbf{A} = \begin{bmatrix} -2(x_2 - x_1) & -2(y_2 - y_1) \\ -2(x_3 - x_1) & -2(y_3 - y_1) \end{bmatrix} \quad (4.8)$$

$$\mathbf{b} = \begin{bmatrix} r_2^2 - x_2^2 - y_2^2 - r_1^2 + x_1^2 + y_1^2 \\ r_3^2 - x_3^2 - y_3^2 - r_1^2 + x_1^2 + y_1^2 \end{bmatrix} \quad (4.9)$$

From the above model the position $\mathbf{x}$ of the target can be obtained as follows :

$$\mathbf{x} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{b} \quad (4.10)$$

The model presented above forms the spatial localization algorithm for an array of sensors that lie in two dimensions. Since the array that is currently being developed lies in only one dimension, the model can be simplified by assuming y coordinates to be zero.

From three sensors, three equations of position are obtained, however the system only requires two spatial coordinates. This result in the system being over constrained since there are more equations than variables. This implies that the system has either no solution or more than one

solution, the latter is true for the current system and is an anomaly occurring due to the geometry of the problem. As shown in **Figure 4-1**, the equation describing the propagation distance is the equation of a circle, as the propagation distance from each transducer is obtained as the radius of the circle.

Figure 4-1: Position localization using TOA technique

Figure 4-1 highlights that two solutions exist, one where the target's approximate distance is in front of the transducer and in the other case is where the distance is behind the transducer. Thus, by neglecting the negative values, the solution still holds and is validated by experiment.

Chapter 5

Sensor Modelling

This chapter presents the development of the analytical and numerical model for the air-capacitive transducer. The analytical model was developed using the vibration equation of continuous systems and aims at providing the vibration mode shapes and modal frequencies. The modal analysis coupled with a known electrostatic force allows for the evaluation of the displacement of the sensor membrane. The results of the analytical analysis are then compared with numerical analysis using software based finite element analysis (FEA) using Ansys Acoustic Analysis package.

5.1 Analytical Model

The analytical model is developed directly from the classical plate theory developed by Liessa [57]. To develop the analytical model, the following assumptions are made:

1. The membrane is clamped around the edges;
2. It has the physical dimensions are outlined in Appendix A; and
3. The properties outlined in Appendix B are homogenous over the entire membrane.

The displacement of a membrane is defined as a vibration of a continuous system constrained by boundary conditions. The free vibration solution for a continuous system can be found using the method of separation of variable and is given as the product of the time dependent and space dependent functions which are independent of each other [52]:

$$w(x, t) = W(x)T(t) \quad (5.1)$$

Since the displacement is occurring in the transverse plane, equation (5.1) can also be re-written with the Laplacian operator as [67,68,69]:

$$D\nabla^4 w + \rho \frac{\partial^2 w}{\partial t^2} = 0 \quad (5.2)$$

Where D is the flexural rigidity given by:

$$D^* = \frac{Eh^3}{12(1 - \nu^2)} \quad (5.3)$$

In free vibration, the time dependent forcing function is absent, therefore the only mode of vibration is free vibration. This reduces the equation (5.1) to:

$$w(x, t) = W \cos \omega t \quad (5.4)$$

Where, $\omega = \text{circular frequency}$

By substituting equation 5.4 into 5.2 the following relationship is obtained [68,69] :

$$(\nabla^4 - k^4)W = 0 \quad (5.5)$$

Where $k = \text{convenience factor}$

$$k^4 = \frac{\rho\omega^2}{D^*}$$

The above equation can be factored and rewritten as [67,68] :

$$(\nabla^2 - k^2)(\nabla^2 + k^2)W = 0 \quad (5.6)$$

By applying the theory of linear differential equations to equation 5.6, the following two solutions are obtained [67,68] :

$$\nabla^2 W_1 + k^2 W_1 = 0$$

$$\nabla^2 W_2 - k^2 W_2 = 0 \quad (5.7)$$

Since the plate being assessed is circular therefore the coordinate system used for evaluating the solution is based on polar coordinates, where the displacement function is given as the sum of all of the Fourier series [67] :

$$W(r, \theta) = \sum_{n=0}^{\infty} W_n(r) \cos(n\theta) + \sum_{n=0}^{\infty} W_n^*(r) \sin(n\theta) \quad (5.8)$$

By substituting the Fourier series into equation (5.7), the following two functions are obtained:

$$\begin{aligned} \frac{d^2 W_{n_1}}{dr^2} + \frac{1}{r} \frac{dW_{n_1}}{dr} - \left(\frac{n^2}{r^2} - k^2 \right) W_{n_1} &= 0 \\ \frac{d^2 W_{n_2}}{dr^2} + \frac{1}{r} \frac{dW_{n_2}}{dr} - \left(\frac{n^2}{r^2} - k^2 \right) W_{n_2} &= 0 \end{aligned} \quad (5.9)$$

Similarly, two identical equations are obtained for the W_n^* . It is important to note that the above equations are recognized as the Bessel's function, having the following solution:

$$\begin{aligned} W_{n_1} &= A_n J_n(kr) + B_n Y_n(kr) \\ W_{n_2} &= C_n I_n(kr) + D_n K_n(kr) \end{aligned} \quad (5.10)$$

Where $J_n = \text{Bessel's function of the first kind}$

$I_n = \text{Modified Bessel's function of the first kind}$

Since the plate has no internal hole, the Bessel's function of the second kind and the modified Bessel's function of the second kind are discarded. This reduces the final equation to the sum of the two displacements W_{n_1} and W_{n_2} and can be written as follows [67] :

$$W_n = [A_n J_n(kr) + C_n I_n(kr)] \cos n\theta \quad (5.11)$$

The following boundary conditions were used for the clamped plate analysis [67,68,69]

$$\begin{aligned} W(a) &= 0 \\ \frac{\partial W(a)}{\partial r} &= 0 \end{aligned} \quad (5.12)$$

By substituting equation (5.12) into (5.11) the following characteristic determinant is obtained

$$\begin{vmatrix} J_n(\lambda^*) & I_n(\lambda^*) \\ J_n'(\lambda^*) & I_n'(\lambda^*) \end{vmatrix} = 0 \quad (5.13)$$

The following recursion relationship can be used to find out the derivative of the Bessel's function

$$\begin{aligned} \lambda J_n'(\lambda^*) &= n J_n(\lambda^*) - \lambda^* J_{n+1}(\lambda^*) \\ \lambda I_n'(\lambda^*) &= n I_n(\lambda^*) + \lambda^* I_{n+1}(\lambda^*) \end{aligned} \quad (5.14)$$

By expanding equation 5.13 the following relationship can be obtained.

$$J_n(\lambda^*) I_{n+1}(\lambda^*) + I_n(\lambda^*) J_{n+1}(\lambda^*) = 0 \quad [9] \quad (5.15)$$

Using equation (5.15) an iterative solver was developed in MATLAB to solve for the eigenvalues.

The roots of these equations were obtained for desired frequency ranges and are outlined in Table 5-1.

Table 5-1 Frequencies and mode shapes from ANSYS and MATLAB

Mode Shape	ANSYS [Hz]	MATLAB [Hz]	% Difference
1	114.97	158.2	27.3
2	239.21	247	3.2
3	392.54	355.6	10.4
4	514.37	483.9	6.3
5	684.65	631.9	8.3
6	784.17	799.7	1.9
7	952.41	987.2	3.5
8	1003.5	1194.5	16.0

Table 5-1 highlight the comparison between analytical method and Galerkin's method. The analytical method relies on the eigenvalues of the solution in equation (5.15) whereas the numerical approach relies on solving the wave equation numerically and obtaining the results. The main reason for the disparity in values is mainly due to structural damping that is taken into account by Ansys Workbench and is observed in the dataset where the frequency outputs are lower than the values obtained from the analytical analysis.

5.2 Numerical Modelling Approach

Unlike the analytical approach, the numerical modelling approach relies on the elemental deflections which are translated into internal and external forces. By evaluating these internal and external forces, a more accurate propagation model can be approximated. Also, the numerical modelling approach allows for the inclusion of the coupling medium inside and around the transducer. As seen from the equation (5.1), the analytical analysis lacks the structural feedback from the coupled medium which includes the reverberation occurring within the structure of the transducer. The numerical model can be extended further to consider the impedance mismatch at the surface.

The harmonic response of a structural system with mass matrix $[M]$, damping matrix $[C]$, stiffness matrix $[K]$ and a force vector $\{f\}$ with nodal displacement $\{u\}$ is given as follows [reference]

$$[M_s]\{\ddot{U}\} + [C_s]\{\dot{U}\} + [K_s]\{U\} = \{F_s\} \quad (5.16)$$

Equation (5.16) can be represented in terms of the harmonic frequencies as follows:

$$(-\omega^2[M_s] + j\omega[C_s] + [K_s])\{U\} = \{F_s\} \quad (5.17)$$

Therefore, the nodal displacement vector can be expressed as:

$$\{U\} = (-\omega^2[M_s] + j\omega[C_s] + [K_s])^{-1} \{F_s\} \quad (5.18)$$

Similarly, by using the pressure-formulated element approach outlined in ref. 60, the forces nodal forces on the fluid elements can be expressed as a function of pressure as shown [60] :

$$[M_f]\{\ddot{p}\} + [C_f]\{\dot{p}\} + [K_f]\{p\} = \{F_f\} \quad (5.19)$$

For a coupled analysis, the mass, stiffness and damping of the coupled medium along with the interaction surface is accounted by the introducing the coupling matrix $[R]$. The resulting expression highlighting the coupling is shown as [70]

$$\begin{bmatrix} M_s & 0 \\ \rho_0 R^T & M_f \end{bmatrix} \begin{Bmatrix} \ddot{U} \\ \ddot{p} \end{Bmatrix} + \begin{bmatrix} C_s & 0 \\ 0 & C_f \end{bmatrix} \begin{Bmatrix} \dot{U} \\ \dot{p} \end{Bmatrix} + \begin{bmatrix} K_s & -R \\ 0 & K_f \end{bmatrix} \begin{Bmatrix} U \\ p \end{Bmatrix} = \begin{Bmatrix} F_s \\ F_f \end{Bmatrix} \quad (5.20)$$

For harmonic analysis, Equation (5.20) can be reduced to the following expression without the higher order terms.

$$\begin{bmatrix} -\omega^2 M_s + j\omega C_s + K_s & -R \\ -\omega^2 \rho_0 R^T & -\omega^2 M_f + j\omega C_f + K_f \end{bmatrix} \begin{Bmatrix} U \\ p \end{Bmatrix} = \begin{Bmatrix} F_s \\ F_f \end{Bmatrix} \quad (5.21)$$

The unsymmetric matrix shown in Equation (5.21) requires higher computational time as the off diagonal entries are not transposes of each other. This inversion of an unsymmetric matrix is very computationally intensive and requires considerable amount of computation time. To reduce the computation time, the geometry of the sensor is simplified by using symmetric planes.

To model the sensor using numerical FEA approach, Ansys Workbench Acoustics analysis software was selected. A modal analysis using a circular disc, clamped at the edges, was conducted in Ansys Workbench. The geometry used for the analysis is shown in **Figure 5-1** and a detailed

model is available in Appendix C along with the material properties for Mylar listed in Appendix B. The resulting mode shapes and their corresponding frequencies are outlined in **Figure 5-1**.

Figure 5-1: Air-coupled transducer frequency response and transducer deflection amplitude

From **Figure 5-1**, the mode shapes are readily visible as the intermediate peaks occurring as the transducer is excited over a range of frequencies. The lower frequencies have a very high amplitude, however after passing the second mode shape the amplitude reduces drastically. In the range of operation of the current design, operating between 30 to 100 kHz, the output deflection is observed to be an order of magnitude lower when compared to low frequency excitation.

A mesh studies was performed to validate the selection of mesh size and is available in **Table 5-2**. The element size for the FEA analysis is inversely proportional to the computation time, making larger elements preferable. However, as stated in the Ansys software guidelines [71], in order to capture the full wave vibratory motion of the disc, the largest element size should be

1/10 of the wavelength, placing a limit on the maximum element size. Therefore, an element size of 0.1 mm was selected for further FEA analysis.

Table 5-2: Mesh studies analysis with computation time

Mode #	Theoretical	0.02	%error	0.05	%ERROR	0.10	%ERROR	0.20	%ERROR
		mm		mm		mm		mm	
	Computation Time (Minutes)	10		187		100		36	
1	1160.484	1160.4	0.007	1160.7	0.019	1161.1	0.053	1162	0.1
6	4517.169	4517.2	0.001	4518.2	0.023	4519.9	0.060	4523.7	0.1
15	10120.16	10119	0.012	10121	0.008	10125	0.048	10135	0.1
30	17967.11	17960	0.040	17964	0.017	17973	0.033	17995	0.1
51	28054.42	28037	0.062	28044	0.037	28059	0.016	28110	0.2
74	40384.23	40347	0.092	40357	0.067	40384	0.001	40493	0.2
105	54953.68	54884	0.127	54899	0.099	54946	0.014	55165	0.3
140	71768.48	71646	0.171	71666	0.143	71741	0.038	72168	0.5
175	90824.36	90624	0.221	90653	0.189	90767	0.063	91632	0.8
222	112121.3	111810	0.278	111850	0.242	112040	0.073	113660	1.3

The results from the air-coupled harmonic analysis is show in **Figure 5-2**. It can be seen that the natural frequencies outlined by the harmonic analysis with and without air are offset due to the air and structural coupling. The analysis was conducted for frequencies between the range of 1 Hz to 150 kHz which includes the operating range of the transducer under consideration.

Figure 5-2: Comparison of frequency vs mode shape for analytical and numerical methods

The sound pressure level in the field by extrapolating the transducer's film displacement and accounting for the static pressure. The results are used for comparison to the experimental performance in the later chapters of this thesis.

5.3 Sensor Modelling Summary

The analysis outlined in this chapter highlight the importance of mathematical modelling used to approximate the transducer's performance. The air coupling modelling is emphasized and used for developing the model as it allows for a more accurate representation of the operation of the sensor. The analytical model presented, is used as a feedback mechanism to establish a coarse co-relation between air coupled frequencies and non-coupled frequencies.

Chapter 6

Sensor Construction

In this Chapter, the construction and development of the air coupled array and the accompanying circuitry are described. The printed circuit board (PCB) designed for the sensor array was built using the photolithography technique. This technique allows for the layout of smaller traces and component pad widths necessary for surface mount devices (SMD), while offering increased simplicity, reliability and repeatability.

6.1 Construction of the sensor

The air capacitive sensor consists of a back plate and a metallized membrane as show in **Figure 6-1**. The, back plate is made from copper and the membrane is made from metallized biaxially-oriented polyethylene terephthalate (BoPET) film, commercially known as Mylar. The thickness of the membrane was selected to be 10 micrometer (0.00039 inches) in order to reduce the inertia of the membrane at high acoustic frequencies [38].

Figure 6-1: Model of an air-capacitive transducer with Mylar film[38,27]

The film was first put in tension such that all folds and kinks are removed. A paint can was used to hold the film in tension while pre-machined rings are attached to the film using ultraviolet glue. The film was then cut and removed along with excess film around the sensor resulting in the assembly as shown in **Figure 6-2**.

Figure 6-2: Air-Capacitive sensor array of 3 elements

The membrane was placed such that the non-metalized face of the film was between the back plate and the metalized face as shown in **Figure 6-1**. The non-metalized face of the film served as the partial dielectric along with air gap between the film and the back plate. Finally, the membrane was bonded to the back plate using ultraviolet glue. The back plate was designed using Cadsoft Eagle CAD software and was manufactured using the process outlined in **Figure 6-3**.

Figure 6-3: PCB fabrication process layout

6.2 PCB fabrication method

To design and manufacture the PCB, photolithographic techniques were used. **Figure 6-3** outlines a flowchart outlining the construction methodology adopted for the PCB fabrication methodology. A PCB layout, developed using Cadsoft Eagle® electronics CAD design package, was printed on a transparency as shown in **Figure 6-4**.

Figure 6-4: Circuit design on transparency

The transparency is placed above the positively pre-sensitized PCB (MG Chemical CAT No. 690) and is exposed to ultraviolet (UV) light for ten minutes' while being pressed down by sheet of UV transparent plexiglass as shown in **Figure 6-5**.

Figure 6-5: UV exposure chamber setup

After the UV exposure, the board is placed in a positive developer fluid (MG Chemicals CAT No. 418) and stirred for two minutes. The resulting design on the copper clad board is shown in **Figure 6-6**.

Figure 6-6: Pre-sensitized board after photo development process

The PCB was later etched using a mixture 2:1 volumetric ratio of hydrogen peroxide and muriatic acid (HCl) 31.45% concentration for 5 minutes. The etchant reacts with the exposed copper producing the board shown in **Figure 6-7**.

Figure 6-7: Etching process using Muriatic acid.

