Passive Noise Control in Incubators

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ABSTRACT

Incubators in the Neonatal Intensive Care Unit (NICU) are known to produce high Sound Pressure Levels (SPL) that can have detrimental effects on infants. Currently measured SPL in NICU’s using traditional incubators are above the recommended 45 dB[A] threshold value [1]. Due to operating equipment and environmental noise, the sound level that is perceived by the developing newborn can cause both short and long term hearing loss as well as psychological damage [1].

This thesis presents a study on how passive noise control devices can be used to reduce SPL levels in incubator NICU environments. A combination of experimental testing coupled with Finite Element simulations were performed for a modern incubator. In the experimental portion, porous mattresses were analyzed to reduce SPL values. These same test scenarios were modeled using the FE software. Using this model, extensive studies were performed on an arrangement of porous mattress materials with simple foam shapes to determine sound absorbing characteristics of several designs.

Data was collected and studied at a NICU at Children’s Hospital in Norfolk, Va. Experimental work showed improvement in reducing SPL with multiple thicknesses for different sound absorbing mattresses. The experimental outcomes validated the FE simulation model by showing similar trends at the baby’s ears. In simulation work, polyimide foam had the best low frequency performance while polyurethane had the greatest performance in middle and high frequencies. Designs that used full-width foam treatments across the incubator produced the overall greatest reduction in noise around the baby control volume by approximately 26%.
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Chapter 1. Introduction

1.1 Problem Statement

When babies are born prematurely, an incubator in the Neonatal Intensive Care Unit (NICU) hospital environment is often necessary to ensure the baby’s health. An incubator is a three dimensional rectangular structure with an enclosure that provides infants with a stable environment until they are well enough to be relocated. The incubators located in the NICU are specifically designed to provide many general services such as oxygen, protection, nutrition, heat and cooling and the distribution of fluids to the neonate [2]. All incubators are comprised of specific equipment that allows them to perform these operations. Some of which include, a ventilator pump, heaters, a servo-control, as well as accessible areas for nursing [2]. Because of these demands, the apparatus’s functions are running almost continually in order to maintain suitable conditions for the growing infant. In addition to the incubator equipment noise, there are also contributing noise sources coming from the surroundings, including other medical testing equipment, and exposure to NICU patients and staff. The accumulation of all these noises contributes to the high noise levels heard inside the operating incubator. The primary concern is the high sound pressure levels that are heard at the infant’s ears that is above recommended sound levels, which as a result, is a leading cause to future hearing loss and psychological damage to the baby and increases the recovery time of the prenate [1]. Applying passive noise control techniques to the interior of the incubator will allow greater comfort for the infant producing a quieter, healthier environment which results in improved sleep, reduced heart rate, and overall improved neonatal response behaviors.

1.2 Background Description

1.2.1 Hearing Literature

A basic understanding of how hearing loss is initiated can be best understood by examining how the ear hears and processes sound. There are three parts to a human ear: the outer, middle and inner ear, or cochlea [3]. Each has their individual purpose and process which together, results in sending an impulse to the brain that interprets the sound. When any sound is heard, it is carried from the outer ear to the middle ear which changes the energy of the sound wave into vibrations of the bone structure. These vibrations are then converted to a compressional wave to the inner ear [3]. Once in the inner ear, the energy of the compressional wave is transformed to nerve impulses which are then transferred to the brain. When loud noise is present, minute structures located in the cochlea can be fatigued, which causes a temporary loss of hearing. If this noise level persists, eternal damage results [4]. As the neonates experience this discomfort, the result is potentially both short and long term hearing damage.

There is a range of frequencies in which a human is able to identify sound. Sound is defined as “a mechanical wave that is an oscillation of pressure transmitted through a solid, liquid or gas, composed of frequencies within the range of hearing” [5]. This audible range exists from about 20 to 20000 Hz. [6]. There is however a variation with age as frequency increases or decreases that will affect how well one hears at a specific noise level.
Sound pressure levels are a logarithmic measure of the effective sound pressure of a sound relative to a reference value [1]. The number of sound pressure level vibrations per second denotes the frequency, or cycles per second [6]. This sound pressure level reference value varies, depending if calculations are done in air, water etc. For the following experiments, a reference value for air, equaling 20 μPa (10^{-6} Pa) is used. The most common logarithmic scale for describing these sound levels is the decibel (dB) scale, although sound measurements require the selection of a weighting network that is mostly used for hearing in adults [7]. The significance of this is to confirm that measured loudness corresponds well with subjectively perceived loudness. It is basically a means of adjusting a “linear noise spectrum to closely reflect the response of the human ear.” This A-weighting filter is most often used when dealing with frequencies where the ear is most sensitive and used for relatively quiet sounds. Furthermore, it takes into account the human ear being more “deaf” at the lower and higher frequencies [8]. The verge of hearing has a range of approximately 10 to 140 dB[A]. Examples of these levels would be for around 50 dB[A], a light traffic, whereas around 90 dB[A] a loud pneumatic drill is a good representative. If relating to an incubator, these are like the background noise and closing the metal cabinet doors under the incubator, respectively [1]. See table 1 below for further example levels.

### Table 1. Noise level comparison table

<table>
<thead>
<tr>
<th>Quality</th>
<th>Peak Intensity, dB[A]</th>
<th>Example2</th>
<th>Inside Incubator6</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Just audible</td>
<td>10</td>
<td>Heartbeat</td>
<td></td>
<td>&lt;35 dB[A] desired for sleep</td>
</tr>
<tr>
<td>Very quiet</td>
<td>20-30</td>
<td>Whisper</td>
<td></td>
<td>&lt;50 dB[A] desired for work</td>
</tr>
<tr>
<td>Quiet</td>
<td>40</td>
<td>Average home</td>
<td>Background</td>
<td>Motor on and off</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>Light traffic</td>
<td></td>
<td>Annoyance</td>
</tr>
<tr>
<td>Moderately loud</td>
<td>60</td>
<td>Normal conversation</td>
<td>Tapping incubator with fingers</td>
<td>Hearing loss with persistent exposure</td>
</tr>
<tr>
<td>Loud</td>
<td>70</td>
<td>Vacuum cleaner</td>
<td>Bubbling in ventilator tubing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>Heavy traffic</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>Telephone ringing</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pneumatic drill</td>
<td>Closing the metal cabinet doors under the incubator</td>
<td></td>
</tr>
<tr>
<td>Very loud</td>
<td>100</td>
<td>Power mower</td>
<td>Closing solid plastic porthole</td>
<td>Pain and distress</td>
</tr>
<tr>
<td>Uncomfortably loud</td>
<td>120</td>
<td>Boom box in car</td>
<td>Dropping the head of the mattress</td>
<td></td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>Jet plane 30 m overhead</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ambient sound levels in the NICU have been reported to range from 50 to 90 dB[A] [9]. The American Academy of Pediatrics has issued a set of recommendations that requires the SPL to not exceed 45 dB[A] inside all operating incubators [1]. Because this value is not achieved, there have been multiple side effects on the infant, both short and long term. Some of these would include hearing loss, behavioral and physiological damage. To explain, a premature baby has different capabilities of processing noise around them. While an infant is still in the womb, the fetus is completely protected from high frequency sounds, (>250 Hz) through reduction by maternal tissue [7]. When the baby is born prematurely and is residing in the incubator, it does not have that protection [7]. The medical equipment noise removes any protection the baby would normally have in the womb. Results of these disturbances can also affect neurological development. Research has shown over the past few years that these high noise levels exceeding the recommended value are linked to language development [10]. Reasoning for this is that “a baby that goes full term is only exposed to lower frequency noises (<250 Hz) during the brain and sensory development stages” [10]. Some of the long – term follow up studies of preterm
infants have reported increased prevalence of speech delay, language related problems and a wide range of learning disorders that may be related to auditory sensory overload [7]. In addition to direct auditory effects of noise, noise also influences the cardiovascular system, respiratory system, sleep patterns and stress levels of neonates. When sound intensity is greater than 80 dB[A], the heart accelerates, causing a stress pattern [11]. It is now apparent that many problems arise as a result of these high noise levels.