To protect the traces from corrosion and to improve the adherence of solder to the pads, the PCB was submerged in a liquid tin solution (MG Chemicals CAT No. 421). The solution chemically reacts with copper to form a thin layer of tin on top of the surface as shown in **Figure 6-8**. Based on the time deposition rate graph shown in **Figure 6-9**, a one minute deposition time was selected.

Figure 6-8: PCB appearance following the tinning step.

Figure 6-9: Time rate deposition of Liquid Tin solution (MG Chemicals CAT No. 421) [72]

Finally, holes were drilled in the PCB with a number 60 drill bit to attach pin headers to make the board mountable on a breadboard for testing purposes.

In the last step a solder mask layer was applied to further protect the traces and the surface of the PCB from environmental degradation. An adhesive solder mask film was attached to the surface of the PCB and a transparency with the pad layout is placed above the solder mask. The board is exposed to UV light. The uncured mask beneath the printed pad layout is removed by using a basic solution of 1 Mol, Sodium Hydroxide (NaOH) solution.

6.3 Methodology discussion

The photolithographic technique offers the most repeatable results while only requiring the printed transparency. The final circuit design outlined in Appendix D is developed using the methodology outlined in this chapter and the results boards are shown in **Figure 6-10**.

Figure 6-10: Consistency and repeatability test results

To measure the repeatability of the process 2 different integrated circuits (IC) with 2 different pin spacing are considered as shown in **Figure 6-11**. To measure repeatability of the process, 3 measurements were taken for each set and compared to the design value and are results are listed in **Table 6-1**.

a) AND gate

b) MAX 660

Figure 6-11: Pad layout for two ICs,

Table 6-1: Repeatability test based on IC pin spacing for three PCBs

Chipset	Theoretical Dimension (mm) [73,74]	Sample 1 (mm)	Sample 2 (mm)	Sample 3 (mm)
AND gate pos. 1	0.65	0.655	0.65	0.66
AND gate pos. 2	0.65	0.65	0.65	0.65
MAX660 pos. 1	1.27	1.27	1.26	1.26
MAX660 pos. 2	1.27	1.250	1.275	1.270

Based on results obtained from **Table 6-1**, the maximum error of 1.5% is observed. Therefore, the board layout and manufacturing process outlined in this chapter was used to manufacture all the boards for the current research.

Chapter 7

Digital Circuit Design

The system design requirements from chapter 3 outline the performance of the sensor array. This chapter focuses on the discussion regarding the circuit design used to achieve the desired frequency and phase performance. The system design is broken into two phases section; namely, transmission and reception.

In the transmission phase, the wave generation, synchronization and sensor capacitance plays an important role as each sensor's phase determines the constructive and destructive sound pattern as shown by **Figure 7-1**.

Figure 7-1: Constructive and destructive pattern produced by a two element array [61]

The propagating wave is reflected from the target and is picked up during the receiver phase. In the reception phase the beamforming algorithm, signal filtering and amplification reduce the noise and focus the reception pattern along the direction of reception. The final signal output produced from the reception process is passed through signal processing phase where the range and the angular position are approximated. **Figure 7-2**, shows the layout used during the transmission and reception phase.

Figure 7-2: High level sensor system architecture.

7.1 System 1: Master Device

System 1 functions as a higher level node or a master device with Systems 2, 3 and 4 acting as slave devices. System 1 serves the client computer directly via USB interface and accepts inputs in the form of user defined angles and frequencies. These angles are then forwarded to System 2 for evaluation of phased array's time delay calculation. Upon reception, the calculated data from System 3 and 4 is forwarded to System 1 to be converted into reception angle, which is the output forwarded to the client computer.

7.2 .1 System 2: Signal generation

The variable frequency design under consideration has an operating frequency range of 30 kHz to 100 kHz. Since crystal oscillators and resonators are only available for a specific frequency, by employing a frequency divider (using J-K flip-flop) the output frequency range could be achieved [1]. However, the frequency output would be limited by the frequency of the crystal and the number of flip flop switches used. This dependency on the number of flip flops essentially makes the solution infeasible as the output resolution becomes a direct function of cost and component footprint on the board.

To achieve the desired performance, with a higher resolution, an LM555 timer is used in the asynchronous mode as shown in **Figure 7-3**, where the frequency is controlled directly by varying the resistance across a digital potentiometer. This arrangement allows for 256 bit resolution on the frequency and eliminates the use of a crystal oscillator completely. Thus reducing the number of components required while providing adequate frequency resolution.

Figure 7-3: Digital potentiometer controlled oscillator

7.2.2 Phasing and Timing algorithm

The signal produced by the LM555 timer is used as an external clock input; this input is then used by the internal counter on system 2 to produce the desired frequency that forms the enveloping signal. By changing the phase of the enveloping signal the output beam can be phased in different direction. The rising edge of each enveloping function is synchronized to the enveloped signal in

order to achieve a phased wave front. The time delay between the rising edges dictates the angle of propagation.

The ATmega 328P-AU microcontroller was selected for the signal processing as it is available in a surface mount 32-pin quad-flat package (QFP) [2]. This package requires smaller footprint and offers two 8-bit timers and one 16-bit timer which are used extensively in the phasing of the transmitted waveform. In order to use the ATmega microcontroller, an Arduino bootloader was installed onto the system for programming and interfacing purposes.

The ATmega timers can be preconfigured and have two registers that store the timing configuration as shown in **Figure 7-4**.

TCCR0A – Timer/Counter Control Register A

Bit	7	6	5	4	3	2	1	0	
0x24 (0x44)	COM0A1	COM0A0	COM0B1	COM0B0	–	–	WGM01	WGM00	TCCR0A
Read/Write	R/W	R/W	R/W	R/W	R	R	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

TCCR0B – Timer/Counter Control Register B

Bit	7	6	5	4	3	2	1	0	
0x25 (0x45)	FOC0A	FOC0B	–	–	WGM02	CS02	CS01	CS00	TCCR0B
Read/Write	W	W	R	R	R/W	R/W	R/W	R/W	
Initial Value	0	0	0	0	0	0	0	0	

Figure 7-4: Timer counter control register 0A and 0B [3]

By setting the TCCRA and TCCRB registers, the output of all three timers can be synchronized. The desired output pulse is passed through an AND gate as shown in to remove any nonlinearities in the signal during transient stages.

Since the transducer's source capacitance is very low, a higher voltage is applied to produce a greater force between the two plates of the capacitor. This is achieved by using a voltage doubler circuit that is connected to the transducer, and controlled by the output signal from the AND gate shown in **Figure 7-5a**. The output signal from the microcontroller is fed directly to the B input of the AND gate, while the input A is connected to the variable frequency oscillator described previously. Since the AND gate can only output 5 V, a bipolar junction transistor (BJT) is employed in a common emitter amplifier configuration shown in **Figure 7-5b**. The common emitter amplifier configuration acts as a signal inverter, to prevent from signal inversion a NPN BJT was employed such that the output signal stayed in phase with the input signal. The voltage doubler design used is presented in **Figure 7-5c**.

Figure 7-5: Ultrasonic wave transmitter amplification circuit

7.3 Signal reception

The received signal is the sum of desired signal and the noise signal. Since the received signal has a 1 mV amplitude, any filtration performed at this stage would result in further reduction of the amplitude and possible signal loss. To prevent amplitude reduction, the signal is first passed through an amplification stage. Here the signal is amplified by a factor of 60 dB or 1000 times, by a non-inverting amplifier configuration.

However, no off-the-shelf audio amplifier was available to perform a 60 dB amplification in a single stage due to the gain bandwidth product (GBWP), as shown below.

$$GBWP = Gain \times Frequency \quad (7.1)$$

Since, GBWP is an operational amplifier's performance characteristic and is a fixed value, increasing the input frequency reduces the output gain achievable using the operational amplifier (op-amp). For an op-amp such as the Texas Instrument's TL074, the GBWP is listed as 3 Mhz. In order to amplify the frequencies at 100 kHz, the available gain is 30 times or 29.5 dB. The output range and gain of the amplifier can be increased by using amplification in stages, where the output of one stage is the input of the next stage. This allows for higher gains while also broadening the effective bandwidth and is given by the following relationship:

$$BW_{total} = BW \times \sqrt{\frac{1}{2^{stages}} - 1} \quad (7.2)$$

According to the current design

$$BW_{total} = \frac{3 \text{ Mhz}}{10} \times \sqrt{\frac{1}{2^3} - 1} = 152.95 \text{ kHz} \quad (7.3)$$

The three stage amplification is selected as the final design to amplify the signal by 60 dB and the layout is shown in **Figure 7-6**.

Figure 7-6: Three stage amplifier using Texas Instrument TL074CPWR

7.4 Signal Filtration

After the amplification stage, the signal is passed through a filter that rejects any frequencies outside the range of 30-100 kHz. While ideal performance of a band-pass filter corresponds to the “brick wall effect” as shown in **Figure 7-7**, the practical performance however offers a larger bandwidth with linear tapering effects.

Figure 7-7: Ideal (top) filter performance versus actual (bottom) performance of a filter [75]

To improve on the bandwidth performance, filter designs with higher Q values are considered for analysis and along with higher order as they offer steeper roll off slopes allowing for narrower bandwidths. **Figure 7-8** shows the roll off slopes of various filter designs.

Figure 7-8: Filter types and the effect of the order of the filter. Adapted from [75]

To isolate the reflected signal a fourth-order multiple feedback band-pass filter was designed and is shown in **Figure 7-9**.

Figure 7-9: Fourth order multiple feedback bandpass filter design

The filter design has two second order multiple feedback system's attached in stages to achieve a fourth order roll-off effect. The center frequency for the first stage is set close to 45 KHz and the second stage is to 67.6 kHz as shown in **Figure 7-10**. The final fourth order filter has an amplitude that is curved at higher frequencies due to the attenuation of the second stage second order filter. While the reduction in amplitude is unfavorable, a benefit in the form of steep roll off of 80 dB/Decade is more attractive as it reduces noise elimination in post-processing. The amplitude loss is recovered by amplifying the output signal by 20 dB by using another operational amplifier.

Figure 7-10: Filter frequency vs amplitude performance

7.5 Phase determination

The captured signal provides two strands of information namely; position and angle. The angular information is extracted by measuring the relative time delay between two pulses. This can be simply done by using a phase comparator. A block diagram of types of phase comparators available in a phased locked loop are shown in **Figure 7-11**.

Figure 7-11: Phase comparator selection within a phased lock loop schematic [76]

There are two types of phase comparators available on board, the type 1 phase comparator provides the information about phase difference while type 2 phase comparator provides lead lag information along with phase difference information. It was experimentally found that performance of type 2 phase comparator degrades at frequencies above 90 KHz and is therefore rejected for phase delay evaluation.

In order to determine the angle of the received wave for a 3 element array, two phase comparators are employed; the two phase comparators compare the time difference between pulse 2 and 3 with respect to pulse 1 and are given by Phase1_2 and Phase 1_3 respectively. **Figure 7-12** shows the two cases possible for phase determination.

Figure 7-12: Two cases of phase comparator output

The microphone phased input is given by MIC 1, 2 and 3; upon signal reception, the microphone inputs are compared to the phase comparator outputs. In the case where signal is first received by microphone 1 (Microphone 1 leading), the output of the microphone is compared to the phase comparator signal.

To associate the phased response with the angle of the sensor an AND gate is employed. The AND gate uses the Mic 3 and Phase1_2 as input producing a time signal time plot as shown in **Figure 7-13**.

Figure 7-13: Lead/Lag timing diagram for phase for quadrant determination

In case A, when the output of the Mic 3 and Phase1_2 is 1, this implies that signal 1 is lagging and signal 3 is leading thus concluding that the source is in the 0° - 90° quadrant. Similarly, in case B, when the output of Mic 3 and Phase1_2 is 0, the signal lies in the 90° - 180° quadrant.

7.6 Phase pulse to analog voltage

To reduce the signal processing time, the pulse widths are converted into analog voltage using a pulse width modulate (PWM) to analog voltage converter. The Linear Technology's LTC2644-8 bit DAC allows for the conversion of PWM signal into an 8 bit analog voltage that is connected directly to the 10 bit ADC on the AT-MEGA 328p's analog voltage pin. The conversion to analog domain allows for the signal to be captured over a longer span allowing for the value to stabilize, unlike the digital domain that would require a sampling frequency higher than the clock speed of the microcontroller.

7.7 Mode detection

A mode detection circuit outlined in **Figure 7-14** is now required to complete the feedback loop. The mode detection circuit determines if the system can go into reception mode. The circuit checks

if any of the sensors are actively emitting and once the transmission stops, the circuit returns a HIGH state. This value is connected to the phase output of the phase comparator by an AND gate shown in **Figure 7-14**. This also triggers a timing pin on the AT-MEGA 328p's that starts a timer counter to evaluate the time from transmission to reception. The timing signal is used to evaluate the time between the transmission and reception to estimate the position of the target.

Figure 7-14: Mode sensing circuit using NOR gate and an AND gate.

7.8 Digital Design

The digital design described in this chapter forms the basis for digital signal processing used to emit a phased beam and capture the reflected signal. The integrated circuits selected in this chapter are connected to the PCB design discussed in the previous chapter. In order to focus on characterization of the performance of various sensor types, an open ended design with pin terminations is selected. This allows a variety of transducer designs to be tested without altering the system's parameters.

Two different attachment boards are made, one with a PZT transducer and another with air-capacitive transducer. Both the transducer circuits are design to directly interface with the system design and allow for a direct comparison of performance. The isolation of the system design from the transducer design also allows for the system's power envelope to be defined as a constant. This allows for a direct comparison of the efficiency of each transducer array to convert electrical power to acoustic energy.

Special attention is given to the system power design to avoid noise introduction from the power supplies. Four linear voltage regulators are used to regulate the voltage from the 6 V battery to 5 V, that is used to power the microcontroller and other active analog devices. The main drawback of linear voltage regulator is the heat dissipation required at higher current. To address the heat concern associated with a single regulator, multiple voltage regulators are used to power analog and digital components.

Since digital signal consist of square waves that include high frequencies, these voltage spikes can directly affect the analog circuitry that is used to measure small analog voltages. The spikes in voltage introduced instantaneous voltages that are amplified by the op-amp, thus saturating the output signal. For this reason, the analog and digital ground planes are kept separate in the circuit design and are connected only at the ground pads of the linear voltage regulators.

Chapter 8

Experimental setup

This chapter describes the testing methodology using an anechoic chamber and an automated sound pressure level (SPL) acquisition system design that measure the performance of the PZT and air-capacitive transducer. To quantify the conversion of the electrical signal in space and time domain, parameters such as sound pressure level and propagation range are used to define the transducer's performance. An anechoic chamber is used to isolate the ambient acoustic noise, for an accurate measurement of the transducer's output SPL.

An automated SPL acquisition system is designed, which includes two stepper motors and an ultrasonic microphone that are connected to Mathworks MATLAB 2016a. The position and angular control are manipulates using the two stepper motors and the SPL acquisition is done via the ultrasonic microphone. By automating the process of SPL acquisition at various points in the field of the transducer, reduces the data acquisition time. Also, by employing stepper motors, accurate position and angular control can be achieved.

8.1 Evaluation parameters

Since sound is an alternating pressure wave, the experimental setup aims at evaluating the sound pressure level (SPL) at various angles and distances. The SPL is a relative measurement to a reference sound pressure level and is expressed as [27]:

$$SPL[dB] = 20 \log \left(\frac{p}{p_0} \right) ; p_0 = 20 \mu Pa$$

In equation 8.1, p_0 represents the reference pressure as per the definition of SPL [27]. To convert SPL into a measurable voltage an ultrasonic microphone, Ultramic200K, is used for evaluating the SPL at predetermined locations.

The design of the Ultramic200K includes a microelectromechanical system (MEMS) sensor, specifically, the Knowles® Model: SPU0410LR5H, with the following important specifications:

Table 8-1: Characteristics of Knowles® model: SPU0410LR5H microphone [77]

Parameters	Value
Supply Voltage	1.8 Volts
Sensitivity (94 dB SPL at 1 kHz)	-38 dBV / Pa
Signal to noise ratio (94 dB SPL at 1 kHz, A weighted)	63 dB (A)
Directivity	Omnidirectional

One of the most important performance parameters outlined in **Table 8-1** is the sensitivity of the sensor. The sensitivity determines the sensor's capability to convert pressure into voltage. From equation 8.1, a 1 Pa pressure is the approximately equal to 94 dB SPL which is considered to be the reference pressure for further calculation. Similarly, the reference voltage for dBV scale is 1.000 Volts/Pa. The sensitivity can now be converted from dBV scale to Volts/Pa as follows

The microphone signal is further amplified by 72 dB via the onboard amplifier. Thus increasing the perceived sensitivity by 3981 times, with the final sensitivity of 132db. Using the final sensitivity, **Table 8-2** outlines SPL amplitude of some of the most common condition and the respective output voltages that the sensor will produce

Table 8-2: Sound source to output voltage comparison, adapted from [6]

Sound Source	SPL (dB)	Output Voltage (V)
Passenger Car	70	3.169
Normal Conversation	50	0.3169
Quiet Room	30	0.03169
Reference pressure level	0	0.0010024

8.2 Conversion from analog to digital domain

The signal acquired by the microcontroller on board the Ultramic200K converts the analog signal into a 16 bit digital signal with the output values ranging from 0 to 65535. The highest analog output voltage corresponds to the highest digital output of 65536. These digital values are acquired by Mathworks® MATLAB 2016a software and are expressed as decibel full scale (dBFS) values calculated as follows:

The SPL can now be fully related to the full digital scale value that is used for the mathematical analysis.