1.2.2 Passive Noise Control & Finite Element Modeling

In general, noise control is the process of reducing attenuation of unwanted sound. Because the total energy in a form of sound does not change, there are two ways in which it can be rechanneled: reduction in the total sound power flowing away from a source or redirection of the flow of acoustic energy [3]. In this first approach, a porous material acts as a “noise sponge” by converting the sound energy into a very small amount of heat within the material [12]. The second approach prevents the transmission of noise by the introduction or the erection of some sort of barriers [12]. This paper will focus more on the first approach, producing more “universal” results, by wanting to decrease the noise inside the incubator, specifically at the baby’s ears.

There are two main techniques used for reducing unwanted sounds: Passive noise control and active noise control. Each of these techniques has their individual purpose and significance which will be briefly explained below. Passive noise control techniques would include sound insulation, vibration isolation, sound absorption or vibration damping, each applying its own method to mitigate noise [13]. Sound absorption qualifies as the most appropriate practice since it basically uses porous materials by converting the sound energy into heat within the material. One of the ways to apply this is to use passive noise control (PNC), whose purpose is to reduce sound emissions by noise-isolating materials. Some of these include insulation, silencers, damping treatments, etc. [14]. These types of techniques work best at middle and high frequencies while active noise control techniques (ANC) are more appropriate for lower frequencies [15]. As frequencies increase, the number of modes grows rapidly which is why PNC is more appropriate and why a power source is ineffective. Foams are appropriate for this application because they tend to have low thermal conductivity which does not negatively affect the heat loss from the baby to the mattress. Please refer to section 1.4 for a review on past related work using PNC and ANC techniques.

A finite element model (FEM) is a numerical technique for finding approximate solutions to boundary value problems. It uses a variety of methods to minimize an error function and produce a stable solution [16]. There are two basic steps that take into account the design of a finite element model:

1. Dividing the domain of the problem into a collection of subdomains, with each subdomain representing a set of element equations to the original problems
2. Systematically recombining all sets of element equations into a global system of equations for the final equation. Adequate solutions are reached by creating an effective model through finite element software COMSOL.
See Appendix A for additional discussion on Finite Element Analysis Theory.

By applying acoustic applications through the use of passive noise control practices, the levels heard in the Intensive Care Unit incubator should reduce noise levels to more suitable conditions.

1.3 Research Aims

The primary objective of this independent study was to analyze and design passive acoustic treatments to reduce sound pressure levels inside incubator environments using experimental and simulation techniques. The secondary aims are as follows:

- Understand current noise sources and sound pressure level distributions inside functioning incubators within a NICU hospital environment by collecting and analyzing data.
- Develop a Finite Element model of the incubator setup that predicts pressure acoustics and SPL values for poroelastic materials.
- Extend the finite element model and develop design cases using porous foam inserts inside the incubator that include a variety of shapes, sizes and locations to help reduce SPL.
- Perform numerical simulations for all designs over a target range of frequencies and compute transfer function, overall SPL for the incubator design, and SPL value at the baby’s ear.
- Develop an experimental test plan using an anechoic chamber testing environment and properly positioned microphones to measure SPL levels internal and external to an incubator.
- Perform experimental tests on an incubator comparing original mattress materials as a baseline to replacement mattresses made of sound absorbing porous materials.
- Validate the finite element model by comparison to experimental results.
- Compile and analyze all simulation data and discuss the effects of foam placement on the SPL.
- Identify best performing design features over a range of frequencies bands.
- Provide recommendations for future work.

1.4 Related Past Research on Noise Control Techniques for Incubators

Previous work has been conducted by researchers that have resulted in innovative techniques to improve the acoustic characteristics of incubators. The noise control systems are typically categorized as either passive or active and are both aimed at reducing acoustic levels by altering the “acoustic” environment in which the sound operates. Passive techniques prevent the transmission of noise by introducing mass barriers that either have high density or utilize a porous material for greater (sound) absorption. Active noise control techniques aim at reducing acoustic levels by altering the “acoustic” environment in which the sound operates, by adding additional acoustic field which can then cancel the unwanted noise. A short survey of related past research follows.

*Passive Noise Control*
Avinash Konkani and Barbara Oakley [17] examined some of the best practices and common problems in varying methods commonly applied to reduce noise levels inside intensive care units. Their work focused on passive noise control techniques to keep noise levels inside the incubator to a minimum when exposed to increasing ICU patient and staff.

Wentworth, Crawford and Edwards [18] of the Medical Device Agency performed a technical assessment of sound levels for infants in incubators. The noise levels measured within the baby compartment showed levels exceeding 60 dB[A], depending on whether the cover (canopy) was open or closed. When the plexiglass enclosure was closed, the levels were measured as 55 dB[A] ± 2 dB[A]. When open, 68 dB[A] ± 2 dB[A] was observed. They hypothesized that the 13 dB[A] difference could likely be minimized by using porous foam treatments inside the incubator as a passive noise control device.

P. Kuhn and C. Zones [19] performed an experiment on preemie infants in incubators when subjected to variations of the acoustic environment from a minimum signal-to-noise ratio threshold of 5 to 10 dB[A]. Their observational study was over a ten hour period where infants were evaluated based on their auditory sensitivity to SPL increments below 70-75 dB[A] [19]. Results showed that the infants were able to detect background noise levels when exposed to 10-15 dB[A] sound peaks during their active sleep. The adverse effects included significantly increased mean heart rate and decreased mean respiratory rates.

Zahr [20] designed small ear protections for neonates to reduce noise levels but proved to have little measureable success and could cause ear irritation for the premature infant. Kellam and Bhatia have shown decreasing of the SPL within an incubator if an open cell melamine foam panel is used to cover the plastic walls of the canopy [12]. However, the results are only satisfactory in the high frequency range.

A. Johnson tested the performance of foam to reduce the noise inside an incubator and examined neonatal response behaviors to changes in the environmental noise under three different study conditions [21]. These included a pre-study neonate in an incubator, the neonate in an incubator with a 5x5x1 inch acoustical foam pieces placed in each of four corners, and a post-study recovery of the neonate in the incubator with all of the foam removed. Results showed a significant treatment effect of foam on decreasing environmental noise measurements inside the incubator as well as significantly changed neonatal state response behaviors. The work performed in this thesis considers corner foam treatments as well as several other shapes and sizes.

**Active Noise Control**

There has also been progress in using active noise control (ANC) techniques to quiet environments for newborns inside the incubators and decreasing the risk of health impairment and disability [22]. Two basic approaches for ANC are Active Noise Cancellation and Active Structural-Acoustic Control (ASAC) [12]. These differ in that Active Noise Cancellation uses a control system that drives a loudspeaker to produce a sound field that is the mirror-image of the unwanted sound but is out of phase. Contrastingly, in ASAC the actuators are represented by...
vibration sources which can modify the way in which the structure vibrates, hence changing the way it radiates [12].

Nicola Cau studied problems associated with infant’s sleep-wake cycle when noise levels are too high inside an incubator [12]. In this work, a finite element method model for a generic incubator was developed that included acoustics as well as fluidodynamics and thermodynamics. The acoustics model incorporated internal and external noise sources, and was used to calculate modal shapes and resonances of the acoustic cavity. An ANC system was developed to reduce the sound pressure level within the incubator and used FE modeling that predicted sound pressure levels throughout the incubator, ranging in levels from 65 dB to 75 dB (at 250 Hz). Passive noise control techniques were also implemented but showed very little reduction in dB level.

ANC methods are also used by Dr. Sen-Maw Kuo utilizing an anti-noise signal of the same magnitude and opposite phase to cancel unwanted noise [23]. He notes that preterm infants’ auditory, visual and central nervous systems are the last to mature, occurring while in the incubator and that high noise levels in Neo-natal ICUs and inside incubators are harmful for the development of these babies. The reported noise levels were shown to be above the recommended levels.

Another experiment that used ANC algorithms for infant incubators to reduce recorded NICU noise was performed by Lichuan Liu where her research has shown 10-15% of newborns spend time in the NICU and high noise levels in the infant incubator result in numerous adverse health effects [22]. Her experiments included using actual recorded NICU noise samples and found that an average reduction of 13 dB and 17 dB are obtained by using single-channel and multiple-channel ANC systems.

1.5 Definition of Terms

The following terms are relevant for the current research discussion in addition to possible future work.

_Anechoic chamber_ — a room designed to absorb reflections of either sound or electromagnetic waves and is insulated from exterior sources of noise. All sound energy will be traveling away from the source with minimal reflection down to a certain frequency [24].

_Broadband sound level_ – sounds that are heard on a daily basis in an environment which are composed of a combination of many frequency components [25].

_Tone_ – a sound that can be recognized by its regularity of vibration at a single frequency. The tone of the lowest frequency is called the fundamental while the rest are overtones. When these overtones are multiples of the fundamental, they are entitled the second, third etc. harmonic [26].

_Mode_ – discrete function to a solution of the wave equation. Room modes are resonances that exist in a room when the room is excited by an acoustic source such as a loudspeaker and are represented by a low frequency standing wave. This is the case for the anechoic chamber tests [27].
Tyvek – an acoustically transparent micro-porous material that is very strong and allows water vapor to pass through but not liquid water; mostly composed of high – density polyethylene fibers and is resistant to tearing [28].

Porous materials – a material that is defined by its porosity, permeability or electrical conductivity. Foam has a high porosity and will absorb sound well but will not isolate the sound [29].

Ventilator pump/mechanical ventilator – breathing machine that delivers warmed and humidified air to a baby’s lungs. This ventilator temporarily breathes for them while their lungs recover [30].

C-PAP – air is delivered to a baby’s lungs through these small tubes in the baby’s nose or through a tube that has been inserted into his/hers windpipe. These tubes attach to the mechanical ventilator [31].

*Frequency response function (FRF)/Transfer function (TF) – quantitative measure of the output spectrum of a system in response to a stimulus and is used to characterize the dynamics of the system; a mathematical representation of the relationship between the input and output of a system [32].

Bandwidth – the difference between the upper and lower frequencies in a continuous set of frequencies, measured in Hertz; sometimes referred to as the 3-dB bandwidth which is the frequency range within which the spectral density is above half its maximum value [33].

*Fast Fourier Transform (FFT) – algorithm to compute the Discrete Fourier Transform (DFT) and its inverse; transforms a time domain set of data to a frequency domain data set [34].

Acoustic impedance – a frequency dependent value that indicates how much sound pressure is generated by the vibration of molecules of a particular acoustic medium [35].

Reflection – change in direction of a wavefront at an interface between two different media where the wavefront returns in the medium from which it originated [36].

*1/3rd Octave Transfer Function – when not enough information can be extracted from a noise set of data, the frequency range of data can be split up into sections, or bands. These bands usually have a bandwidth of one octave or one third octave where an octave band is a frequency band where the highest frequency is twice the lowest frequency. For this specific case, the bands are split up into bandwidths of one third octave [37].

Resonance – motion described by normal modes driven at their resonance frequency [38].

*See Appendix B Digital Data Acquisition and Spectral Analysis.

1.6 Thesis Outline

Throughout this paper, chapters are organized according to their functional content. Chapter 1 discusses an introduction to the problem statement, literature review and the project’s significance. Related past research on noise control techniques for incubators and definitions and explanations of important terms used are defined as well. Chapter 2 contains preliminary studies involving hospital experiments performed in a NICU. Chapters 3, 4, and 5 focus on FE methodology and prestudies. Chapter 5 discusses the FE results, discussion and conclusions regarding the FE modeling. Chapter 6 begins the anechoic chamber testing and chapter 7 covers the results, discussion and conclusions for this experimental testing. Chapter 8 then discusses the overall summary and conclusions. The thesis is concluded with Chapter 9 where future research applications are discussed.
Chapter 2. NICU Environment Preliminary Studies

2.1 Hospital NICU Experiment

In order to understand the common problems associated with elevated noise levels inside intensive care units, an experimental test program was prepared and performed at the NICU at the Children’s Hospital of the King’s Daughter’s in Norfolk, VA. An isolated room with one incubator with all the supporting equipment for operation was provided to reproduce a real-world environment for testing and data collection. The test setup and conditions follows.

2.2 Test Setup and Conditions

Figure 1 below shows the test setup including Datex Ohmeda Giraffe Omnibed incubator, baby doll subject, and testing equipment. There were four microphones used in this experiment. Separate microphones were placed in the baby’s right and left ears and a third microphone was located one inch facing the baby’s left ear as shown in Figure 2A. The forth microphone was used as an external reference and had three different locations relative to the ventilator pump (seven inch and four inch distances) and computer fan (five inch distance) depending on the type of test being performed.

For most neonates in the Intensive Care Unit, a tube is inserted into the baby’s mouth that helps them breathe. The tube is connected to a ventilator pump located on the outside the incubator end held by into place by the plexiglass enclosure, as seen in Figure 1. Since an artificial baby doll was used for the tests, the tube was placed underneath the incubator blanket located below the doll’s head, see Figure 2A. Another set of tests included artificial lungs attached to the tube to realistically show the acoustical termination of the oxygen tube as shown in Figure 2B. Note
that these tests were considered since artificial lungs are may be included in the incubator environment for babies that require maximum medical care [39].

Figure 2. A) Baby doll position in incubator and B) artificial lung placement

Figure 3 shows the setup for two additional tests that were performed with the ventilator pump located inside the incubator and near the infant’s head to see the effect of increase noise levels in the vicinity of the head region.

Figure 3. Visual of pump when inside incubator in NICU
A variety of tests were performed in this environment for the purpose of replicating an authentic NICU environment as realistically as possible. The two ventilator pump pressures and frequencies chosen for these experiments were provided by the NICU staff based on the baby’s health condition. The low pressure value corresponded to 24 Pascal with a rate of 420 cycles/min (7 Hz) while the high pressure was 50 Pascal at 500 cycles/min (8.33 Hz). During all tests, the incubator fan was running and circulating warm air. Furthermore, all NICU staff in close proximity were quiet to prevent any unnecessary noise. Measurements were taken for 60 seconds and the top of the incubator was closed for all tests. The matrix of test cases is described below in table 2.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Low/High Pressure</th>
<th>External Reference Microphone Location (next to ventilator pump, away from ventilator pump, near computer fan)</th>
<th>Tube or Tube &amp; Artificial Lungs</th>
<th>Pump Location: inside or outside incubator</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low</td>
<td>Away from pump</td>
<td>Tube</td>
<td>Outside</td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
<td>Away from pump</td>
<td>Tube</td>
<td>Outside</td>
</tr>
<tr>
<td>3</td>
<td>High</td>
<td>Away from pump</td>
<td>Tube</td>
<td>Outside</td>
</tr>
<tr>
<td>4</td>
<td>High</td>
<td>Away from pump</td>
<td>Tube + Lungs</td>
<td>Outside</td>
</tr>
<tr>
<td>5</td>
<td>Low</td>
<td>Away from pump</td>
<td>Tube + Lungs</td>
<td>Outside</td>
</tr>
<tr>
<td>6</td>
<td>Low</td>
<td>Behind pump</td>
<td>Tube + Lungs</td>
<td>Outside</td>
</tr>
<tr>
<td>7</td>
<td>High</td>
<td>Behind pump</td>
<td>Tube + Lungs</td>
<td>Outside</td>
</tr>
<tr>
<td>8</td>
<td>High</td>
<td>Near fan</td>
<td>Tube + Lungs</td>
<td>Outside</td>
</tr>
<tr>
<td>9</td>
<td>High</td>
<td>Behind pump</td>
<td>Tube + Lungs</td>
<td>Inside</td>
</tr>
<tr>
<td>10</td>
<td>High</td>
<td>Behind pump</td>
<td>Tube</td>
<td>Inside</td>
</tr>
</tbody>
</table>