8.3 Experimental setup

The experimental setup comprises of an acoustic chamber that consists of two cardboard boxes with foam lining as shown in **Figure 8-1a** and **Figure 8-1b** . The foam is used to absorb reflected waves providing a characteristic acoustic impedance boundary condition, where waves propagate infinitely.

a) Two cardboard boxes joined to make an anechoic chamber

b) Foam lining for sound isolation

Figure 8-1: Internal layout and design of the anechoic chamber

A wooden plank is used as a base for mounting the automated acquisition assembly along with two different size wooden blocks to serve as the mounting and moving block as shown in **Figure 8-2**.

a) Automated acquisition system layout

b) Layout of transducer and microphone

Figure 8-2: Automated SPL data acquisition setup.

To allow for relative motion between the mounting block and moving block, a stepper motor was employed. The stepper motor is attached to a threaded rod by a coupler, and a hex nut is used in the form of a worm gear assembly, creating translation motion using rotation. Two guide

rails are also attached to the base and the moving block to fix the traveling path and direction. The Ultramic200K assembly is then mounted on the moving block using two loop holders.

The transducers are fitted to the second stepper motor located on the mounting block and is used to rotate the incidence angle of the array. Therefore, by using the two stepper motors in conjunction, allowing for range and angular data acquisition.

The Ultramic200K is connected directly to a computer while the stepper motors are attached to an Arduino® MotorShield as shown in **Figure 8-3**. The data from these devices is directly forwarded to Mathworks® MATLAB 2016a software, where the acoustic data is processed, and a Fast Fourier Transform (FFT) algorithm is used to obtain the dBFS amplitude. These values are collected for all data points and later normalized to generate directivity plots.

Figure 8-3: Data acquisition system layout

The experimental setup is finally assembled by placing the automated SPL acquisition system inside the anechoic chamber as shown in **Figure 8-4**. The final assembly is put on a rubber mat for isolating any low frequency noise generated from the floor.

Figure 8-4: Anechoic chamber assembly with automated SPL acquisition

8.4 Noise characterization

The mathematical analysis outlined in section 8.1 and 8.2 is very sensitive to external noise since all values are calculated with reference to the highest signal amplitude. The anechoic chamber design discussed in section 8.2 is calibrated to account for the external noise present in the system and is shown in **Figure 8-5**.

Figure 8-5: External microphone noise characterization

From **Figure 8-5**, it can be seen that most of the acoustic energy is associated with frequencies below the bandwidth of interest. However, there is acoustic correction required close around 40 kHz range as there is a spike observed. This noise is attributed to the PWM signal used by the motor controller and the stepper motors employed in the anechoic chamber.

Upon further investigation, it was found that in the presence of a 20.63 kHz source, the ambient noise level reduces to levels below -72 dB as shown in **Figure 8-6**. Therefore, a correction factor is developed for frequencies within the bandwidth of interest to account for the increase in amplitude due to ambient noise. Also, to prevent any noise addition from the stepper motors, the Arduino stepper mode code is modified, and a stepper library is developed that shuts off the power to the stepper motor during data acquisition.

Figure 8-6: Noise spectrum relative to a 20.63 kHz PZT source placed at 0.5 m distance

The code used to develop the SPL plots and control the stepper motors is provided in Appendix E.

Chapter 9

Discussion of experimental results

This chapter focuses on the results of the circuit design and the phasing algorithm using the experimental setup and data acquisition methodology described in the previous chapter. Two types of transducers are tested in the experimental analysis; namely PZT and air-capacitive transducers. The PZT transducer is very similar to the transducer found in the Parallax Ping ® ultrasonic range sensor. This allows for a comparison of the PZT transducer's propagation performance to that of an air- capacitive transducer.

Similarly, the reception performance of both the transducers is also compared by their ability to estimate the position of a 3 cm x 3 cm square target at a prespecified spatial location.

Using the automated SPL acquisition system, SPL plots are derived for both the transducers and their beam steering and phased array capabilities are discussed. Effects of range, frequency and phase angle control during propagation and the steering of beam forming algorithm during reception are examined.

9.1 Range vs sensor type

The PZT and air-capacitive transducer are placed in the anechoic chamber for range and phase testing. The range testing results are highlighted in **Figure 9-1** for the PZT and air-capacitive transducer.

a) PZT transducer

b) Air-capacitive transducer

Figure 9-1: Comparison of output SPL between the PZT and air-capacitive transducers.

From the results in the above figure, it can be seen that both the transducers follow the $\frac{1}{r^2}$ relationship for amplitude reduction. Even though both the sensors are operating at the same voltages and frequency, the output sound pressure level observed is not the same. In the case of air-capacitive transducer, the output pressure is consistently observed to be 25 dB below the PZT transducer's output.

This reduction in output SPL can be attributed to the very low electrical capacitance of the air-capacitive transducer. The 2.5 pF capacitance of the air-capacitive transducer requires a 10 VDC to activate the back plate of the transducer. Due to the low source capacitance only small

amounts of charge can be stored on the sensor without damage. The available amplitude range is further reduced by the 10 VDC activation voltage, therefore reducing the output amplitude range that is achievable using the current design.

9.2 Range vs Frequency

As the frequency of the sensor is varied, the range response of the sensors changes dramatically due to acoustic impedance mismatch. As shown in **Figure 9-1**, the increase in frequency has a weighted response on the inverse squared relationship for both types of transducers. In the case of the air-capacitive transducer, at 100 kHz, the output SPL falls below -60 decibels at 50 cm. Based on the pre-amplifier design with a 60 dB maximum amplification, any signal beyond 65 cm becomes undetectable during the reception phase.

9.3 Beam Phasing

The phased array circuit design discussed in Chapter 7 is used to generated a 50 kHz signal for both types of transducers. The phasing algorithm is used to phase the beam at angles of 30° and 60° as shown in **Figure 9-2**.

(c) PZT array at 60 deg

(d) Air-capacitive array at 60 deg

(e) SPL plot of a 3 element phased array beam at 60 degrees at 50 kHz

(f) SPL plot of a 3 element phased array beam at 30 degrees at 50 kHz

Figure 9-2: Comparison of theoretical performance to the actual performance of a PZT and air-capacitive based phased array transducer.

The phased array response for both types of transducers shown in **Figure 9-2** resembles the theoretical performance. The performance difference in the case of the PZT can be attributed to the physical size of the transducer. The PZT transducer is 15 mm in diameter, this increases the distance between the sensors in the array as compared to the air-capacitive transducer, resulting in coarser beam angle control.

On the other hand, the air-capacitive sensor is observed to have an excessive number of grating lobes. These lobes can be a direct result of increased ambient noise and since the sound pressure level previously observed is lower was compared to the PZT transducer.

From the theoretical performance graph shown in **Figure 9-2 e and f**, a significant amount of energy is emitted in the side lobes that do not lie on the desired axis of transmission. In the case

of the anechoic chamber, the foam on the walls absorbs the outgoing wave giving an illusion of an infinite room. In the absence of this characteristic impedance condition, the reverberation from the walls would severely degrade the signal to noise ratio observed by the sensor. The effect of a reduced signal to noise ratio is quite evident in the case of an air-capacitive transducer where large amplitude of noise is present at angles other than the propagation direction.

9.4 Reception Analysis

During the reception phase there is no acoustic aperture to direct energy on PZT element, therefore the analysis was only performed on the air-coupled transducer. To evaluate the performance a 3 cm x 3 cm flat square target was placed at an angle 30 degrees and distance of 55 cm from the transducer. The operating frequency of the array is selected to be 50 kHz. The target's range and the angle are evaluated using TOA algorithm and thirty data points are acquired to perform a statistical analysis.

Figure 9-3: Experimental results of range vs angular position

Figure 9-3 highlights the collected data in terms of range versus angular position; it can readily be seen that there is only one instance where the sensor can correctly identify the exact position of the target. The data acquired has a mean value of 55.06 cm for the range and 28.66 degrees for the angular approximation, along with a standard deviation of 3.73 cm and 4.4 degrees respectively. The standard error in the range is observed to be 0.96 cm and 1.2 degrees in angular control. The results obtained are comparable to that of a commercially available PZT ultrasonic range sensors that offer a 1 cm resolution.

The performance of the phased array system is improved over a single element transducer due to the beamforming effect outlined in section 3.14. Upon selection of the propagation angle, the reception beamforming algorithm is also changed to the same angle. This moves the characteristic null to an off axis direction during reception and amplifies the signal reception in the desired direction as shown in **Figure 9-4**.

Figure 9-4: Effects of moving reception beam former lobe

The movement of the main reception lobe into the direction of propagation reduces the reverberation that is collected from the environment. Also, moving the reception lobe into the

direction of propagation forces the null to be present at approximately 25 degrees away from the reception lobe, thus reducing the ambient noise collected from non-axial sources.

9.5 Reception with holes

During the reception mode, the air-capacitive transducer serves as a microphone to the system. The design of a microphone is discussed extensively by Ford (ref 78); it is suggested that by drilling holes in the back plate, the acoustic response of the microphone improves. The holes convert the microphone design from a directional microphone to an omnidirectional microphone by allowing pressure sensitivity from behind. The presence of holes reduces the intrinsic change in sensitivity due to change in external pressure as observed when varying altitude [5]. The holes' act as a low pass filter allowing the pressure change to be apparent on both, internal and external face of the Mylar film and an array with back plate holes is shown in **Figure 9-5**.

Figure 9-5: Air-capacitive transducer with holes in black plate.

However, this improvement in the sensitivity directly affects the directional nature of the microphone that is critical to the design and is linked to the signal to noise ratio. Also, the holes reduce the surface area of the copper conductor in the back plate, therefore reducing the source

capacitance of the transducer. The reduction in source capacitance will require higher amplification, resulting in a reduced signal to noise ratio. Due to the adverse effects on the performance of the transducer design, the perforated back plate design is rejected.

9.6 Discussion of Results

The phased array design is tested in both as an emitter and as a receiver. From the results it is quite evident that the sensor design and phased array circuitry can work in conjunction to produce a phased beam and locate a target. A good correlation is observed between the theoretical and actual performance of the sensors. Also, both the transducers, PZT and air capacitive have results that are very similar.

However, the performance of the sensor is very poor with respect to the signal to noise ratio during both, propagation and reception. In the case of air-coupled sensor the deterioration in signal to noise ratio is very dominant as expressed by the higher amplitude of the grating lobes. In frequencies above 50 kHz, the SNR described in section 3.14, is drastically reduced rendering the output signal useless beyond 0.65 meters. The performance further degrades with the presence of external acoustic sources.

A qualitative study was conducting to study the effect of film tension on frequency response. To study this effect a new batch of transducers were produced with a 500 g tension weight instead of 1 kg. The reduced film tension seemed to have a significant effect at frequencies above 120 kHz, where a secondary low frequency sound is produced by the transducer. The lower frequency noise is attributed to structural reverberation within the Mylar film.

Chapter 10

Conclusions and Future Work

This chapter outlines a summary of the research results and several important conclusions that were made from this research. The research results are discussed and recommendations for future improvements are also detailed in this chapter.

10.1 Conclusions

- The resonant operating frequencies of the transducer are determined by analytical analysis using vibratory motion. The results from the analytical analysis are compared to numerical analysis. The analytical results are further compared with numerical results that include fluid structure interaction and the resulting air coupled frequencies are used to excite the transducer.
- Time of arrival (TOA) technique was used to determine the position of the target. The TOA equations are nonlinear and are linearized using least square approach. The linearization reduces the complexity and allows the equations to be solved on a microcontroller platform in real time.
- An in-house PCB manufacturing process using photolithographic techniques was described. A repeatability test is performed by measuring the pin spacing of two IC's as predetermined locations. It is found that the test can be repeated with an accuracy of 1.5% error in the pin spacing.
- Circuit design was developed using the preselected performance characteristics. The circuit design involves using a variable frequency oscillator design using an LM555 timer. By

varying the time constant on the charge and discharge cycle, a variable output frequency is observed. A microcontroller based phasing algorithm is developed to phase the propagating beam in the desired direction.

- The circuit design also includes the design of an 8th order multiple feedback band pass filter. The design allows for a steep roll off and a pre-characterized amplitude and phase curve in the band pass region.
- The circuit design developed was tested inside an anechoic chamber that is also developed in-house. The system uses two stepper motors to position an ultrasonic microphone and change the angle of incidence of the sensor array. The system is controlled by Mathworks MATLAB program that interfaces with the stepper motors via an Arduino Uno. The ambient noise inside the closed chamber is characterized and is used to offset the results in the analysis.
- Two transducers, PZT and air-capacitive, are tested for their phasing capabilities. The analysis yields that the PZT is capable of producing ultrasonic waves at higher amplitudes as compared to the air-capacitive transducer. The higher amplitudes allows the waves to propagate over longer distances, therefore increasing the range. It was observed experimentally that the range and detection of the phased beam for the PZT transducer extended beyond 100 cm while the range for an air-capacitive sensor was limited to 60 cm maximum.
- The phasing effects were found to be bottlenecked by the hardware chosen. The AT-Mega 328p platform is unable to generate simultaneous phased pulses at 1 degree resolution at 100 kHz. Using the 15 degree step resolution at 100 kHz, two phase angles, 30 degrees and 60 degrees are used for the analysis.

10.2 Recommendations

- During the course of the research it was observed that the maximum operating frequency of 61 MHz of the AT-Mega 328p poses a severe bottleneck on the phased array performance. It was observed that there is a 23 cycle delay at 16 MHz that is introduced into the system if an analog value is converted into a digital signal. This severely affects the output performance of the phased array transducer as this reduces the minimum phase delay between two signals to a 41 ns. At 100 kHz this minimum phase delay reduces the output resolution to 14.76 degrees per step. To improve on the phasing performance a microcontroller with a higher frequency and accurate timing control need to be investigated.
- Significant improvements in the transducer performance can be achieved by employing micromachining techniques to allow for accurate control of the spacing between the transducer film and back plate. A static port design should be investigated to prevent the change in the transducer's sensitivity with a change in altitude.
- While acceptable results can be achieved with the amateur manufacturing technique involving the film of the transducer, a more robust and repeatable technique shall be investigated such that the performance of each sensor can be standardized.

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Appendix A

All Dimensions are in mm

Appendix B

Data sheet for Mylar film from Dupont

Table 1
Typical Electrical Properties of Mylar Polyester Film

Property	Value	Test Method
DC Dielectric Strength 25 C (77 F)	Typical Value for Mylar 11.0 kV/mil	92 EL/C* 1/4 in upper electrode and flat plate lower electrode. 500 V/sec rate of rise
Gauge and Type at 25 C (77 F)	Minimum Values for Mylar C Film	
6C	0.225 kV	Minimum average voltage of 20 film-foil capacitors, 0.5 F each 100 V/sec rate of rise
7C	0.300 kV	
8C	0.320 kV	
10C	0.490 kV	
12C	0.650 kV	
14C	0.825 kV	
20C	1.500 kV	
24C	2.000 kV	
32C	3.100 kV	
40C	4.100 kV	
48C	4.900 kV	
75C	5.500 kV	
92C	6.000 kV	
AC Dielectric Strength 25 C (77 F)	Typical Value for Mylar 7.0 kV/mil	92 EL/C* ASTM D149 and ASTM D2305 60 Hz 500 V/sec rate of rise
Gauge and Type at 25 C (77 F)	Minimum Values for Mylar EL Film	
48EL	2.8 kV	ASTM D149 and Minimum average voltage of 10 sheet samples 60 Hz 500 V/sec rate of rise
D2305,		
75EL	3.5 kV	
92EL	4.0 kV	
142EL	5.5 kV	
200EL	7.7 kV	
300EL	10.0 kV	
500EL	13.5 kV	
750EL	17.5 kV	
900EL	18.4 kV	
1000EL	19.0 kV	
1400EL	20.0 kV	
Dielectric Constant	Typical Value for Mylar	92 EL/C*
25 C (77 F)—60 Hz	3.3	ASTM D150
25 C (77 F)—1 kHz	3.25	
25 C (77 F)—1 MHz	3.0	
25 C (77 F)—1 GHz	2.8	
150 C (302 F)—60 Hz	3.7	
Dissipation Factor	Typical Value for Mylar	92 EL/C
25 C (77 F)—60 Hz	0.0025	ASTM D150
25 C (77 F)—1 kHz	0.0050	
25 C (77 F)—1 MHz	0.016	
25 C (77 F)—1 GHz	0.008	
150 C (302 F)—60 Hz	0.004	
–269 C (–452 F)—1 kHz (in Helium)	0.0002	

Volume Resistivity	Typical Value for Mylar 92 EL/C	
25 C (77 F)	10^{18} ohm cm	ASTM D257 and D2305
150 C (302 F) (Type C Film)	10^{13} ohm cm	
Surface Resistivity		
23 C (73 F)—30% RH	10^{16} ohm/sq	
23 C (73 F)—80% RH	10^{12} ohm/sq	
Insulation Resistance		
35 C (95 F)—90% RH	10^{12} ohm	
Capacitor Insulation Resistance	Typical Value for Mylar 92 C	
100 C (212 F)	30,000 M - F	Based on 0.5 F film- foil capacitor sections, using single layer, 92 Mylar C
125 C (257 F)	1,000 M - F	
150 C (302 F)	100 M - F	

*Data relevant for other types of Mylar

Appendix C

Ansys ACT acoustics analysis

Project

First Saved	Monday, May 9, 2016
Last Saved	Wednesday, May 11, 2016
Product Version	16.0 Release
Save Project Before Solution	No
Save Project After Solution	No

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Units

TABLE 1

Unit System	Metric (mm, kg, N, s, mV, mA) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

Model (A4, B4, C4)

Geometry

TABLE 2

Model (A4, B4, C4) > Geometry

--	--

Object Name	Geometry
State	Fully Defined
Definition	
Source	C:\Users\Edison\Documents\F_FullAcousticAnalysisWithFSI\FullAcousticAnalysisWithFSI_files\dp0\SYS\DM\SYS.agdb
Type	DesignModeler
Length Unit	Meters
Element Control	Program Controlled
Display Style	Body Color
Bounding Box	
Length X	10. mm
Length Y	10. mm
Length Z	14.124 mm
Properties	
Volume	1389.4 mm ³
Mass	1.0906e-002 kg
Scale Factor Value	1.
Statistics	
Bodies	5
Active Bodies	4
Nodes	366244
Elements	227805
Mesh Metric	None
Basic Geometry Options	
Parameters	Yes
Parameter Key	DS
Attributes	No
Named Selections	No
Material Properties	No
Advanced Geometry Options	
Use Associativity	Yes
Coordinate Systems	No
Reader Mode Saves Updated File	No
Use Instances	Yes
Smart CAD Update	No
Compare Parts On Update	No
Attach File Via Temp File	Yes
Temporary Directory	C:\Users\Edison\AppData\Local\Temp
Analysis	

Type	3-D
Decompose Disjoint Geometry	Yes
Enclosure and Symmetry Processing	Yes

TABLE 3
Model (A4, B4, C4) > Geometry > Body Groups

Object Name	Part
State	Meshed
Graphics Properties	
Visible	Yes
Definition	
Suppressed	No
Assignment	Multiple Materials
Coordinate System	Default Coordinate System
Bounding Box	
Length X	10. mm
Length Y	10. mm
Length Z	14.124 mm
Properties	
Volume	1389.4 mm ³
Mass	1.0906e-002 kg
Centroid X	5.0536 mm
Centroid Y	5.0536 mm
Centroid Z	1.0641 mm
Moment of Inertia Ip1	0.27267 kg·mm ²
Moment of Inertia Ip2	0.27637 kg·mm ²
Moment of Inertia Ip3	0.18053 kg·mm ²
Statistics	
Nodes	366244
Elements	227805
Mesh Metric	None

TABLE 4
Model (A4, B4, C4) > Geometry > Part > Parts

Object Name	<i>Solid</i>	<i>Solid</i>	<i>Solid</i>	<i>Solid</i>	<i>Solid</i>
State	Suppressed	Meshed			
Graphics Properties					
Visible	No	Yes			
Transparency		1	0.1		
Definition					
Suppressed	Yes	No			
Stiffness Behavior	Flexible				
Coordinate System	Default Coordinate System				
Reference Temperature	By Environment				
Material					
Assignment	Structural Steel	Mylar Celplast	Structural Steel		
Nonlinear Effects	Yes				
Thermal Strain Effects	Yes				

Bounding Box					
Length X	4. mm	3. mm	7. mm	3. mm	10. mm
Length Y	4. mm	3. mm	7. mm	3. mm	10. mm
Length Z	2.124 mm	1.2e-002 mm	8.124 mm	5.2e-002 mm	14.124 mm
Properties					
Volume	22.987 mm ³	8.4823e-002 mm ³	374.64 mm ³	0.36757 mm ³	1014.3 mm ³
Mass	1.8045e-004 kg	1.179e-007 kg	2.9409e-003 kg	2.8854e-006 kg	7.9624e-003 kg
Centroid X	1.7616 mm	1.27 mm	3.6088 mm	1.27 mm	5.5887 mm
Centroid Y	1.7616 mm	1.27 mm	3.6088 mm	1.27 mm	5.5887 mm
Centroid Z	0.93309 mm	1.658 mm	1.0692 mm	1.626 mm	1.062 mm
Moment of Inertia Ip1	1.9379e-004 kg·mm ²	9.5429e-008 kg·mm ²	2.9606e-002 kg·mm ²	2.336e-006 kg·mm ²	0.24676 kg·mm ²
Moment of Inertia Ip2	3.3109e-004 kg·mm ²	5.1368e-008 kg·mm ²	2.8557e-002 kg·mm ²	1.2577e-006 kg·mm ²	0.22718 kg·mm ²
Moment of Inertia Ip3	4.1859e-004 kg·mm ²	1.4679e-007 kg·mm ²	2.3909e-002 kg·mm ²	3.5924e-006 kg·mm ²	0.13969 kg·mm ²
Statistics					
Nodes	0	5810	120810	5810	266683
Elements	0	791	70056	791	156167
Mesh Metric	None				

Coordinate Systems

TABLE 5
Model (A4, B4, C4) > Coordinate Systems > Coordinate System

Object Name	Global Coordinate System		YZPlane	ZXPlane
State	Fully Defined			
Definition				
Type	Cartesian			
Coordinate System ID	0.		Program Controlled	
Coordinate System				
Suppressed			No	
Origin				
Origin X	0. mm			
Origin Y	0. mm			
Origin Z	0. mm			
Define By			Global Coordinates	
Location			Defined	
Directional Vectors				
X Axis Data	[1. 0. 0.]		[0. 1. 0.]	[0. 0. 1.]
Y Axis Data	[0. 1. 0.]		[0. 0. 1.]	[1. 0. 0.]
Z Axis Data	[0. 0. 1.]		[1. 0. 0.]	[0. 1. 0.]
Principal Axis				
Axis			X	
Define By			Fixed Vector	
Orientation About Principal Axis				
Axis			Y	
Define By			Fixed Vector	
Transformations				
Base Configuration			Absolute	
Transformed Configuration			[0. 0. 0.]	

Symmetry

TABLE 6
Model (A4, B4, C4) > Symmetry

Object Name	<i>Symmetry</i>
State	Fully Defined

TABLE 7
Model (A4, B4, C4) > Symmetry > Symmetry Region

Object Name	Symmetry Region	Symmetry Region 2
State	Fully Defined	
Scope		
Scoping Method	Named Selection	
Named Selection	Symmetry:YZPlane	Symmetry:ZXPlane
Definition		
Scope Mode	Automatic	
Type	Symmetric	
Coordinate System	YZPlane	ZXPlane
Symmetry Normal	Z Axis	
Suppressed	No	

Connections

TABLE 8
Model (A4, B4, C4) > Connections

Object Name	<i>Connections</i>
State	Fully Defined
Auto Detection	
Generate Automatic Connection On Refresh	Yes
Transparency	
Enabled	Yes

Mesh

TABLE 9
Model (A4, B4, C4) > Mesh

Object Name	<i>Mesh</i>
State	Solved
Display	
Display Style	Body Color
Defaults	
Physics Preference	Mechanical
Relevance	0
Sizing	
Use Advanced Size Function	Off (Part Size Seed)
Relevance Center	Coarse
Element Size	0.10 mm
Initial Size Seed	Part
Smoothing	Medium
Transition	Fast
Span Angle Center	Coarse
Minimum Edge Length	1.2e-002 mm
Inflation	
Use Automatic Inflation	None
Inflation Option	Smooth Transition
Transition Ratio	0.272

Maximum Layers	5
Growth Rate	1.2
Inflation Algorithm	Pre
View Advanced Options	No
Patch Conforming Options	
Triangle Surface Mesher	Program Controlled
Patch Independent Options	
Topology Checking	No
Advanced	
Number of CPUs for Parallel Part Meshing	Program Controlled
Shape Checking	Standard Mechanical
Element Midside Nodes	Program Controlled
Straight Sided Elements	No
Number of Retries	Default (4)
Extra Retries For Assembly	Yes
Rigid Body Behavior	Dimensionally Reduced
Mesh Morphing	Disabled
Defeaturing	
Pinch Tolerance	Please Define
Generate Pinch on Refresh	No
Automatic Mesh Based Defeaturing	On
Defeaturing Tolerance	Default
Statistics	
Nodes	366244
Elements	227805
Mesh Metric	None

Named Selections

TABLE 10
Model (A4, B4, C4) > Named Selections > Named Selections

Object Name	Open Domain	Symmetry:YZPlane	Symmetry:ZXPlane	Problematic Geometry
State	Fully Defined			Suppressed
Scope				
Scoping Method	Geometry Selection			
Geometry	4 Faces			No Selection
Definition				
Send to Solver	Yes	No		Yes
Visible	Yes			
Program Controlled Inflation	Exclude			
Statistics				
Type	Imported			Manual
Total Selection	4 Faces	5 Faces		No Selection
Suppressed	0	1		0
Used by Mesh Worksheet	No			

Harmonic Response (B5)

TABLE 11
Model (A4, B4, C4) > Analysis

Object Name	<i>Harmonic Response (B5)</i>
State	Solved
Definition	

Physics Type	Structural
Analysis Type	Harmonic Response
Solver Target	Mechanical APDL
Options	
Environment Temperature	22. °C
Generate Input Only	No

TABLE 12
Model (A4, B4, C4) > Harmonic Response (B5) > Initial Condition

Object Name	<i>Pre-Stress/Modal (None)</i>
State	Fully Defined
Definition	
Pre-Stress Environment	None
Modal Environment	None

TABLE 13
Model (A4, B4, C4) > Harmonic Response (B5) > Analysis Settings

Object Name	<i>Analysis Settings</i>
State	Fully Defined
Options	
Frequency Spacing	Linear
Range Minimum	0. Hz
Range Maximum	1.5e+005 Hz
Solution Intervals	300
Solution Method	Full
Variational Technology	No
Rotordynamics Controls	
Coriolis Effect	Off
Output Controls	
Stress	Yes
Strain	Yes
Nodal Forces	No
Calculate Reactions	Yes
General Miscellaneous	Yes
Damping Controls	
Constant Damping Ratio	0.
Stiffness Coefficient Define By	Direct Input
Stiffness Coefficient	0.
Mass Coefficient	0.
Analysis Data Management	
Solver Files Directory	C:\Users\Edison\Documents\F_FullAcousticAnalysisWithFSI\FullAcousticAnalysisWithFSI_files\dp0\SYS-1\MECH\

Future Analysis	None
Scratch Solver Files Directory	
Save MAPDL db	Yes
Delete Unneeded Files	Yes
Solver Units	Active System
Solver Unit System	mm

TABLE 14
Model (A4, B4, C4) > Harmonic Response (B5) > Loads

Object Name	Force		Fixed Support
State	Fully Defined		
Scope			
Scoping Method	Geometry Selection		
Geometry	1 Vertex	1 Face	
Definition			
Type	Force	Fixed Support	
Define By	Components		
Coordinate System	Global Coordinate System		
X Component	0. N		
Y Component	0. N		
Z Component	3.88e-006 N		
X Phase Angle	0. °		
Y Phase Angle	0. °		
Z Phase Angle	0. °		
Suppressed	No		

TABLE 15
Model (A4, B4, C4) > Harmonic Response (B5) > Loads

Object Name		Acoustic Body	Acoustic Body 2	Acoustic Pressure
State		Fully Defined		
Scope				
Scoping Method		Geometry Selection		
Geometry		2 Bodies	1 Body	4 Faces
Definition				
Frequency Dependency		No		
Mass Density		1.2041E-09 [kg mm^-1 mm^-1 mm^-1]		
Sound Speed		343240 [mm sec^-1]		
Dynamic Viscosity		0 [MPa sec]		
Bulk Viscosity		0 [MPa sec]		
Thermal Conductivity		0 [W mm^-1 C^-1]		
Specific Heat Cp		0 [J kg^-1 C^-1]		
Specific Heat Cv		0 [J kg^-1 C^-1]		
Equivalent Fluid of Perforated Material		No		
Low Reduced Frequency Model		No		
Reference Pressure		2E-11 [MPa]		
Reference Static Pressure		0.101325 [MPa]		
Acoustic-Structural Coupled Body Options		Program Controlled Coupled		
Perfectly Matched Layers (PML)		Off	On	

PML Options		Off	
Element Coordinate System Number		0	
Pressure (Real)			0 [MPa]
Pressure (Im)			0 [MPa]

Solution (B6)

TABLE 16
Model (A4, B4, C4) > Harmonic Response (B5) > Solution

Object Name	<i>Solution (B6)</i>
State	Solved
Adaptive Mesh Refinement	
Max Refinement Loops	1.
Refinement Depth	2.
Information	
Status	Done
Post Processing	
Calculate Beam Section Results	No

FIGURE 1
Model (A4, B4, C4) > Harmonic Response (B5) > Solution (B6)

TABLE 17
Model (A4, B4, C4) > Harmonic Response (B5) > Solution (B6) > Solution Information

Object Name	<i>Solution Information</i>
State	Solved
Solution Information	
Solution Output	Solver Output
Newton-Raphson Residuals	0
Update Interval	2.5 s

Display Points	All
FE Connection Visibility	
Activate Visibility	Yes
Display	All FE Connectors
Draw Connections Attached To	All Nodes
Line Color	Connection Type
Visible on Results	No
Line Thickness	Single
Display Type	Lines

TABLE 18**Model (A4, B4, C4) > Harmonic Response (B5) > Solution (B6) > Result Charts**

Object Name	<i>Frequency Response</i>
State	Solved
Scope	
Scoping Method	Geometry Selection
Geometry	1 Body
Spatial Resolution	Use Average
Definition	
Type	Directional Deformation
Orientation	Z Axis
Suppressed	No
Options	
Frequency Range	Use Parent
Minimum Frequency	0. Hz
Maximum Frequency	1.5e+005 Hz
Display	Bode
Chart Viewing Style	Log Y
Results	
Maximum Amplitude	1.5212e-004 mm
Frequency	8500. Hz
Phase Angle	-28.527 °
Real	1.3365e-004 mm
Imaginary	-7.265e-005 mm

FIGURE 2**Model (A4, B4, C4) > Harmonic Response (B5) > Solution (B6) > Frequency Response**

TABLE 19**Model (A4, B4, C4) > Harmonic Response (B5) > Solution (B6) > Acoustic Pressure**

Object Name	<i>Acoustic Pressure</i>
State	Solved
Scope	
Scoping Method	Geometry Selection
Geometry	3 Bodies
Definition	
Type	User Defined Result
Expression	= PRES
Input Unit System	Metric (mm, kg, N, s, mV, mA)
Output Unit	Pressure
By	Frequency
Frequency	Last
Sweeping Phase	0. °
Coordinate System	Global Coordinate System
Identifier	
Suppressed	No
Results	
Minimum	-1.0995e-005 MPa
Maximum	2.2149e-005 MPa
Minimum Occurs On	Solid
Maximum Occurs On	Solid
Information	
Reported Frequency	1.5e+005 Hz

FIGURE 3**Model (A4, B4, C4) > Harmonic Response (B5) > Solution (B6) > Acoustic Pressure**

TABLE 20
Model (A4, B4, C4) > Harmonic Response (B5) > Solution (B6) > Acoustic Pressure

Set	Frequency [Hz]
1.	500.
2.	1000.
3.	1500.
4.	2000.
5.	2500.
6.	3000.
7.	3500.
8.	4000.
9.	4500.
10.	5000.
11.	5500.
12.	6000.
13.	6500.
14.	7000.
15.	7500.
16.	8000.
17.	8500.
18.	9000.
19.	9500.
20.	10000
21.	10500
22.	11000
23.	11500
24.	12000
25.	12500
26.	13000

27.	13500
28.	14000
29.	14500
30.	15000
31.	15500
32.	16000
33.	16500
34.	17000
35.	17500
36.	18000
37.	18500
38.	19000
39.	19500
40.	20000
41.	20500
42.	21000
43.	21500
44.	22000
45.	22500
46.	23000
47.	23500
48.	24000
49.	24500
50.	25000
51.	25500
52.	26000
53.	26500
54.	27000
55.	27500
56.	28000
57.	28500
58.	29000
59.	29500
60.	30000
61.	30500
62.	31000
63.	31500
64.	32000
65.	32500
66.	33000
67.	33500
68.	34000
69.	34500
70.	35000
71.	35500
72.	36000
73.	36500
74.	37000
75.	37500
76.	38000
77.	38500
78.	39000
79.	39500
80.	