2.3 Experimental Procedure

Figure 4 provides a schematic of the data collection path. Recall from above that three microphones, two for the baby ears and one additional internal microphone were all located inside the incubator. These are symbolically illustrated in the incubator box below. The external microphone was positioned at different locations relative to the ventilator pump A and computer fan B. All four microphones were connected to the DAQ using BNC. The output of the DAQ was connected to the laptop. For further information on Data Acquisition systems, refer to Appendix B, Digital Data Acquisition and Spectral Analysis.
The parameters that define the communication link between the DAQ and MATLAB and control the data acquisition process are defined using a Graphical User Interface tool (developed in MATLAB) as shown in Figure 5.

![Figure 5](image.png)

**Figure 5.** Visual that represents how data was collected

The input parameters shown in Figure 5 above are used during post processing. A summary of the values are provided below in Table 3.

Table 3. Display of parameter inputs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of channels</td>
<td>4</td>
</tr>
<tr>
<td>Sampling Frequency</td>
<td>51200 samples/second</td>
</tr>
<tr>
<td>Measurement Time</td>
<td>60 seconds</td>
</tr>
<tr>
<td>NFFT</td>
<td>65536 samples</td>
</tr>
<tr>
<td>Overlap samples</td>
<td>16384 samples</td>
</tr>
<tr>
<td>Reference channel</td>
<td>External microphone</td>
</tr>
<tr>
<td>Frequency Resolution</td>
<td>1 Hz</td>
</tr>
</tbody>
</table>
During the 60 second data collection period, the data for four graphs will be calculated and displayed as a function of frequency as shown above including time domain data, power spectral density, transfer function (TF) magnitude, and coherence.

Additional parameters were required to support post processing the hospital test data including channel gain and calibration factors. Those values were as follows: channels 1 and 2 had 0 dB gain; channels 3 and 4 had 40 dB gain. The microphone calibration factors were 1.1971 V/Pa, 1.1974 V/Pa, 0.0125 V/Pa and 0.0125 V/Pa for the baby right ear, baby left ear, internal microphone and external microphone, respectively.

2.4 Results and Discussions

For all test cases, the sound pressure levels were computed at the internal microphone and right and left microphones in the baby ears. Results are for the following

Comparison of Tube vs. Tube & Lungs

The first set of results presented in Figure 6 shows the effects of the artificial lungs on the SPL due to acoustic disturbances, i.e. that they generate noise by vibrating and disturbing the acoustic flow. This result corresponds to Tests 1 and 5 from Table 2 above.

![Figure 6](image)

**Figure 6.** Broadband SPL (solid line) and cumulative SPL (dotted line) at the internal microphone for the low pressure tube (top graph) and low pressure tube plus lungs (bottom graph)

In Figure 6 above, tones occurring from 30 Hz to 100 Hz represent the pulsation due to the ventilator pump. Comparing the two plots, there are similar SPL values in the 30-100 Hz frequency range. The maximum SPL for both curves is approximately 45 dB[A] and occurs around 50 Hz. Other tones are noticed around 250 Hz and could be representative of fan noise inside the ventilator pump. The second curve shown on each plot is a cumulative sum all of the
dB[A] levels over the complete frequency range. Note that the maximum value for this curve is provided on the right hand side margin of each plot, corresponding to 59 dB[A] and 56.9 dB[A] for the tube only and tube and lung, respectively.

Similar to Figure 6, Figure 7 below shows the sound pressure levels for the same cases measured at the external microphone.

Figure 7. Broadband SPL (solid line) and cumulative SPL (dotted line) at the external microphone for the low pressure tube (top graph) and low pressure tube plus lungs (bottom graph)

In Figure 7 above, the first several tones represent a pulsation due to the ventilator pump in the range 0 to 20 dB[A] from 30 to 100 Hz. The maximum SPL for both curves is approximately 50 dB[A] and occurs around 475 Hz. Additional tones that appear around 160 Hz for both cases could be representative of a fan noise from within the ventilator pump. The tones occurring around 700 Hz are potentially background noise from outside sources or possibly the incubator fan. The two values of 54.7 dB[A] and 54.3 dB[A] are the cumulative sound pressure levels at the end of the frequency range for the tube case and tube plus lungs case, respectively. This shows that at the internal microphone, the artificial lungs contribute very little to the sound pressure level measured at the external microphone.
Figure 8 below shows the SPL measured at the baby’s right and left ear microphones. Note the similarity in tonal spacing from 30Hz to 100Hz for all results. This frequency spacing coincides with the pulsation frequency of the ventilator pump for each case and indicates the tones are radiating from the ventilator pump and the oxygen supply tube.

These tones have dB[A] levels ranging from 30 to 45 dB[A], reaching a maximum of 50 Hz. Individual tones starting around 200 Hz in increments of 100 Hz are representative of fan tones from either the incubator environment heating system or nearby equipment fans. Broadband fan noise due to air flow also contributes to the spectrum. The cumulative SPL for the entire frequency range reaches values of 59 dB[A] and 57 dB[A] for the tube and tube plus lungs, respectively. As expected, both sets of SPL values should be relatively the same for the right and left baby’s ears.

Discussion

Table 4 below summarizes the results for this test and shows that the placement of the artificial lungs affects the measured SPL at all microphones, with the greatest difference at the baby ear locations.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Tube or Tube &amp; Lungs</th>
<th>Microphone</th>
<th>Cumulative SPL dB[A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tube</td>
<td>Internal</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>External</td>
<td>54.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Baby Ears (Right, Left)</td>
<td>58.6; 58.5</td>
</tr>
<tr>
<td>5</td>
<td>Tube &amp; Lungs</td>
<td>Internal</td>
<td>56.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>External</td>
<td>54.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Baby Ears (Right, Left)</td>
<td>56.9; 56.2</td>
</tr>
</tbody>
</table>
Comparison of External Reference Microphone Location

The next set of results determines whether the location of the external reference microphone affects the sound pressure levels measured at the internal microphone. The results are compared by showing the SPL at the internal microphone. The coherence plot between the internal and external microphone for each are also displayed.

The first result shown in Figure 9 below compares the SPL measured at the reference microphone located behind the pump and near the computer fan. High pressure pump conditions were used corresponding to cases 7 and 8 from Table 3 above.