	40000
81.	40500
82.	41000
83.	41500
84.	42000
85.	42500
86.	43000
87.	43500
88.	44000
89.	44500
90.	45000
91.	45500
92.	46000
93.	46500
94.	47000
95.	47500
96.	48000
97.	48500
98.	49000
99.	49500
100.	50000
101.	50500
102.	51000
103.	51500
104.	52000
105.	52500
106.	53000
107.	53500
108.	54000
109.	54500
110.	55000
111.	55500
112.	56000
113.	56500
114.	57000
115.	57500
116.	58000
117.	58500
118.	59000
119.	59500
120.	60000
121.	60500
122.	61000
123.	61500
124.	62000
125.	62500
126.	63000
127.	63500
128.	64000
129.	64500
130.	65000
131.	65500
132.	66000
133.	

	66500
134.	67000
135.	67500
136.	68000
137.	68500
138.	69000
139.	69500
140.	70000
141.	70500
142.	71000
143.	71500
144.	72000
145.	72500
146.	73000
147.	73500
148.	74000
149.	74500
150.	75000
151.	75500
152.	76000
153.	76500
154.	77000
155.	77500
156.	78000
157.	78500
158.	79000
159.	79500
160.	80000
161.	80500
162.	81000
163.	81500
164.	82000
165.	82500
166.	83000
167.	83500
168.	84000
169.	84500
170.	85000
171.	85500
172.	86000
173.	86500
174.	87000
175.	87500
176.	88000
177.	88500
178.	89000
179.	89500
180.	90000
181.	90500
182.	91000
183.	91500
184.	92000
185.	92500
186.	

	93000
187.	93500
188.	94000
189.	94500
190.	95000
191.	95500
192.	96000
193.	96500
194.	97000
195.	97500
196.	98000
197.	98500
198.	99000
199.	99500
200.	1.e+005
201.	1.005e+005
202.	1.01e+005
203.	1.015e+005
204.	1.02e+005
205.	1.025e+005
206.	1.03e+005
207.	1.035e+005
208.	1.04e+005
209.	1.045e+005
210.	1.05e+005
211.	1.055e+005
212.	1.06e+005
213.	1.065e+005
214.	1.07e+005
215.	1.075e+005
216.	1.08e+005
217.	1.085e+005
218.	1.09e+005
219.	1.095e+005
220.	1.1e+005
221.	1.105e+005
222.	1.11e+005
223.	1.115e+005
224.	1.12e+005
225.	1.125e+005
226.	1.13e+005
227.	1.135e+005
228.	1.14e+005
229.	1.145e+005
230.	1.15e+005
231.	1.155e+005
232.	1.16e+005
233.	1.165e+005
234.	1.17e+005
235.	1.175e+005
236.	1.18e+005
237.	1.185e+005
238.	1.19e+005
239.	

	1.195e+005
240.	1.2e+005
241.	1.205e+005
242.	1.21e+005
243.	1.215e+005
244.	1.22e+005
245.	1.225e+005
246.	1.23e+005
247.	1.235e+005
248.	1.24e+005
249.	1.245e+005
250.	1.25e+005
251.	1.255e+005
252.	1.26e+005
253.	1.265e+005
254.	1.27e+005
255.	1.275e+005
256.	1.28e+005
257.	1.285e+005
258.	1.29e+005
259.	1.295e+005
260.	1.3e+005
261.	1.305e+005
262.	1.31e+005
263.	1.315e+005
264.	1.32e+005
265.	1.325e+005
266.	1.33e+005
267.	1.335e+005
268.	1.34e+005
269.	1.345e+005
270.	1.35e+005
271.	1.355e+005
272.	1.36e+005
273.	1.365e+005
274.	1.37e+005
275.	1.375e+005
276.	1.38e+005
277.	1.385e+005
278.	1.39e+005
279.	1.395e+005
280.	1.4e+005
281.	1.405e+005
282.	1.41e+005
283.	1.415e+005
284.	1.42e+005
285.	1.425e+005
286.	1.43e+005
287.	1.435e+005
288.	1.44e+005
289.	1.445e+005
290.	1.45e+005
291.	1.455e+005
292.	

	1.46e+005
293.	1.465e+005
294.	1.47e+005
295.	1.475e+005
296.	1.48e+005
297.	1.485e+005
298.	1.49e+005
299.	1.495e+005
300.	1.5e+005

TABLE 21
Model (A4, B4, C4) > Harmonic Response (B5) > Solution (B6) > Loads

Object Name	<i>Acoustic Far Field</i>
State	Solved
Properties	
Define By	Result Set
Result Set	4
Boundary Condition On Model Symmetric Plane	No
Result	SPL In Cartesian Plot
Starting Angle Phi (From X Axis Toward Y Axis)	0 [°]
Ending Angle Phi	0 [°]
Number Of Divisions Phi	0
Starting Angle Theta (From Z Axis Toward X Axis)	0 [°]
Ending Angle Theta	90 [°]
Number Of Divisions Theta	180
Sphere Radius	3 [mm]
Y Axis Rotated	No
Model Thickness in Z Direction (2D extension)	0 [mm]
Spatial Radiation Angle	Full Space
Results	
Maximum Sound Pressure Level	0 [dB]
Maximum A-weighted Sound Pressure Level	0 [dB]
Maximum Pressure Amplitude	0 [MPa]
Maximum Pressure Phase	0 [°]
Maximum Directivity	0
Maximum Scattered Pressure Amplitude	0 [MPa]
Maximum Target Strength	0 [dB]
Maximum Sound Power Level	0 [dB]

Modal (C5)

TABLE 22
Model (A4, B4, C4) > Analysis

Object Name	<i>Modal (C5)</i>
State	Solved
Definition	
Physics Type	Structural
Analysis Type	Modal
Solver Target	Mechanical APDL
Options	
Environment Temperature	22. °C
Generate Input Only	No

TABLE 23
Model (A4, B4, C4) > Modal (C5) > Initial Condition

Object Name	<i>Pre-Stress (None)</i>
State	Fully Defined
Definition	
Pre-Stress Environment	None

TABLE 24
Model (A4, B4, C4) > Modal (C5) > Analysis Settings

Object Name	<i>Analysis Settings</i>
State	Fully Defined
Options	
Max Modes to Find	5000
Limit Search to Range	Yes
Range Minimum	1. Hz
Range Maximum	1.5e+005 Hz
Solver Controls	
Damped	No
Solver Type	Unsymmetric
Rotordynamics Controls	
Coriolis Effect	Off
Campbell Diagram	Off
Output Controls	
Stress	Yes
Strain	Yes
Nodal Forces	No
Calculate Reactions	Yes
Store Modal Results	For Future Analysis
General Miscellaneous	Yes
Analysis Data Management	
Solver Files Directory	C:\Users\Edison\Documents\F_FullAcousticAnalysisWithFSI\FullAcousticAnalysisWithFSI_files\dp0\SYS-2\MECH\
Future Analysis	MSUP Analyses
Scratch Solver Files Directory	
Save MAPDL db	Yes
Delete Unneeded Files	Yes
Solver Units	Active System
Solver Unit System	nmm

TABLE 25
Model (A4, B4, C4) > Modal (C5) > Loads

--	--

Object Name	<i>Fixed Support</i>
State	Fully Defined
Scope	
Scoping Method	Geometry Selection
Geometry	1 Face
Definition	
Type	Fixed Support
Suppressed	No

TABLE 26
Model (A4, B4, C4) > Modal (C5) > Loads

Object Name	Acoustic Body	Acoustic FSI Interface
State	Fully Defined	
Scope		
Scoping Method	Geometry Selection	
Geometry	3 Bodies	2 Faces
Definition		
Frequency Dependency	No	
Mass Density	1.2041E-09 [kg mm^-1 mm^-1 mm^-1]	
Sound Speed	343240 [mm sec^-1]	
Dynamic Viscosity	0 [MPa sec]	
Bulk Viscosity	0 [MPa sec]	
Thermal Conductivity	0 [W mm^-1 C^-1]	
Specific Heat Cp	0 [J kg^-1 C^-1]	
Specific Heat Cv	0 [J kg^-1 C^-1]	
Reference Pressure	2E-11 [MPa]	
Reference Static Pressure	0.101325 [MPa]	
Acoustic-Structural Coupled Body Options	Program Controlled Coupled	

Solution (C6)

TABLE 27
Model (A4, B4, C4) > Modal (C5) > Solution

Object Name	<i>Solution (C6)</i>
State	Solved
Adaptive Mesh Refinement	
Max Refinement Loops	1.
Refinement Depth	2.
Information	
Status	Done
Post Processing	
Calculate Beam Section Results	No

The following bar chart indicates the frequency at each calculated mode.

FIGURE 4
Model (A4, B4, C4) > Modal (C5) > Solution (C6)

TABLE 28
Model (A4, B4, C4) > Modal (C5) > Solution (C6)

Mode	Frequency [Hz]	Stability [Hz]
1.	2972.	-8.9069
2.	3102.1	-9.2809
3.	6985.3	-20.937
4.	8376.5	-25.068
5.	8546.7	-25.489
6.	11442	-1.4059e-003
7.	12086	-36.229
8.	14867	-44.53
9.	16128	-48.168
10.	16289	-48.291
11.	17048	-1.0311e-002
12.	17349	-6.7836e-002
13.	18256	-54.726
14.	19880	-1.6383e-002
15.	21007	-2.8115e-004
16.	22461	-67.301
17.	24004	-2.5852e-002
18.	24807	-0.11921
19.	24961	-74.701
20.	25480	-76.383
21.	26145	-77.88
22.	26227	-72.041
23.	26494	-4.9368
24.	29651	-7.9475e-004
25.	30729	-8.4381e-002
26.	31177	-93.435

27.	33065	-0.46322
28.	33744	-101.16
29.	34110	-3.1164e-003
30.	34190	-4.6508e-003
31.	34924	-104.6
32.	35298	-0.19085
33.	36303	-6.8501e-003
34.	36358	-1.0889e-002
35.	37292	-111.46
36.	37646	-8.3714
37.	38142	-0.64971
38.	38339	-3.1606
39.	38359	-100.13
40.	38378	-110.49
41.	40107	-1.2903e-002
42.	40162	-3.0815e-002
43.	40274	-3.283e-005
44.	41009	-122.91
45.	41864	-0.43772
46.	41981	-3.1288e-003
47.	42824	-0.13745
48.	43038	-129.02
49.	44907	-0.31772
50.	45464	-1.0254e-003
51.	46039	-137.93
52.	48355	-0.54387
53.	48652	-2.4209
54.	49096	-7.6258e-002
55.	49469	-8.6527e-003
56.	49578	-148.39
57.	50005	-1.2623e-003
58.	51164	-40.486
59.	51418	-4.4214e-003
60.	51447	-18.31
61.	51679	-1.0343e-002
62.	51846	-154.57
63.	51949	-155.7
64.	52115	-50.75
65.	52436	-0.20174
66.	52727	-153.48
67.	52789	-6.0966
68.	52873	-3.3316e-002
69.	52907	-1.6164e-003
70.	53353	-159.94
71.	54076	-0.56879
72.	54328	-2.4337
73.	54396	-1.2261e-003
74.	55481	-9.298e-005
75.	55502	-0.75175
76.	55959	-12.806
77.	56772	-0.68168
78.	57283	-2.5321e-004
79.	58270	-10.456
80.		

	58312	-174.74
81.	59035	-1.3172e-003
82.	59712	-4.3363e-003
83.	60287	-0.24374
84.	60289	-0.8238
85.	60468	-3.7017e-003
86.	61053	-14.518
87.	61659	-3.1506e-003
88.	62001	-8.1952e-002
89.	62044	-3.3643e-002
90.	62345	-16.938
91.	62415	-1.8092e-003
92.	62626	-0.62297
93.	63006	-1.6411e-002
94.	63039	-188.79
95.	63070	-6.8582e-005
96.	63125	-8.5183e-005
97.	63733	-20.967
98.	63980	-191.78
99.	64682	-193.9
100.	64710	-8.0981e-002
101.	64737	-1.2663
102.	65035	-0.2383
103.	66452	-198.67
104.	66506	-0.17933
105.	66724	-0.15435
106.	68075	-23.939
107.	68168	-0.53818
108.	68596	-203.25
109.	68621	-143.33
110.	68880	-1.7644
111.	69125	-3.3185
112.	69312	-6.8074
113.	69666	-4.936e-002
114.	69692	-0.15751
115.	70055	-2.4542
116.	70234	-6.3957e-002
117.	70817	-6.952
118.	71132	-1.8637
119.	71283	-1.5482
120.	71391	-12.275
121.	71422	-1.5827e-002
122.	71732	-214.96
123.	71756	-5.9866e-002
124.	71769	-4.3516e-003
125.	71831	-1.5708e-004
126.	72116	-147.68
127.	72292	-1.74
128.	72342	-0.49702
129.	72865	-2.4157e-002
130.	73303	-2.0508
131.	73587	-1.3366
132.	73787	-5.2619e-003
133.		

	73945	-8.833e-003
134.	74427	-2.7156
135.	75128	-1.0864
136.	75225	-4.1706
137.	75910	-0.16858
138.	76323	-0.7787
139.	76577	-1.979e-002
140.	76705	-0.53992
141.	76839	-8.3161e-002
142.	76991	-4.6408e-002
143.	77020	-230.89
144.	77093	-231.09
145.	77437	-0.31413
146.	77684	-232.72
147.	77703	-3.7954e-002
148.	77730	-3.7645e-004
149.	78449	-4.9569
150.	78744	-0.72815
151.	78858	-2.5658e-003
152.	78940	-1.7551e-002
153.	79490	-1.5315e-002
154.	79505	-8.7791e-002
155.	79578	-0.10011
156.	79861	-4.3341
157.	80277	-38.469
158.	80762	-6.8994e-002
159.	80989	-1.3507e-003
160.	81172	-0.14261
161.	81215	-0.25128
162.	81308	-21.098
163.	81720	-0.16005
164.	82242	-246.15
165.	82498	-0.31843
166.	84074	-1.7384
167.	84329	-2.2777
168.	84543	-2.079
169.	84585	-5.3374
170.	84728	-5.6757e-003
171.	85268	-0.73941
172.	85512	-2.3322
173.	85540	-255.
174.	85573	-3.0033
175.	85764	-1.0137
176.	85835	-0.22658
177.	86208	-0.18298
178.	86285	-258.6
179.	86331	-5.9645
180.	86437	-0.1057
181.	86647	-1.4959e-002
182.	86658	-0.19377
183.	86703	-4.4732e-003
184.	86712	-6.0508e-002
185.	86738	-1.5006e-003
186.		

	86823	-1.47e-002
187.	86948	-0.5361
188.	87398	-252.66
189.	87404	-0.99209
190.	87467	-1.2677
191.	87770	-15.978
192.	87971	-3.6691
193.	88255	-14.924
194.	88292	-1.5578
195.	88509	-58.851
196.	88683	-16.98
197.	88913	-2.3995
198.	88965	-18.292
199.	89060	-3.4383
200.	89729	-26.133
201.	89833	-13.77
202.	89922	-2.1884
203.	90107	-23.287
204.	90362	-270.88
205.	90500	-6.7606
206.	90659	-2.1786
207.	90773	-22.124
208.	90820	-0.92923
209.	91286	-273.63
210.	91566	-0.73076
211.	91569	-84.983
212.	91641	-2.1922
213.	91855	-37.901
214.	92016	-15.863
215.	92423	-7.1207e-002
216.	92496	-9.8936
217.	92567	-19.701
218.	92769	-4.3938
219.	92792	-2.9118
220.	93200	-6.8371e-002
221.	93272	-3.5979e-002
222.	93290	-9.0173e-002
223.	93317	-0.23374
224.	93336	-0.11051
225.	93339	-0.61708
226.	93393	-3.0657
227.	93507	-280.16
228.	94060	-6.8641
229.	94328	-19.452
230.	94613	-0.14011
231.	94651	-1.2742
232.	94929	-33.602
233.	95552	-4.6841
234.	95650	-0.58786
235.	96248	-0.93408
236.	96504	-3.0141
237.	97263	-2.2233
238.	97515	-9.6817e-003
239.		

	97547	-0.52746
240.	97581	-2.4176
241.	97932	-6.1013e-002
242.	97971	-0.21908
243.	98453	-0.18161
244.	98600	-5.1844e-003
245.	98683	-0.61975
246.	98884	-0.27163
247.	99118	-8.518e-002
248.	99214	-0.16216
249.	99229	-297.14
250.	99251	-0.48008
251.	99411	-0.12556
252.	99572	-6.1632e-002
253.	99615	-0.26971
254.	1.0004e+005	-4.2347e-002
255.	1.0013e+005	-5.2859e-003
256.	1.0017e+005	-0.85376
257.	1.0029e+005	-0.10477
258.	1.0036e+005	-0.54769
259.	1.0067e+005	-0.3616
260.	1.0089e+005	-3.5653e-002
261.	1.0091e+005	-3.3625e-003
262.	1.0098e+005	-2.3181e-002
263.	1.0105e+005	-0.26535
264.	1.0118e+005	-0.11486
265.	1.0164e+005	-0.17065
266.	1.0195e+005	-3.0246e-002
267.	1.0196e+005	-305.6
268.	1.0208e+005	-0.21144
269.	1.0311e+005	-1.403
270.	1.0315e+005	-6.0396e-002
271.	1.0324e+005	-0.26972
272.	1.0331e+005	-0.22813
273.	1.0366e+005	-309.86
274.		-0.90255
275.	1.0371e+005	-0.54732
276.	1.0375e+005	-6.3069e-004
277.	1.0385e+005	-0.28903
278.	1.0387e+005	-0.41678
279.	1.0421e+005	-2.1981e-002
280.	1.0426e+005	-1.086
281.	1.0436e+005	-0.11284
282.	1.0441e+005	-0.62896
283.	1.0471e+005	-313.88
284.	1.0474e+005	-1.3688
285.	1.0485e+005	-0.15062
286.	1.0489e+005	-9.6775e-004
287.	1.0504e+005	-8.3904e-002
288.	1.0513e+005	-9.8346e-002
289.	1.0521e+005	-8.2755e-003
290.	1.0523e+005	-3.1182e-002
291.	1.0524e+005	-4.6826e-002

292.	1.0538e+005	-7.2265e-002
293.	1.054e+005	-7.6316e-003
294.	1.06e+005	-15.523
295.	1.0614e+005	-0.53058
296.	1.0629e+005	-1.6593
297.	1.0631e+005	-0.13778
298.	1.0643e+005	-22.251
299.	1.065e+005	-0.53743
300.	1.0654e+005	-319.28
301.	1.0659e+005	-157.48
302.	1.0681e+005	-315.91
303.	1.0701e+005	-1.1452
304.	1.0707e+005	-3.8002
305.	1.0735e+005	-12.534
306.	1.0797e+005	-0.12985
307.	1.0816e+005	-1.6585
308.	1.0871e+005	-3.4486
309.	1.0872e+005	-0.64277
310.	1.0901e+005	-1.2904
311.	1.0903e+005	-4.3599
312.	1.0907e+005	-0.63011
313.	1.093e+005	-1.0947
314.	1.0937e+005	-0.27092
315.	1.094e+005	-9.0192e-002
316.	1.0942e+005	-9.8182e-002
317.	1.0952e+005	-1.3143
318.	1.0978e+005	-0.40034
319.	1.1009e+005	-2.7314
320.	1.1014e+005	-0.5137
321.	1.1024e+005	-4.8624
322.	1.1044e+005	-0.33074
323.	1.1047e+005	-0.71022
324.	1.1049e+005	-0.28601
325.	1.105e+005	-331.11
326.	1.1055e+005	-1.2095
327.	1.1067e+005	-0.43601
328.	1.1073e+005	-5.1624e-002
329.	1.1074e+005	-0.2356
330.	1.108e+005	-3.0363e-002
331.	1.1092e+005	-1.5841
332.	1.1096e+005	-2.4243
333.	1.1116e+005	-5.1007e-002
334.	1.1125e+005	-7.5455
335.	1.1146e+005	-3.5824
336.	1.1151e+005	-297.23
337.	1.1153e+005	-1.0979
338.	1.1178e+005	-6.5099
339.	1.1193e+005	-25.563
340.	1.1211e+005	-62.484
341.	1.1229e+005	-201.45
342.	1.1255e+005	-0.13607
343.	1.1261e+005	-0.11411
344.	1.1275e+005	-2.5582
345.		

	1.1306e+005	-0.20587
346.	1.1345e+005	-9.2848
347.	1.1356e+005	-1.0712
348.	1.1366e+005	-16.53
349.	1.1404e+005	-0.30396
350.	1.1411e+005	-0.40966
351.	1.1412e+005	-8.5868
352.	1.1434e+005	-1.8952
353.	1.1447e+005	-0.28915
354.	1.1451e+005	-0.33292
355.	1.1453e+005	-1.2957
356.	1.148e+005	-4.2946
357.	1.1489e+005	-0.6612
358.	1.1498e+005	-47.765
359.	1.1505e+005	-2.6854
360.	1.1516e+005	-2.5287e-002
361.	1.1553e+005	-0.11744
362.	1.1555e+005	-1.7875
363.	1.1566e+005	-0.39504
364.	1.1579e+005	-21.862
365.	1.1591e+005	-0.1055
366.	1.1601e+005	-0.15699
367.	1.1606e+005	-0.17904
368.	1.1608e+005	-0.71918
369.	1.1647e+005	-3.6914e-003
370.	1.1653e+005	-6.2521
371.	1.1669e+005	-0.173
372.	1.1714e+005	-3.1562
373.	1.1717e+005	-0.10846
374.	1.1741e+005	-5.1573
375.	1.1742e+005	-351.71
376.	1.177e+005	-1.1102
377.	1.1771e+005	-0.26631
378.	1.182e+005	-0.26818
379.	1.1831e+005	-7.0248e-002
380.	1.1861e+005	-3.8625e-002
381.	1.1876e+005	-355.96
382.	1.1902e+005	-4.1401
383.	1.1936e+005	-0.24483
384.	1.1941e+005	-0.53502
385.	1.1979e+005	-0.41172
386.		-0.16362
387.	1.1998e+005	-7.5966e-003
388.	1.2006e+005	-359.89
389.	1.2009e+005	-0.84992
390.	1.2017e+005	-1.0314
391.	1.2047e+005	-0.71576
392.	1.2051e+005	-0.23416
393.	1.2064e+005	-6.3768e-002
394.	1.2068e+005	-9.1785e-002
395.	1.2071e+005	-7.1872e-002
396.	1.2076e+005	-0.4683
397.	1.2092e+005	-0.10325

398.	1.2094e+005	-9.0485e-003
399.	1.21e+005	-1.0866e-002
400.	1.2106e+005	-7.5512e-003
401.	1.2107e+005	-4.3415e-003
402.	1.2112e+005	-1.058e-002
403.	1.213e+005	-0.13145
404.	1.2141e+005	-0.28084
405.	1.2142e+005	-0.54437
406.	1.2158e+005	-4.949e-002
407.	1.2161e+005	-4.2292e-002
408.	1.2168e+005	-1.1425e-002
409.	1.217e+005	-0.46867
410.	1.22e+005	-0.18696
411.	1.2212e+005	-4.2471e-003
412.	1.2217e+005	-0.41188
413.	1.2221e+005	-4.916e-003
414.	1.2222e+005	-1.4252e-002
415.	1.2229e+005	-4.9171e-002
416.	1.2257e+005	-9.912e-002
417.	1.2276e+005	-5.6878e-002
418.	1.2281e+005	-1.5873e-002
419.	1.2283e+005	-9.1265e-002
420.	1.2286e+005	-368.26
421.	1.2299e+005	-368.03
422.	1.2314e+005	-0.85934
423.	1.2316e+005	-0.31843
424.	1.2324e+005	-9.8441e-002
425.	1.2328e+005	-3.5648e-002
426.	1.2363e+005	-3.605e-003
427.	1.2385e+005	-7.0628e-002
428.	1.2386e+005	-0.87154
429.	1.239e+005	-8.1031e-003
430.	1.2395e+005	-3.7558e-002
431.	1.2416e+005	-6.496e-003
432.	1.2441e+005	-2.4477e-003
433.	1.2442e+005	-3.266e-002
434.	1.2449e+005	-3.1165e-003
435.	1.2463e+005	-0.34441
436.	1.2472e+005	-1.5821e-003
437.	1.2477e+005	-2.1997e-002
438.	1.2501e+005	-0.86414
439.	1.2504e+005	-0.22753
440.	1.2525e+005	-5.5036e-002
441.	1.2529e+005	-8.0679e-003
442.	1.2538e+005	-4.2724e-002
443.	1.2555e+005	-2.7828e-002
444.		-5.2076e-002
445.	1.2576e+005	-5.4899e-002
446.	1.2578e+005	-0.12645
447.	1.2588e+005	-4.0955e-003
448.	1.2589e+005	-1.4101e-002
449.	1.2592e+005	-4.6287e-002
450.	1.2598e+005	-1.9626e-002

451.	1.2626e+005	-1.6105e-002
452.	1.2628e+005	-1.1601e-002
453.	1.2644e+005	-0.54318
454.	1.2672e+005	-0.28643
455.	1.2675e+005	-5.5614e-002
456.	1.269e+005	-6.7812e-002
457.	1.2694e+005	-0.10515
458.	1.2697e+005	-0.13445
459.	1.2708e+005	-0.19893
460.	1.2713e+005	-4.0376e-002
461.	1.2719e+005	-0.1946
462.	1.2726e+005	-1.4869e-002
463.	1.2731e+005	-379.4
464.	1.2742e+005	-0.1866
465.	1.2749e+005	-6.5612e-002
466.	1.28e+005	-0.46643
467.	1.2811e+005	-0.3424
468.	1.2866e+005	-385.54
469.	1.2894e+005	-0.11117
470.	1.2896e+005	-0.17471
471.	1.2911e+005	-0.64836
472.	1.2914e+005	-0.32686
473.	1.294e+005	-0.15674
474.	1.2966e+005	-0.55296
475.	1.2984e+005	-0.30767
476.	1.2986e+005	-9.9566e-002
477.	1.2992e+005	-0.40335
478.	1.2996e+005	-367.8
479.	1.3008e+005	-0.35867
480.	1.3017e+005	-9.3954e-002
481.	1.303e+005	-0.62767
482.	1.3032e+005	-0.46185
483.	1.3047e+005	-0.30589
484.	1.3052e+005	-1.0238
485.	1.3059e+005	-0.10715
486.	1.3063e+005	-0.12775
487.	1.3077e+005	-0.12473
488.	1.3082e+005	-2.7342e-002
489.	1.3098e+005	-0.94984
490.	1.3106e+005	-5.483e-002
491.	1.3108e+005	-0.78365
492.	1.3117e+005	-2.5461e-002
493.	1.3128e+005	-0.1677
494.	1.3136e+005	-4.3864
495.	1.3154e+005	-4.7507e-002
496.	1.3169e+005	-0.11627
497.	1.317e+005	-6.6719e-002
498.	1.3177e+005	-1.5987
499.	1.3182e+005	-2.0607
500.	1.3185e+005	-1.3136
501.	1.3205e+005	-1.3382
502.	1.3233e+005	-1.2196
503.	1.3254e+005	-26.49
504.		

	1.3279e+005	-115.37
505.	1.3297e+005	-0.95157
506.	1.3303e+005	-5.7129
507.	1.3317e+005	-4.1241
508.	1.3324e+005	-10.403
509.	1.3347e+005	-25.682
510.	1.3348e+005	-0.37018
511.	1.3361e+005	-46.977
512.	1.3387e+005	-19.114
513.	1.3407e+005	-3.3366
514.	1.3412e+005	-38.115
515.	1.3413e+005	-15.649
516.	1.3423e+005	-5.5494
517.	1.343e+005	-161.2
518.	1.3443e+005	-21.335
519.		-1.5882
520.	1.3452e+005	-27.939
521.	1.3454e+005	-45.967
522.	1.3468e+005	-29.45
523.	1.3478e+005	-245.12
524.	1.3486e+005	-1.6628
525.	1.3498e+005	-30.427
526.	1.3508e+005	-0.47485
527.	1.351e+005	-43.875
528.	1.3513e+005	-1.8669
529.	1.3516e+005	-7.3801
530.	1.3533e+005	-7.8251
531.	1.3554e+005	-3.4528
532.	1.3567e+005	-14.655
533.	1.3579e+005	-0.49226
534.	1.3587e+005	-2.0291
535.	1.3594e+005	-3.1147
536.	1.3599e+005	-3.3485
537.	1.3604e+005	-1.2433
538.	1.361e+005	-1.2017
539.	1.3627e+005	-6.8588
540.	1.3639e+005	-2.5331
541.	1.3641e+005	-408.92
542.	1.3643e+005	-0.75576
543.	1.3661e+005	-4.2597
544.	1.3669e+005	-409.68
545.	1.3681e+005	-409.84
546.	1.3708e+005	-27.171
547.	1.3715e+005	-1.7779
548.	1.3731e+005	-1.8635
549.	1.3743e+005	-1.8899
550.	1.3778e+005	-0.90329
551.	1.3802e+005	-8.06
552.	1.3805e+005	-3.5644
553.	1.3819e+005	-8.4031
554.	1.3832e+005	-1.3641
555.	1.3835e+005	-2.5161
556.	1.3838e+005	-0.4145

557.	1.3842e+005	-0.74263
558.	1.3844e+005	-0.2499
559.	1.3856e+005	-1.7868
560.	1.3859e+005	-27.851
561.	1.388e+005	-1.3115
562.	1.3887e+005	-10.022
563.	1.3898e+005	-0.66106
564.	1.3902e+005	-2.4317
565.	1.3907e+005	-10.738
566.	1.3919e+005	-0.12855
567.	1.3922e+005	-0.34248
568.	1.3931e+005	-0.56741
569.	1.3934e+005	-3.841
570.	1.3935e+005	-3.9007
571.	1.3938e+005	-2.4856
572.	1.394e+005	-3.4351e-002
573.	1.3944e+005	-7.6902e-002
574.	1.3947e+005	-0.43407
575.	1.3953e+005	-9.0796e-002
576.	1.3955e+005	-6.8312e-002
577.	1.396e+005	-0.27336
578.	1.3966e+005	-0.67316
579.	1.3979e+005	-0.13528
580.	1.398e+005	-0.40002
581.	1.3988e+005	-0.13802
582.	1.3999e+005	-0.23543
583.	1.401e+005	-8.5534
584.	1.4019e+005	-0.15269
585.	1.4025e+005	-420.39
586.		-0.38294
587.	1.404e+005	-1.8921e-002
588.	1.4055e+005	-0.13117
589.	1.4056e+005	-0.64477
590.	1.4061e+005	-5.8755e-003
591.	1.4089e+005	-0.11165
592.	1.4097e+005	-3.3303
593.	1.4105e+005	-4.668
594.	1.412e+005	-0.16906
595.	1.4123e+005	-2.2833
596.	1.4135e+005	-0.73572
597.	1.4143e+005	-8.9344e-002
598.	1.4161e+005	-0.90303
599.	1.4176e+005	-13.595
600.	1.4196e+005	-4.4439
601.	1.42e+005	-0.71026
602.	1.4215e+005	-1.6281
603.	1.4223e+005	-1.2
604.	1.4225e+005	-0.60688
605.	1.4237e+005	-0.19458
606.	1.4244e+005	-3.844
607.	1.4247e+005	-3.9019
608.	1.4268e+005	-4.0943e-002
609.	1.427e+005	-1.3726e-002

610.	1.4282e+005	-1.0356
611.	1.429e+005	-6.9256e-002
612.	1.4296e+005	-0.1979
613.	1.4317e+005	-1.5698
614.	1.4333e+005	-0.30537
615.	1.434e+005	-0.16631
616.	1.4341e+005	-0.37849
617.	1.4348e+005	-0.20504
618.	1.4351e+005	-0.10045
619.	1.4357e+005	-429.78
620.	1.4363e+005	-7.1499
621.	1.4371e+005	-1.431
622.	1.4375e+005	-1.034e-002
623.		-3.8263e-002
624.	1.4378e+005	-2.7001e-002
625.	1.4411e+005	-0.23954
626.	1.4419e+005	-0.12799
627.	1.4429e+005	-7.241e-002
628.	1.4438e+005	-0.64654
629.	1.4446e+005	-1.1028
630.	1.4447e+005	-0.44141
631.	1.4455e+005	-0.35402
632.	1.4468e+005	-0.68177
633.	1.4484e+005	-0.10742
634.	1.4493e+005	-0.44465
635.	1.4504e+005	-0.17084
636.	1.4531e+005	-0.83741
637.	1.4535e+005	-0.18252
638.	1.4548e+005	-0.90114
639.	1.4586e+005	-0.37781
640.	1.4591e+005	-5.8753e-002
641.	1.4605e+005	-0.65463
642.	1.4659e+005	-25.771
643.	1.4661e+005	-0.45922
644.	1.467e+005	-0.66438
645.	1.4673e+005	-0.68494
646.	1.4681e+005	-6.6856
647.	1.4684e+005	-0.2314
648.	1.4694e+005	-1.798
649.		-26.573
650.	1.47e+005	-0.15898
651.	1.4716e+005	-6.5915
652.	1.4726e+005	-0.32311
653.	1.474e+005	-0.54856
654.	1.4741e+005	-0.2464
655.	1.4745e+005	-1.7867
656.	1.4746e+005	-1.324
657.	1.4754e+005	-0.1092
658.	1.4762e+005	-2.7276
659.	1.4767e+005	-0.65342
660.	1.4781e+005	-0.92041
661.	1.4784e+005	-5.8556
662.	1.4788e+005	-0.52415