![Figure 9](image)

**Figure 9.** Broadband SPL (solid line) and cumulative SPL (dotted line) at the internal microphone for the high pressure with external microphone behind the pump (top graph) and high pressure with external microphone near the computer fan (bottom graph)

Similar to prior results, the tones observed from 20Hz to 100 Hz represent the pulsation due to the ventilator. Both results have similar dB[A] values throughout the frequency range plotted. The maximum SPL is 45 dB[A] for both curves and occurs at approximately 60 Hz. The additional tones from 200 Hz – 300 Hz could be representative of a fan noise inside the ventilator pump. The tones in the 500-1500 Hz are possibly background noise. The two values of 59.6 dB[A] and 59.3 dB[A] are the cumulative sound pressure levels in the frequency range. Based on the similarity of these results, the internal SPL value was not affected by external microphone location.
Figure 10 shows the coherence between the internal microphone and baby left ear microphone. Recall that coherence is a function of frequency and is an indicator on how well the input corresponds to the output at each frequency [40].

![Coherence Graph](image)

**Figure 10.** Coherence between the internal microphone and baby left ear microphone for the high pressure with external microphone behind the pump (top graph) and high pressure with external microphone near the computer fan (bottom graph).

From Figure 10, a coherence of one is observed for frequencies up to 150 Hz, demonstrating a strong correlation between the two microphones. As a result, either of the two microphones used in this case can be used as a reference. The internal microphone is not a good replacement for the baby left ear microphone for frequencies greater than 250 Hz.
Figure 11 below shows the SPL measured at the internal microphone comparing cases 5 and 6.

![Figure 11](image)

**Figure 11.** Broadband SPL (solid line) and cumulative SPL (dotted line) at the internal microphone for the low pressure with external microphone away from the pump (top graph) and low pressure with external microphone behind the pump (bottom graph).

As can be seen above, the tones observed from 20Hz to 100 Hz represent the pulsation due to the ventilator. Both results have similar dB[A] values throughout the frequency range plotted. The maximum SPL is 45 dB[A] for both curves and occurs at approximately 55 Hz. The other tones in the 250 Hz – 450 Hz could be from background noise sources. The two values of 56.9 dB[A] and 57.2 dB[A] are the cumulative SPL for the external microphone away from the pump and behind the pump, respectively. Note the (slightly) higher SPL at the external microphone when the microphone is positioned behind the pump which is probably due to it higher levels of measured pump noise.
Figure 12 shows the coherence between the internal microphone and the baby left ear microphone for cases 5 and 6.

![Coherence plots](image)

**Figure 12.** Coherence between the internal microphone and baby left ear microphone for the low pressure with external microphone away from the pump (top graph) and low pressure with external microphone behind the pump (bottom graph).

Figure 12 shows very good coherence for frequencies up to 150 Hz. For frequencies above 200 Hz the coherence becomes weaker.
Figure 13 compares cases 4 and 8 from table 8. In this study, the external microphone is located away from the pump and near the computer fan.

Looking at Figure 13 above, the first few tones representing the pulsation due to the ventilator pump have similar dB[A] values up to 60 Hz and then exhibit small differences up to 140 Hz. When the external microphone is away from the pump (top graph), the maximum tone occurs at 50 Hz as opposed to 100 Hz when the external microphone is located near the fan. The additional tones observed at frequencies greater than 200 Hz could be coming from background noise.
Figure 14 shows the coherence between the internal microphone and baby left ear microphone for case 4 and 8.

![Coherence between the internal microphone and baby left ear microphone for case 4 and 8.](image)

**Figure 14.** Coherence between the internal microphone and baby left ear microphone for the low pressure with external microphone away the pump (top graph) and low pressure with external microphone near the computer fan (bottom graph)

From Figure 14, high coherence is observed for frequencies up to 150 Hz. demonstrating a strong correlation between the two microphones. Above 300 Hz the coherence drops significantly.

**Discussion**

Table 5 below summarizes the results for this test. As can be seen for the high pressure case, the fan produced slightly less sound pressure levels by only 0.5 dB[A] for case 1 and 1.5 dB[A] for case 3. This result demonstrates very low noise contribution into the incubator system. Additionally it was shown that was very good coherence for all three cases in the frequency range from 30 Hz to 150 Hz.

<table>
<thead>
<tr>
<th>Case</th>
<th>Test Number</th>
<th>Low/High Pressure</th>
<th>Ext. Ref. Microphone Location</th>
<th>Microphone</th>
<th>Cumulative SPL dB[A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>High</td>
<td>Behind Pump</td>
<td>Internal</td>
<td>59.6</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td></td>
<td>Near Fan</td>
<td></td>
<td>59.3</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>Low</td>
<td>Away from Pump</td>
<td></td>
<td>56.9</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
<td>Behind Pump</td>
<td></td>
<td>57.2</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
<td>High</td>
<td>Away from Pump</td>
<td></td>
<td>60.5</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td></td>
<td>Near Fan</td>
<td></td>
<td>59.3</td>
</tr>
</tbody>
</table>
Comparison of High & Low Ventilator Pressures

The next set of plots shows the effects of ventilator pressure on sound pressure levels. The tests compare the results for cases 4 and 5 where the microphone is located away from the pump and both the tube and lungs are used. The results are compared by showing the SPL at the internal microphone. The coherence plot between the internal and external microphone for each are also displayed.

The first result shown in Figure 15 below compares the SPL measured at the internal microphone for low and high ventilator pressures.

![Figure 15. Broadband SPL (solid line) and cumulative SPL (dotted line) at the internal microphone for the low (top graph) and high pressure (bottom graph)](image)

From the figure above, the first few tones representing the pulsation due to the ventilator pump have similar dB[A] values up to 100 Hz at which point the spacing between tones increases slightly for the high pressure case. The maximum SPL is 45 dB[A] for both curves and occurs at approximately 50 Hz. The overall SPL at frequencies greater than 200 Hz are higher for the high pressure ventilator case.
Figure 16 below shows the SPL measured at the external microphone located away from the pump for the same case as above.

![Figure 16. Broadband SPL (solid line) and cumulative SPL (dotted line) at the external microphone for the low (top graph) and high pressure (bottom graph)](image)

From the figure above, the tones observed from 20Hz to 180 Hz represent the pulsation due to the ventilator pump and have nearly identical dB[A] values throughout this frequency range. The maximum SPL is 50 dB[A] for both curves and occurs at approximately 475 Hz. The SPL values above 200 Hz are very similar. Note that the cumulative sound pressure levels of 54.3 dB[A] and 54.6 dB[A] are almost equivalent confirming that the two different ventilator pressures have minimal influence on the SPL measured by the external microphone.
Figure 17 below shows the sound pressure levels measured at the microphones in the baby’s right and left ears for the low and high pressure cases.

![Figure 17](image)

**Figure 17.** Broadband SPL (solid line) and cumulative SPL (dotted line) at the baby’s right and left ears for the low (top graph) and high pressure (bottom graph).

From the above figure, the tones up to 100 Hz are separated by a constant frequency spacing of about 5.5 Hz for the low pressure and 6 Hz for the high pressure. This frequency spacing coincides with the pulsation frequency of the ventilator pump. These tones have dB[A] levels ranging from 30 to 45 dB[A], reaching a maximum at 50 Hz. The tones in the 200 Hz – 400 Hz range are possibly background fan tones. Broadband fan noise due to air flow also contributes to the spectrum at higher frequencies. The cumulative SPL for the entire frequency range reaches 57 dB[A] and 60 dB[A] for low pressure and high pressure, respectively.

**Discussion**

Table 6 below summarizes the results for this test. As can be seen and as expected, the high pressure ventilator produced higher SPL values at all microphone locations. This result is important in that it shows an opportunity to add passive noise treatments to reduce the noise from the ventilator pump.