663.	1.479e+005	-0.562
664.	1.4792e+005	-0.60608
665.	1.4799e+005	-443.5
666.	1.4816e+005	-6.8341e-002
667.	1.4821e+005	-1.3101e-002
668.	1.4825e+005	-0.34854
669.	1.4834e+005	-1.3112
670.	1.4846e+005	-1.4418
671.	1.4858e+005	-0.10745
672.	1.486e+005	-0.38031
673.	1.4868e+005	-9.1371e-002
674.	1.4873e+005	-0.12467
675.	1.4891e+005	-2.2593
676.		-3.351
677.	1.4892e+005	-0.21003
678.	1.4893e+005	-4.2471e-002
679.	1.4901e+005	-444.94
680.	1.4916e+005	-0.12097
681.	1.4929e+005	-1.7586e-002
682.	1.4931e+005	-0.1455
683.	1.4935e+005	-0.32499
684.	1.4954e+005	-4.8595e-002
685.	1.4958e+005	-4.6355e-002
686.	1.4981e+005	-0.59712

TABLE 29
Model (A4, B4, C4) > Modal (C5) > Solution (C6) > Solution Information

Object Name	<i>Solution Information</i>
State	Solved
Solution Information	
Solution Output	Solver Output
Newton-Raphson Residuals	0
Update Interval	0.5 s
Display Points	All
FE Connection Visibility	
Activate Visibility	Yes
Display	All FE Connectors
Draw Connections Attached To	All Nodes
Line Color	Connection Type
Visible on Results	No
Line Thickness	Single
Display Type	Lines

TABLE 30
Model (A4, B4, C4) > Modal (C5) > Solution (C6) > Results

Object Name	<i>Total Deformation</i>
State	Solved
Scope	
Scoping Method	Geometry Selection
Geometry	All Bodies
Definition	
Type	Total Deformation
Mode	1.
Sweeping Phase	0. °

Identifier	
Suppressed	No
Results	
Minimum	0. mm
Maximum	8.1148e-003 mm
Minimum Occurs On	Solid
Maximum Occurs On	Solid
Information	
Frequency	2972. Hz
Stability	-8.9069 Hz

TABLE 31
Model (A4, B4, C4) > Modal (C5) > Solution (C6) > Total Deformation

Mode	Frequency [Hz]	Stability [Hz]
1.	2972.	-8.9069
2.	3102.1	-9.2809
3.	6985.3	-20.937
4.	8376.5	-25.068
5.	8546.7	-25.489
6.	11442	-1.4059e-003
7.	12086	-36.229
8.	14867	-44.53
9.	16128	-48.168
10.	16289	-48.291
11.	17048	-1.0311e-002
12.	17349	-6.7836e-002
13.	18256	-54.726
14.	19880	-1.6383e-002
15.	21007	-2.8115e-004
16.	22461	-67.301
17.	24004	-2.5852e-002
18.	24807	-0.11921
19.	24961	-74.701
20.	25480	-76.383
21.	26145	-77.88
22.	26227	-72.041
23.	26494	-4.9368
24.	29651	-7.9475e-004
25.	30729	-8.4381e-002
26.	31177	-93.435
27.	33065	-0.46322
28.	33744	-101.16
29.	34110	-3.1164e-003
30.	34190	-4.6508e-003
31.	34924	-104.6
32.	35298	-0.19085
33.	36303	-6.8501e-003
34.	36358	-1.0889e-002
35.	37292	-111.46
36.	37646	-8.3714
37.	38142	-0.64971
38.	38339	-3.1606
39.	38359	-100.13
40.	38378	-110.49

41.	40107	-1.2903e-002
42.	40162	-3.0815e-002
43.	40274	-3.283e-005
44.	41009	-122.91
45.	41864	-0.43772
46.	41981	-3.1288e-003
47.	42824	-0.13745
48.	43038	-129.02
49.	44907	-0.31772
50.	45464	-1.0254e-003
51.	46039	-137.93
52.	48355	-0.54387
53.	48652	-2.4209
54.	49096	-7.6258e-002
55.	49469	-8.6527e-003
56.	49578	-148.39
57.	50005	-1.2623e-003
58.	51164	-40.486
59.	51418	-4.4214e-003
60.	51447	-18.31
61.	51679	-1.0343e-002
62.	51846	-154.57
63.	51949	-155.7
64.	52115	-50.75
65.	52436	-0.20174
66.	52727	-153.48
67.	52789	-6.0966
68.	52873	-3.3316e-002
69.	52907	-1.6164e-003
70.	53353	-159.94
71.	54076	-0.56879
72.	54328	-2.4337
73.	54396	-1.2261e-003
74.	55481	-9.298e-005
75.	55502	-0.75175
76.	55959	-12.806
77.	56772	-0.68168
78.	57283	-2.5321e-004
79.	58270	-10.456
80.	58312	-174.74
81.	59035	-1.3172e-003
82.	59712	-4.3363e-003
83.	60287	-0.24374
84.	60289	-0.8238
85.	60468	-3.7017e-003
86.	61053	-14.518
87.	61659	-3.1506e-003
88.	62001	-8.1952e-002
89.	62044	-3.3643e-002
90.	62345	-16.938
91.	62415	-1.8092e-003
92.	62626	-0.62297
93.	63006	-1.6411e-002
94.		

	63039	-188.79
95.	63070	-6.8582e-005
96.	63125	-8.5183e-005
97.	63733	-20.967
98.	63980	-191.78
99.	64682	-193.9
100.	64710	-8.0981e-002
101.	64737	-1.2663
102.	65035	-0.2383
103.	66452	-198.67
104.	66506	-0.17933
105.	66724	-0.15435
106.	68075	-23.939
107.	68168	-0.53818
108.	68596	-203.25
109.	68621	-143.33
110.	68880	-1.7644
111.	69125	-3.3185
112.	69312	-6.8074
113.	69666	-4.936e-002
114.	69692	-0.15751
115.	70055	-2.4542
116.	70234	-6.3957e-002
117.	70817	-6.952
118.	71132	-1.8637
119.	71283	-1.5482
120.	71391	-12.275
121.	71422	-1.5827e-002
122.	71732	-214.96
123.	71756	-5.9866e-002
124.	71769	-4.3516e-003
125.	71831	-1.5708e-004
126.	72116	-147.68
127.	72292	-1.74
128.	72342	-0.49702
129.	72865	-2.4157e-002
130.	73303	-2.0508
131.	73587	-1.3366
132.	73787	-5.2619e-003
133.	73945	-8.833e-003
134.	74427	-2.7156
135.	75128	-1.0864
136.	75225	-4.1706
137.	75910	-0.16858
138.	76323	-0.7787
139.	76577	-1.979e-002
140.	76705	-0.53992
141.	76839	-8.3161e-002
142.	76991	-4.6408e-002
143.	77020	-230.89
144.	77093	-231.09
145.	77437	-0.31413
146.	77684	-232.72
147.		

	77703	-3.7954e-002
148.	77730	-3.7645e-004
149.	78449	-4.9569
150.	78744	-0.72815
151.	78858	-2.5658e-003
152.	78940	-1.7551e-002
153.	79490	-1.5315e-002
154.	79505	-8.7791e-002
155.	79578	-0.10011
156.	79861	-4.3341
157.	80277	-38.469
158.	80762	-6.8994e-002
159.	80989	-1.3507e-003
160.	81172	-0.14261
161.	81215	-0.25128
162.	81308	-21.098
163.	81720	-0.16005
164.	82242	-246.15
165.	82498	-0.31843
166.	84074	-1.7384
167.	84329	-2.2777
168.	84543	-2.079
169.	84585	-5.3374
170.	84728	-5.6757e-003
171.	85268	-0.73941
172.	85512	-2.3322
173.	85540	-255.
174.	85573	-3.0033
175.	85764	-1.0137
176.	85835	-0.22658
177.	86208	-0.18298
178.	86285	-258.6
179.	86331	-5.9645
180.	86437	-0.1057
181.	86647	-1.4959e-002
182.	86658	-0.19377
183.	86703	-4.4732e-003
184.	86712	-6.0508e-002
185.	86738	-1.5006e-003
186.	86823	-1.47e-002
187.	86948	-0.5361
188.	87398	-252.66
189.	87404	-0.99209
190.	87467	-1.2677
191.	87770	-15.978
192.	87971	-3.6691
193.	88255	-14.924
194.	88292	-1.5578
195.	88509	-58.851
196.	88683	-16.98
197.	88913	-2.3995
198.	88965	-18.292
199.	89060	-3.4383
200.		

	89729	-26.133
201.	89833	-13.77
202.	89922	-2.1884
203.	90107	-23.287
204.	90362	-270.88
205.	90500	-6.7606
206.	90659	-2.1786
207.	90773	-22.124
208.	90820	-0.92923
209.	91286	-273.63
210.	91566	-0.73076
211.	91569	-84.983
212.	91641	-2.1922
213.	91855	-37.901
214.	92016	-15.863
215.	92423	-7.1207e-002
216.	92496	-9.8936
217.	92567	-19.701
218.	92769	-4.3938
219.	92792	-2.9118
220.	93200	-6.8371e-002
221.	93272	-3.5979e-002
222.	93290	-9.0173e-002
223.	93317	-0.23374
224.	93336	-0.11051
225.	93339	-0.61708
226.	93393	-3.0657
227.	93507	-280.16
228.	94060	-6.8641
229.	94328	-19.452
230.	94613	-0.14011
231.	94651	-1.2742
232.	94929	-33.602
233.	95552	-4.6841
234.	95650	-0.58786
235.	96248	-0.93408
236.	96504	-3.0141
237.	97263	-2.2233
238.	97515	-9.6817e-003
239.	97547	-0.52746
240.	97581	-2.4176
241.	97932	-6.1013e-002
242.	97971	-0.21908
243.	98453	-0.18161
244.	98600	-5.1844e-003
245.	98683	-0.61975
246.	98884	-0.27163
247.	99118	-8.518e-002
248.	99214	-0.16216
249.	99229	-297.14
250.	99251	-0.48008
251.	99411	-0.12556
252.	99572	-6.1632e-002
253.		

	99615	-0.26971
254.	1.0004e+005	-4.2347e-002
255.	1.0013e+005	-5.2859e-003
256.	1.0017e+005	-0.85376
257.	1.0029e+005	-0.10477
258.	1.0036e+005	-0.54769
259.	1.0067e+005	-0.3616
260.	1.0089e+005	-3.5653e-002
261.	1.0091e+005	-3.3625e-003
262.	1.0098e+005	-2.3181e-002
263.	1.0105e+005	-0.26535
264.	1.0118e+005	-0.11486
265.	1.0164e+005	-0.17065
266.	1.0195e+005	-3.0246e-002
267.	1.0196e+005	-305.6
268.	1.0208e+005	-0.21144
269.	1.0311e+005	-1.403
270.	1.0315e+005	-6.0396e-002
271.	1.0324e+005	-0.26972
272.	1.0331e+005	-0.22813
273.	1.0366e+005	-309.86
274.		-0.90255
275.	1.0371e+005	-0.54732
276.	1.0375e+005	-6.3069e-004
277.	1.0385e+005	-0.28903
278.	1.0387e+005	-0.41678
279.	1.0421e+005	-2.1981e-002
280.	1.0426e+005	-1.086
281.	1.0436e+005	-0.11284
282.	1.0441e+005	-0.62896
283.	1.0471e+005	-313.88
284.	1.0474e+005	-1.3688
285.	1.0485e+005	-0.15062
286.	1.0489e+005	-9.6775e-004
287.	1.0504e+005	-8.3904e-002
288.	1.0513e+005	-9.8346e-002
289.	1.0521e+005	-8.2755e-003
290.	1.0523e+005	-3.1182e-002
291.	1.0524e+005	-4.6826e-002
292.	1.0538e+005	-7.2265e-002
293.	1.054e+005	-7.6316e-003
294.	1.06e+005	-15.523
295.	1.0614e+005	-0.53058
296.	1.0629e+005	-1.6593
297.	1.0631e+005	-0.13778
298.	1.0643e+005	-22.251
299.	1.065e+005	-0.53743
300.	1.0654e+005	-319.28
301.	1.0659e+005	-157.48
302.	1.0681e+005	-315.91
303.	1.0701e+005	-1.1452
304.	1.0707e+005	-3.8002
305.	1.0735e+005	-12.534

306.	1.0797e+005	-0.12985
307.	1.0816e+005	-1.6585
308.	1.0871e+005	-3.4486
309.	1.0872e+005	-0.64277
310.	1.0901e+005	-1.2904
311.	1.0903e+005	-4.3599
312.	1.0907e+005	-0.63011
313.	1.093e+005	-1.0947
314.	1.0937e+005	-0.27092
315.	1.094e+005	-9.0192e-002
316.	1.0942e+005	-9.8182e-002
317.	1.0952e+005	-1.3143
318.	1.0978e+005	-0.40034
319.	1.1009e+005	-2.7314
320.	1.1014e+005	-0.5137
321.	1.1024e+005	-4.8624
322.	1.1044e+005	-0.33074
323.	1.1047e+005	-0.71022
324.	1.1049e+005	-0.28601
325.	1.105e+005	-331.11
326.	1.1055e+005	-1.2095
327.	1.1067e+005	-0.43601
328.	1.1073e+005	-5.1624e-002
329.	1.1074e+005	-0.2356
330.	1.108e+005	-3.0363e-002
331.	1.1092e+005	-1.5841
332.	1.1096e+005	-2.4243
333.	1.1116e+005	-5.1007e-002
334.	1.1125e+005	-7.5455
335.	1.1146e+005	-3.5824
336.	1.1151e+005	-297.23
337.	1.1153e+005	-1.0979
338.	1.1178e+005	-6.5099
339.	1.1193e+005	-25.563
340.	1.1211e+005	-62.484
341.	1.1229e+005	-201.45
342.	1.1255e+005	-0.13607
343.	1.1261e+005	-0.11411
344.	1.1275e+005	-2.5582
345.	1.1306e+005	-0.20587
346.	1.1345e+005	-9.2848
347.	1.1356e+005	-1.0712
348.	1.1366e+005	-16.53
349.	1.1404e+005	-0.30396
350.	1.1411e+005	-0.40966
351.	1.1412e+005	-8.5868
352.	1.1434e+005	-1.8952
353.	1.1447e+005	-0.28915
354.	1.1451e+005	-0.33292
355.	1.1453e+005	-1.2957
356.	1.148e+005	-4.2946
357.	1.1489e+005	-0.6612
358.	1.1498e+005	-47.765
359.		