**Table 6. Results comparing high and low ventilator pressures**

<table>
<thead>
<tr>
<th>Test Number</th>
<th>High/Low Pressure</th>
<th>Microphone</th>
<th>Cumulative SPL dB[A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>High</td>
<td>Internal</td>
<td>60.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>External</td>
<td>54.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Baby Ears (Right, Left)</td>
<td>60.4; 59.8</td>
</tr>
<tr>
<td>5</td>
<td>Low</td>
<td>Internal</td>
<td>56.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>External</td>
<td>54.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Baby Ears (Right, Left)</td>
<td>56.9; 56.2</td>
</tr>
</tbody>
</table>
Comparison of Pump Location

The next set of plots display the results comparing the ventilator pump location, case 7 versus 9 from Table 3 for high pressure. Note the external microphone is located behind the pump and both the tube and lungs are part of the experimental setup.

Figure 18 below shows the SPL measured at the internal microphone comparing cases 7 and 9.

![Figure 18. Broadband SPL (solid line) and cumulative SPL (dotted line) at the internal microphone for the high pressure case when the ventilator pump was located outside the incubator (top graph) and inside the incubator (bottom graph)](image)

The first few tones representing the pulsation from the ventilator pump have similar dB[A] values up to 100 Hz. With the pump located on the outside of the incubator, the maximum SPL value is 42 dB[A] and occurs at 100 Hz. When the pump is located inside the incubator, this sound pressure level maximum is 50 dB[A], which is expected when the pump is located inside the incubator. The tones higher than 200 Hz are possibly a result from background fan noise. Looking at the results, these tones cover a larger range of dB[A] values for when the pump is located inside the incubator.
Figure 19 below shows the SPL measured at the external microphone comparing cases 7 and 9.

![Figure 19](image)

**Figure 19.** Broadband SPL (solid line) and cumulative SPL (dotted line) at the external microphone for the high pressure case when the ventilator pump was located outside the incubator (top graph) and inside the incubator (bottom graph).

From Figure 19 above, the tones observed from 20Hz to 150 Hz represent the pulsation due to the ventilator pump. When the pump is inside the incubator (lower figure), these tones are much less noticeable and have lower dB[A] values in the same frequency range. For the externally mounted ventilator, the maximum SPL value of 50 dB[A] occurs at 140 Hz as compared to a SPL value of 60 dB[A] at 475 Hz when mounted inside. The tones for higher frequencies could be from background noise sources. The higher cumulative sound pressure level value of 73.2 dB[A] for the externally mounted ventilator is expected when considering the location of the external microphone.
Figure 20 below shows the SPL measured at the baby’s right and left ears.

![Figure 20](image)

**Figure 20.** Broadband SPL (solid line) and cumulative SPL (dotted line) at the baby’s right and left ears for the high pressure case when the ventilator pump was located outside the incubator (top graph) and inside the incubator (bottom graph).

From the above figure, the tones up to 100 Hz are separated by a constant frequency spacing of about 5.5 Hz for the low pressure and 6 Hz for the high pressure. This frequency spacing coincides with the pulsation frequency of the ventilator pump. These tones have dB[A] levels ranging from 25 to 45 dB[A], reaching a maximum at 50 Hz. The tones in the 200 Hz – 400 Hz range are possibly background fan tones. Broadband fan noise due to air flow also contributes to the spectrum at higher frequencies. As can be seen from the cumulative SPL curve there is little variation in the cumulative dB[A] level regardless of the pump location.

**Discussion**

The location of the ventilator pump has become a primary contributing factor in affecting the dB level inside an incubator. The results show that the main contributor to noise levels at low frequencies is the pump location. Table 7 provides a summary of the cumulative SPL levels. Note that the external microphone measured an SPL value about 10 dB[A] lower when the pump is on the inside, which is expected, demonstrating the sensitivity of noise level based on pump location.

**Table 7. Results comparing pump location**

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Pump Location</th>
<th>Microphone</th>
<th>Cumulative SPL dB[A]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Internal</td>
<td>58.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>External</td>
<td>73.2</td>
</tr>
<tr>
<td>7</td>
<td>Outside</td>
<td>Baby Ears (Right, Left)</td>
<td>58.8; 59.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Internal</td>
<td>59.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>External</td>
<td>64.1</td>
</tr>
<tr>
<td>9</td>
<td>Inside</td>
<td>Baby Ears (Right, Left)</td>
<td>59.8; 58.8</td>
</tr>
</tbody>
</table>
2.5 Conclusions

Successful experiments were performed at the hospital NICU to determine the major sound contributors in incubator environment. Based on the results presented above, the following conclusions are drawn.

- The ventilator pump is the most substantial contributor to the overall SPL in the frequency range up to 150 Hz.
- The sound levels heard were quietest at the internal microphone when the external microphone was located near the computer fan, concluding that the fan is not a large contributor to noise levels.
- When comparing high and low pressures of the ventilator pump, the levels heard at all microphones were lower in SPL for the lower pressure cases.
- When the ventilator pump is located on the outside of the incubator the noise levels measured inside in incubator are only slightly quieter by less than 1 dB.
- Although not expected, the results also showed that the tube with artificial lungs had a quieter sound level as compared to the tube alone.
Chapter 3. Finite Element Methodology

3.1 Introduction

Finite Element (FE) analysis is a method of analysis in which the field equations of mathematical physics are approximated over simple regions and then assembled together so that the equilibrium or continuity is satisfied at all nodes that constitute a domain [41]. Several commercially available tools are currently used to perform these analyses. In this research, all FE models were created and numerical investigations performed using COMSOL. COMSOL was selected because of its extensive multiphysics modeling capability, particularly in the area of computational acoustics for poroelastic materials. There are several types of physics modules available in COMSOL including electrical, mechanical, fluid, and chemical for modeling and analyzing complex designs. Many of these modules are compatible with one another to allow for multidisciplinary design analyses for real world cases with user friendly interfaces to accommodate ease of model setup. In this research, the acoustics module is used extensively for analyzing designs involving devices that produce, measure and track acoustic waves [42]. For more details on FE modeling analysis theory using COMSOL, see Appendix B Finite Element Analysis Theory.

The following sections provide a high level summary on using COMSOL to analyze and design passive noise control treatments to quiet incubator environments.

3.2 Baseline Geometry Model

The main components for the geometry modeled in this work include an anechoic chamber, Drager 8000 SC incubator, baby doll, mattresses, and various foam shapes and sizes. Precisely scaled models of these components were constructed in COMSOL. All foam thicknesses and shapes were accurately created and located in the incubator depending on the design features. Due to total number size of the FE models, geometric symmetry was assumed allowing the computational domains to be reduced in half.

The incubator was modeled using in COMSOL as seen in Figure 21. The original incubator had a rectangular shape with a slanted hooded canopy. This slanted top was not considered in order to preserve the symmetry of the model. The incubator dimensions were 0.7801 m x 0.42815 m x 0.4736 m and had a thickness of 0.02 m by 0.03 m 0.02 m throughout. This accounted for the plexiglass material. The mattress that supports the infant is shown in part B. The mattress thickness was an independent variable in the testing process, ranging between 0.0254 m and 0.1016 m (1 and 4 inches) with a length and width of 0.6416 m and 0.3493 m respectively. To create an infant likeness, two ellipsoids, one for the baby body and one for the head were produced. The sizes of these ellipsoids were based off the doll used in the chamber. The remainder of the infant’s body was not designed since the area of focus is near the baby’s ears. A cube measuring 0.1143 meters on each side represented the control volume and was created to enclose the baby’s head and neck where sound pressure levels were computed.
Next, the outer domain surrounding the incubator was constructed using a spherically shaped perfectly matched layer (PML) modeling approach. This is a powerful technique for efficiently modeling outer boundaries.

A) Basic model design  
B) Close up view of incubator

**Figure 21.** COMSOL Geometry model of Incubator Environment

### 3.3 Passive Noise Control Designs

After the basic parts are modeled, additional foam designs which included new geometries, sizes and positions, were created. These foam geometries were only placed inside the incubator. Additional improvement to reduce noise in the nearby surroundings such as inserting ceiling absorbing panels were plausible, but for this paper, the focus was primarily on the addition of foam in different locations inside the incubator.

When deciding on locations for the foam inside the incubator, some general restrictions disallowed foam to be in certain positions and areas for convenience. This included not placing large foam on the incubator sides that provide access for medical attention or other invention. Furthermore, foam was not placed on all sides of the incubator as it would impede any visibility. The location of the foam impacts its absorption rate within the incubator. Absorption can be increased by ensuring that there was an air gap between the foam and the walls. Ensuring the air gap exposes a larger surface area of the foam to incident waves increases the amount of absorption [43]. Therefore there were some designs where there was minimal contact to the surface of the interior incubator walls. For the previous reasons and explanations stated, the following designs were considered and created.
**Case A: Tetrahedron Treatment**
For the first addition of foam, a tetrahedron shaped piece that fits in 8 corners of the incubator was generated. This can be seen in figure 22 below. To not create maneuverability problems, these pieces placed in upper corner of the front side of the incubator would be attached to the side and not the opening portion. When considering this design, versatility was a requirement such that all designs have the option to be applied to any variation of incubator design. This tetrahedron shape had dimensions of 0.0996 m x 0.0915 m x 0.1318 m and prevented any physical location inconvenience. Furthermore, the foam was not focused on one area of the incubator but instead covered multiple interior corners. This strategy was hypothesized to create the most convenient, obtrusive and easiest to install design. If multiple sound sources from different areas were coming in contact with the incubator, foam is present at more than one spot to absorb the sound. See figure 22 below for geometric view.

![Image of Tetrahedron Treatment](image)

**Figure 22. Geometric view of Case A**

**Case B: Prism Edge Treatment**
For this design, a vertical box was created that was cut in half diagonally in order to appear as an extruded isosceles triangle. See figure 23 below for a visual of Case B design. This had the same height as the incubator and was 0.0889 meters in width and depth. It was placed also in the corners inside the incubator except only in the back left and right corners to avoid inconvenience of the nurses. This design was created to see if improvement in foam volume from case A made a reasonable improvement in sound absorption. See figure 23 below for geometric view.
Case C: Vertical Hanging Blocks Treatment-(1x5)
The next case run involved the addition of foam hanging down from the inside top of the incubator. Figure 24 below displays Case C design. The first of two versions of this test were performed, with the first having five pieces of foam, all rectangular prism appearances; three of them being 0.0508 m x 0.0508 m x 0.2032 m and the other two 0.0508 m x 0.0508 m x 0.1524 m, hanging with altering dimensions. These were centered both in the x and y direction with respect to the width and depth of the incubator respectively. Because foam absorbs more sound when in less direct contact with a solid surface, this should prove to be an effective design since only one boundary of each piece hanging was in contact with the incubator surface. This design also should reduce SPL because it was in direct contact with the plane wave once it entered the incubator which should allow for a greater effect in sound reduction. See figure 24 below for geometric view.

Case D: Vertical Hanging Blocks Treatment-(3x5)
This was the second version of the foam hanging from the inside top, Case D. This treatment design is seen in figure 25 below. In this design the same appearance of rectangular prisms were shown with the addition of two more rows of the same size. These pieces were also centered as a group along the inside top of the incubator. The purpose of this design was to analyze the simple effect of adding more area of foam, but in the same general location. The results for this design
should show an improvement when compared to Case C due to the increased amount of foam. See figure 25 below for geometric view.

![Figure 25. Geometric view of Case D](image)

**Case E: Above Head Block Treatment**
A fifth design, seen in figure 26 below, that was executed included a 0.2032 m by 0.1143 m by 0.0508 m piece of foam horizontally above the baby’s head attached to the side wall of the incubator. Even though little foam is used in this trial, having foam placed very close to the infant’s head could absorb just enough sound that the infant will hear less noise. See figure 26 below for geometric view.

![Figure 26. Geometric view of Case E](image)

**Case F: Horizontal Hanging Blocks Treatment-(3x5)**
This design had a similar layout to the ones for cases C and D except the rectangular prisms of foam were on the back inside of the incubator; when sticking out horizontally they were perpendicular to the length of the baby. See figure 27 below for a representation. These rectangular prisms all were 0.0508 meters for the width and depth and had a height of 0.2032 meters. The location of these pieces should provide more of a difference in sound reduction throughout the incubator as opposed to on one end of the incubator due to the wide placement of the foam. See figure 27 below for geometric view.
Case G: Vertical Hanging Blocks Treatment-(1x3)

For this design, a similar set up was created to case C except the width of the foam pieces were the same size as the width of the incubator. See figure 28 below for a visual. Three pieces of foam with width 0.42815 meters were positioned equally widthwise in the incubator hanging from the top down. The significance of this design was to show that since the foam was positioned parallel to the incoming wave and covering the entire width of the incubator it would absorb most of the sound before it gets to the infant. See figure 28 below for geometric view.

Case H: Top Covered Angle Treatment

This last design had a 0.0254 meter thick piece of foam that was the same width as the incubator but was positioned at an angle so that it was connected to the interior top of the incubator and was hanging at a 120° to the left where it connected with the left side of the incubator. See figure 29 below. This design was unlike the others in that it was placed at an angle other than 90° or 180° which would have a different impact on how much sound it absorbed. When these pieces connected to the side wall of the incubator, they were about halfway down so that viewers could still see the infant. See figure 29 below for geometric view.
Before creating additional foam geometries and placing them inside the modeled incubator, validation plots must confirm that the model is designed correctly. These plots will consist of the comparison between experimental tests in the anechoic chamber to those in the simulation model. The selections of tests that are used in comparison were the minimum and maximum thickness for polyimide, melamine and polyurethane, as it is assumed that the remaining thicknesses in between these values are designed correctly. A comparison with no mattress as well as the original mattress with the plastic covering is matched as well. A representation of these tests are seen below in table 8.

**Table 8. Tests for validation plots**

<table>
<thead>
<tr>
<th>Mattress Material</th>
<th>Thickness (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Mattress</td>
<td>---</td>
</tr>
<tr>
<td>Original</td>
<td>1</td>
</tr>
<tr>
<td>Polyimide</td>
<td>1</td>
</tr>
<tr>
<td>Polyimide</td>
<td>3</td>
</tr>
<tr>
<td>Melamine</td>
<td>2</td>
</tr>
<tr>
<td>Melamine</td>
<td>4</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>1</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>4</td>
</tr>
</tbody>
</table>

The results from the simulation model with the previous defined tests will represent how the individual new foam mattresses affect the sound pressure level inside the incubator and inside the control volume.