	1.1505e+005	-2.6854
360.	1.1516e+005	-2.5287e-002
361.	1.1553e+005	-0.11744
362.	1.1555e+005	-1.7875
363.	1.1566e+005	-0.39504
364.	1.1579e+005	-21.862
365.	1.1591e+005	-0.1055
366.	1.1601e+005	-0.15699
367.	1.1606e+005	-0.17904
368.	1.1608e+005	-0.71918
369.	1.1647e+005	-3.6914e-003
370.	1.1653e+005	-6.2521
371.	1.1669e+005	-0.173
372.	1.1714e+005	-3.1562
373.	1.1717e+005	-0.10846
374.	1.1741e+005	-5.1573
375.	1.1742e+005	-351.71
376.	1.177e+005	-1.1102
377.	1.1771e+005	-0.26631
378.	1.182e+005	-0.26818
379.	1.1831e+005	-7.0248e-002
380.	1.1861e+005	-3.8625e-002
381.	1.1876e+005	-355.96
382.	1.1902e+005	-4.1401
383.	1.1936e+005	-0.24483
384.	1.1941e+005	-0.53502
385.	1.1979e+005	-0.41172
386.		-0.16362
387.	1.1998e+005	-7.5966e-003
388.	1.2006e+005	-359.89
389.	1.2009e+005	-0.84992
390.	1.2017e+005	-1.0314
391.	1.2047e+005	-0.71576
392.	1.2051e+005	-0.23416
393.	1.2064e+005	-6.3768e-002
394.	1.2068e+005	-9.1785e-002
395.	1.2071e+005	-7.1872e-002
396.	1.2076e+005	-0.4683
397.	1.2092e+005	-0.10325
398.	1.2094e+005	-9.0485e-003
399.	1.21e+005	-1.0866e-002
400.	1.2106e+005	-7.5512e-003
401.	1.2107e+005	-4.3415e-003
402.	1.2112e+005	-1.058e-002
403.	1.213e+005	-0.13145
404.	1.2141e+005	-0.28084
405.	1.2142e+005	-0.54437
406.	1.2158e+005	-4.949e-002
407.	1.2161e+005	-4.2292e-002
408.	1.2168e+005	-1.1425e-002
409.	1.217e+005	-0.46867
410.	1.22e+005	-0.18696
411.	1.2212e+005	-4.2471e-003

412.	1.2217e+005	-0.41188
413.	1.2221e+005	-4.916e-003
414.	1.2222e+005	-1.4252e-002
415.	1.2229e+005	-4.9171e-002
416.	1.2257e+005	-9.912e-002
417.	1.2276e+005	-5.6878e-002
418.	1.2281e+005	-1.5873e-002
419.	1.2283e+005	-9.1265e-002
420.	1.2286e+005	-368.26
421.	1.2299e+005	-368.03
422.	1.2314e+005	-0.85934
423.	1.2316e+005	-0.31843
424.	1.2324e+005	-9.8441e-002
425.	1.2328e+005	-3.5648e-002
426.	1.2363e+005	-3.605e-003
427.	1.2385e+005	-7.0628e-002
428.	1.2386e+005	-0.87154
429.	1.239e+005	-8.1031e-003
430.	1.2395e+005	-3.7558e-002
431.	1.2416e+005	-6.496e-003
432.	1.2441e+005	-2.4477e-003
433.	1.2442e+005	-3.266e-002
434.	1.2449e+005	-3.1165e-003
435.	1.2463e+005	-0.34441
436.	1.2472e+005	-1.5821e-003
437.	1.2477e+005	-2.1997e-002
438.	1.2501e+005	-0.86414
439.	1.2504e+005	-0.22753
440.	1.2525e+005	-5.5036e-002
441.	1.2529e+005	-8.0679e-003
442.	1.2538e+005	-4.2724e-002
443.	1.2555e+005	-2.7828e-002
444.		-5.2076e-002
445.	1.2576e+005	-5.4899e-002
446.	1.2578e+005	-0.12645
447.	1.2588e+005	-4.0955e-003
448.	1.2589e+005	-1.4101e-002
449.	1.2592e+005	-4.6287e-002
450.	1.2598e+005	-1.9626e-002
451.	1.2626e+005	-1.6105e-002
452.	1.2628e+005	-1.1601e-002
453.	1.2644e+005	-0.54318
454.	1.2672e+005	-0.28643
455.	1.2675e+005	-5.5614e-002
456.	1.269e+005	-6.7812e-002
457.	1.2694e+005	-0.10515
458.	1.2697e+005	-0.13445
459.	1.2708e+005	-0.19893
460.	1.2713e+005	-4.0376e-002
461.	1.2719e+005	-0.1946
462.	1.2726e+005	-1.4869e-002
463.	1.2731e+005	-379.4
464.	1.2742e+005	-0.1866

465.	1.2749e+005	-6.5612e-002
466.	1.28e+005	-0.46643
467.	1.2811e+005	-0.3424
468.	1.2866e+005	-385.54
469.	1.2894e+005	-0.11117
470.	1.2896e+005	-0.17471
471.	1.2911e+005	-0.64836
472.	1.2914e+005	-0.32686
473.	1.294e+005	-0.15674
474.	1.2966e+005	-0.55296
475.	1.2984e+005	-0.30767
476.	1.2986e+005	-9.9566e-002
477.	1.2992e+005	-0.40335
478.	1.2996e+005	-367.8
479.	1.3008e+005	-0.35867
480.	1.3017e+005	-9.3954e-002
481.	1.303e+005	-0.62767
482.	1.3032e+005	-0.46185
483.	1.3047e+005	-0.30589
484.	1.3052e+005	-1.0238
485.	1.3059e+005	-0.10715
486.	1.3063e+005	-0.12775
487.	1.3077e+005	-0.12473
488.	1.3082e+005	-2.7342e-002
489.	1.3098e+005	-0.94984
490.	1.3106e+005	-5.483e-002
491.	1.3108e+005	-0.78365
492.	1.3117e+005	-2.5461e-002
493.	1.3128e+005	-0.1677
494.	1.3136e+005	-4.3864
495.	1.3154e+005	-4.7507e-002
496.	1.3169e+005	-0.11627
497.	1.317e+005	-6.6719e-002
498.	1.3177e+005	-1.5987
499.	1.3182e+005	-2.0607
500.	1.3185e+005	-1.3136
501.	1.3205e+005	-1.3382
502.	1.3233e+005	-1.2196
503.	1.3254e+005	-26.49
504.	1.3279e+005	-115.37
505.	1.3297e+005	-0.95157
506.	1.3303e+005	-5.7129
507.	1.3317e+005	-4.1241
508.	1.3324e+005	-10.403
509.	1.3347e+005	-25.682
510.	1.3348e+005	-0.37018
511.	1.3361e+005	-46.977
512.	1.3387e+005	-19.114
513.	1.3407e+005	-3.3366
514.	1.3412e+005	-38.115
515.	1.3413e+005	-15.649
516.	1.3423e+005	-5.5494
517.	1.343e+005	-161.2
518.		

		-21.335
519.	1.3443e+005	-1.5882
520.	1.3452e+005	-27.939
521.	1.3454e+005	-45.967
522.	1.3468e+005	-29.45
523.	1.3478e+005	-245.12
524.	1.3486e+005	-1.6628
525.	1.3498e+005	-30.427
526.	1.3508e+005	-0.47485
527.	1.351e+005	-43.875
528.	1.3513e+005	-1.8669
529.	1.3516e+005	-7.3801
530.	1.3533e+005	-7.8251
531.	1.3554e+005	-3.4528
532.	1.3567e+005	-14.655
533.	1.3579e+005	-0.49226
534.	1.3587e+005	-2.0291
535.	1.3594e+005	-3.1147
536.	1.3599e+005	-3.3485
537.	1.3604e+005	-1.2433
538.	1.361e+005	-1.2017
539.	1.3627e+005	-6.8588
540.	1.3639e+005	-2.5331
541.	1.3641e+005	-408.92
542.	1.3643e+005	-0.75576
543.	1.3661e+005	-4.2597
544.	1.3669e+005	-409.68
545.	1.3681e+005	-409.84
546.	1.3708e+005	-27.171
547.	1.3715e+005	-1.7779
548.	1.3731e+005	-1.8635
549.	1.3743e+005	-1.8899
550.	1.3778e+005	-0.90329
551.	1.3802e+005	-8.06
552.	1.3805e+005	-3.5644
553.	1.3819e+005	-8.4031
554.	1.3832e+005	-1.3641
555.	1.3835e+005	-2.5161
556.	1.3838e+005	-0.4145
557.	1.3842e+005	-0.74263
558.	1.3844e+005	-0.2499
559.	1.3856e+005	-1.7868
560.	1.3859e+005	-27.851
561.	1.388e+005	-1.3115
562.	1.3887e+005	-10.022
563.	1.3898e+005	-0.66106
564.	1.3902e+005	-2.4317
565.	1.3907e+005	-10.738
566.	1.3919e+005	-0.12855
567.	1.3922e+005	-0.34248
568.	1.3931e+005	-0.56741
569.	1.3934e+005	-3.841
570.	1.3935e+005	-3.9007

571.	1.3938e+005	-2.4856
572.	1.394e+005	-3.4351e-002
573.	1.3944e+005	-7.6902e-002
574.	1.3947e+005	-0.43407
575.	1.3953e+005	-9.0796e-002
576.	1.3955e+005	-6.8312e-002
577.	1.396e+005	-0.27336
578.	1.3966e+005	-0.67316
579.	1.3979e+005	-0.13528
580.	1.398e+005	-0.40002
581.	1.3988e+005	-0.13802
582.	1.3999e+005	-0.23543
583.	1.401e+005	-8.5534
584.	1.4019e+005	-0.15269
585.	1.4025e+005	-420.39
586.		-0.38294
587.	1.404e+005	-1.8921e-002
588.	1.4055e+005	-0.13117
589.	1.4056e+005	-0.64477
590.	1.4061e+005	-5.8755e-003
591.	1.4089e+005	-0.11165
592.	1.4097e+005	-3.3303
593.	1.4105e+005	-4.668
594.	1.412e+005	-0.16906
595.	1.4123e+005	-2.2833
596.	1.4135e+005	-0.73572
597.	1.4143e+005	-8.9344e-002
598.	1.4161e+005	-0.90303
599.	1.4176e+005	-13.595
600.	1.4196e+005	-4.4439
601.	1.42e+005	-0.71026
602.	1.4215e+005	-1.6281
603.	1.4223e+005	-1.2
604.	1.4225e+005	-0.60688
605.	1.4237e+005	-0.19458
606.	1.4244e+005	-3.844
607.	1.4247e+005	-3.9019
608.	1.4268e+005	-4.0943e-002
609.	1.427e+005	-1.3726e-002
610.	1.4282e+005	-1.0356
611.	1.429e+005	-6.9256e-002
612.	1.4296e+005	-0.1979
613.	1.4317e+005	-1.5698
614.	1.4333e+005	-0.30537
615.	1.434e+005	-0.16631
616.	1.4341e+005	-0.37849
617.	1.4348e+005	-0.20504
618.	1.4351e+005	-0.10045
619.	1.4357e+005	-429.78
620.	1.4363e+005	-7.1499
621.	1.4371e+005	-1.431
622.	1.4375e+005	-1.034e-002
623.		-3.8263e-002

624.	1.4378e+005	-2.7001e-002
625.	1.4411e+005	-0.23954
626.	1.4419e+005	-0.12799
627.	1.4429e+005	-7.241e-002
628.	1.4438e+005	-0.64654
629.	1.4446e+005	-1.1028
630.	1.4447e+005	-0.44141
631.	1.4455e+005	-0.35402
632.	1.4468e+005	-0.68177
633.	1.4484e+005	-0.10742
634.	1.4493e+005	-0.44465
635.	1.4504e+005	-0.17084
636.	1.4531e+005	-0.83741
637.	1.4535e+005	-0.18252
638.	1.4548e+005	-0.90114
639.	1.4586e+005	-0.37781
640.	1.4591e+005	-5.8753e-002
641.	1.4605e+005	-0.65463
642.	1.4659e+005	-25.771
643.	1.4661e+005	-0.45922
644.	1.467e+005	-0.66438
645.	1.4673e+005	-0.68494
646.	1.4681e+005	-6.6856
647.	1.4684e+005	-0.2314
648.	1.4694e+005	-1.798
649.		-26.573
650.	1.47e+005	-0.15898
651.	1.4716e+005	-6.5915
652.	1.4726e+005	-0.32311
653.	1.474e+005	-0.54856
654.	1.4741e+005	-0.2464
655.	1.4745e+005	-1.7867
656.	1.4746e+005	-1.324
657.	1.4754e+005	-0.1092
658.	1.4762e+005	-2.7276
659.	1.4767e+005	-0.65342
660.	1.4781e+005	-0.92041
661.	1.4784e+005	-5.8556
662.	1.4788e+005	-0.52415
663.	1.479e+005	-0.562
664.	1.4792e+005	-0.60608
665.	1.4799e+005	-443.5
666.	1.4816e+005	-6.8341e-002
667.	1.4821e+005	-1.3101e-002
668.	1.4825e+005	-0.34854
669.	1.4834e+005	-1.3112
670.	1.4846e+005	-1.4418
671.	1.4858e+005	-0.10745
672.	1.486e+005	-0.38031
673.	1.4868e+005	-9.1371e-002
674.	1.4873e+005	-0.12467
675.	1.4891e+005	-2.2593
676.		-3.351

677.	1.4892e+005	-0.21003
678.	1.4893e+005	-4.2471e-002
679.	1.4901e+005	-444.94
680.	1.4916e+005	-0.12097
681.	1.4929e+005	-1.7586e-002
682.	1.4931e+005	-0.1455
683.	1.4935e+005	-0.32499
684.	1.4954e+005	-4.8595e-002
685.	1.4958e+005	-4.6355e-002
686.	1.4981e+005	-0.59712

Material Data

Structural Steel

TABLE 32
Structural Steel > Constants

Density	7.85e-006 kg mm ⁻³
Coefficient of Thermal Expansion	1.2e-005 C ⁻¹
Specific Heat	4.34e+005 mJ kg ⁻¹ C ⁻¹
Thermal Conductivity	6.05e-002 W mm ⁻¹ C ⁻¹
Resistivity	1.7e-004 ohm mm

TABLE 33
Structural Steel > Compressive Ultimate Strength

Compressive Ultimate Strength MPa
0

TABLE 34
Structural Steel > Compressive Yield Strength

Compressive Yield Strength MPa
250

TABLE 35
Structural Steel > Tensile Yield Strength

Tensile Yield Strength MPa
250

TABLE 36
Structural Steel > Tensile Ultimate Strength

Tensile Ultimate Strength MPa
460

TABLE 37
Structural Steel > Isotropic Secant Coefficient of Thermal Expansion

Reference Temperature C
22

TABLE 38
Structural Steel > Alternating Stress Mean Stress

Alternating Stress MPa	Cycles	Mean Stress MPa
3999	10	0
2827	20	0

1896	50	0
1413	100	0
1069	200	0
441	2000	0
262	10000	0
214	20000	0
138	1.e+005	0
114	2.e+005	0
86.2	1.e+006	0

TABLE 39
Structural Steel > Strain-Life Parameters

Strength Coefficient MPa	Strength Exponent	Ductility Coefficient	Ductility Exponent	Cyclic Strength Coefficient MPa	Cyclic Strain Hardening Exponent
920	-0.106	0.213	-0.47	1000	0.2

TABLE 40
Structural Steel > Isotropic Elasticity

Temperature C	Young's Modulus MPa	Poisson's Ratio	Bulk Modulus MPa	Shear Modulus MPa
	2.e+005	0.3	1.6667e+005	76923

TABLE 41
Structural Steel > Isotropic Relative Permeability

Relative Permeability
10000

Mylar Celplast

TABLE 42
Mylar Celplast > Constants

Density	1.39e-006 kg mm ⁻³
Coefficient of Thermal Expansion	1.7e-005 C ⁻¹
Thermal Conductivity	1.5481e-004 W mm ⁻¹ C ⁻¹
Resistivity	1.e+020 ohm mm

TABLE 43
Mylar Celplast > Isotropic Elasticity

Temperature C	Young's Modulus MPa	Poisson's Ratio	Bulk Modulus MPa	Shear Modulus MPa
	4088.4	0.38	5678.3	1481.3

TABLE 44
Mylar Celplast > Constant Damping Coefficient

Constant Damping Coefficient
3.e-003

TABLE 45
Mylar Celplast > Tensile Ultimate Strength

Tensile Ultimate Strength MPa
199.95

TABLE 46
Mylar Celplast > Tensile Yield Strength

Tensile Yield Strength MPa
96.527

Appendix D

Electrical circuit design

Power Supply

Arduino Systems

LED Lights

I2C Data Line

Porgrammers

System 1 Circuitry

System 2 Circuitry

I/O Connector

System 3 Circuitry

Band Pass Filter

Appendix E

SPL Code

```

% Audio Reception

info=audiodevinfo; % checks for devices
Fs=200000;
T=1/Fs;
Bits=16;
Channels=1;
DeviceID=1;
RecTime=5;
L=RecTime*Fs;
t=(0:L-1)*T;
support = audiodevinfo(1,DeviceID,Fs,Bits,Channels);% checks for microphone
as device 2
%recObj = audiorecorder(Fs,Bits,Channels,DeviceID);

recObj = audiorecorder(44100,16,1,1);

get(recObj);
disp('Start speaking.')
recordblocking(recObj, 10);
disp('End of Recording.');
```

% Play back the recording.

```

%play(recObj);

% Store data in double-precision array.
myRecording = getaudiodata(recObj);
figure
plot(myRecording);
%myRecordingnew=(myRecording*((2^Bits)/2));
% Plot the waveform.
```

%k=20*log(((myRecording*32768))*8.5806*10^-4)/(20*10^-6))

```

%Y=fft(myRecording);
Y=fft(myRecording);
P2=abs(Y/L);
P1=P2(1:L/2+1);
P1(2:end-1) = 2*P1(2:end-1);
f = Fs*(0:(L/2))/L;
%convert to DB
MAG_dB = 20*log10((P1*3.3/65536)/50.1187)/(20*10^-6));
figure
plot(f,P1);
title('Single-Sided Amplitude Spectrum of X(t)')
xlabel('f (Hz)')
ylabel('|P1(f)|')
figure
plot(f,MAG_dB);
title('Single-Sided Amplitude Spectrum of X(t)')
xlabel('f (Hz)')
ylabel('mag dB')

%[spec phase]=myfft(myRecording,Fs)
```