Seen below in table 9 are the remaining tests that will be run in the simulation model. These include the original mattress and the maximum thickness of the polyimide, melamine and polyurethane foam with the addition of each case that was previously discussed. These cases are not performed without a mattress because in general, there will always be a mattress in the incubator so it is unnecessary to perform such tests.
Table 9. Display of FE modeling tests

<table>
<thead>
<tr>
<th>Case</th>
<th>Mattress Material</th>
<th>Thickness (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Original</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Polyimide</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Melamine</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Polyurethane</td>
<td>4</td>
</tr>
<tr>
<td>B</td>
<td>Original</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Polyimide</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Melamine</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Polyurethane</td>
<td>4</td>
</tr>
<tr>
<td>C</td>
<td>Original</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Polyimide</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Melamine</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Polyurethane</td>
<td>4</td>
</tr>
<tr>
<td>D</td>
<td>Original</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Polyimide</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Melamine</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Polyurethane</td>
<td>4</td>
</tr>
<tr>
<td>E</td>
<td>Original</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Polyimide</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Melamine</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Polyurethane</td>
<td>4</td>
</tr>
<tr>
<td>F</td>
<td>Original</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Polyimide</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Melamine</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Polyurethane</td>
<td>4</td>
</tr>
<tr>
<td>G</td>
<td>Original</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Polyimide</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Melamine</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Polyurethane</td>
<td>4</td>
</tr>
<tr>
<td>H</td>
<td>Original</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Polyimide</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Melamine</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Polyurethane</td>
<td>4</td>
</tr>
</tbody>
</table>

3.4 Material Specifications

Materials can be defined either on a domain (volume) or a boundary. The main domain material used was air. The domains to include this space were the PML layer, the air space where the sphere was defined, inside the incubator and the control volume. The second material used for a domain was either the original mattress foam with plastic covering, polyimide, melamine or polyurethane foam. These were used for the mattress and any other foam pieces add to the geometry, dependent upon which case was being performed. The plastic that covered the original mattress was characterized by defining the impedance of plastic as a function of frequency. This will be discussed further in the physics descriptions. The last material used was another plastic that was used for the domain of the Drager incubator walls. The chosen material for this was polyethylene (high density), the most commonly used plastic. This has been FDA approved for hospitals which was a requirement for any type of material that was used in this environment since it must go through inspection first. Polyethylene has been used in direct skin contact with
some cases with infants, therefore is appropriate for the incubator boundary material [44]. Seen below in table 10 were the required material properties used throughout the model.

Table 10. Display of material properties

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Units</th>
<th>Polyimide</th>
<th>Melamine</th>
<th>Polyurethane</th>
<th>Polyethylene</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>9.6</td>
<td>11</td>
<td>25.6</td>
<td>930</td>
</tr>
<tr>
<td>Permeability</td>
<td>m²</td>
<td>0.2E-9</td>
<td>1.5E-9</td>
<td>0.98E-9</td>
<td>-</td>
</tr>
<tr>
<td>Porosity</td>
<td></td>
<td>0.99</td>
<td>0.995</td>
<td>0.96</td>
<td>-</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>Pa</td>
<td>0.135E6</td>
<td>1324000</td>
<td>2.78E6</td>
<td>1E9</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td></td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.46</td>
</tr>
<tr>
<td>Biot-Willis Coefficient</td>
<td></td>
<td>0.99</td>
<td>0.995</td>
<td>0.96</td>
<td>-</td>
</tr>
<tr>
<td>Tortuosity</td>
<td></td>
<td>3.11</td>
<td>1.0059</td>
<td>1.2</td>
<td>-</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
<td>1/K</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>150E-6</td>
</tr>
<tr>
<td>Relative Permeability</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.3</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>W/m*K</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.38</td>
</tr>
<tr>
<td>Speed of Sound</td>
<td>m/s</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1036.95</td>
</tr>
</tbody>
</table>

3.5 Physics Models Selections

Choosing predefined physics’ interfaces that were appropriate for this model were the main factor of the design. They were the basis for where boundary conditions, pressure fields and any additional characteristic besides geometry, material properties and meshing will be defined. For this model, the two types of physics used were acoustic-solid interaction and poroelastic waves. The acoustic-solid interaction was due to the incubator being characterized as a solid structure and acoustics for the type of analysis to be performed. The solid is elastic in connecting the acoustics pressure in a fluid domain with the structural deformation in a solid domain [45]. Therefore, the only part of the model that was defined in this physics is the PML, the sphere and the incubator structure. The poroelastic waves physics, which is also part of the acoustics module, included the remaining portion of the model that was comprised of the air space inside the incubator, mattress, CV and any new foam additions. In this physics, solid properties can be entered directly and damping was accounted for in the simulation automatically. It can be used to model virtually any porous medium for a wide range of frequencies [46].

For the acoustic-solid interaction physics there were multiple definitions and boundary conditions needed. A pressure acoustics is the acoustical interface category where the dependent variable is the acoustic pressure. This was defined to the PML, sphere and the incubator structure. These domains had a linear elastic model which uses material properties of the density and speed of sound specifically. A sound hard boundary wall was applied to the flat edges of the PML, sphere and the incubator layer thickness. This is the same thing as symmetry for this physics and COMSOL understands there is symmetric geometry mirrored to that boundary. A pressure boundary was applied to the five interior layers thickness of the incubator which includes the two sides, top, back and bottom. The same boundaries were defined again in the poroelastic waves physics to couple the pressures between the two different interactions. The dependent variable pressure of the acoustic-solid interaction was defined in the poroelastic waves
physics pressure boundary and vice versa. When the plane wave enters the incubator, there will be a smooth transition between the sphere air space and the incubator. The next design created had to involve generating the noise that will enter the incubator. The source in the anechoic chamber was a loudspeaker which was located approximately 60 inches from the end of the incubator. Because of the sphere’s diameter size limitations, a monopole source to represent the speaker was inapplicable and a different way to represent the noise source is discussed. Initially the speaker radiates equally in all directions because the medium is not changing, but by the time it hits the location of where the external microphone is positioned, the amplitudes will appear to be the same at each location on the plane perpendicular to its direction of travel. At this point the monopole type source can be represented as a plane wave. A background pressure field in COMSOL can produce a variety of plane waves that will have a similar effect as the external microphone used as a reference in the chamber. The external microphone in the chamber is located about 31 inches from the incubator. The distance between the incubator and the PML was designed just large enough to have this same distance which is where the plane wave will originate from.

Plane Wave Amplitudes

To implement a plane wave in COMSOL, pressure amplitudes were provided as a function of frequency. For validation purposes, this value must correspond to the experimentally measured value from the anechoic chamber. Recall previously that since the loudspeaker could not be directly modeled, the signal level heard at the external microphone in an ANC test was used to compute the amplitude of the plane waves. Since all COMSOL analyses were performed with a plane wave amplitude of 1 Pascal, the results were corrected to the appropriate pressure level for each frequency. The procedure for determining the pressure amplitude at the external microphone is discussed below.

Time domain data was collected from an ANC test performed in the chamber using a similar experimental set up for white noise conditions. The data was corrected to units of Pascal using the calibration factor of the external microphone, 0.4476 $\frac{V}{Pa}$. The power spectral density (PSD), $P_{xx}$, was then computed using a Hanning window and a sampling frequency of 51200 samples/second. Note that this procedure for computing PSD was used in all of the anechoic chamber tests.

The sound pressure level equation was then plotted in the form below in equation 1.

$$
SPL \ (dB) = 10log10 \left( \frac{P_{xx} * df}{(P_{ref})^2} \right) 
$$

$P_{ref} = 20 * 10^{-6}$

$df = 0.7813 \ Hz$

The PSD was multiplied by a uniform delta f through the whole frequency range. The delta f is the value between two different frequencies in the spectrum. Specifically, by taking the difference in frequency values between the first and second indexes, gives a value of 0.7813 Hz.
Equation 1 above produced the following SPL plot below in figure 30 at the external microphone location.

![SPL plot](image)

**Figure 30.** SPL heard at the external reference microphone from active noise control test

The dB values corresponding to each frequency in the range of interest (100-1700 Hz) were directly taken from figure 30 above. The dB values were then factored in to determining the appropriate plane wave amplitudes. The 10-12 dB increase occurring around 2000 Hz will be investigated further for a more clear understanding of its trend. For further discussion on power spectral densities please refer to Appendix B.

Each design that was investigated using COMSOL was analyzed over a frequency range of 100 Hz to 1700 Hz, at 50 Hz intervals, totaling 33 independent frequency domain analyses. Since all of the results were based on a plane wave magnitude of 1 Pa (94 dB), a correction factor needed to be applied to properly scale the incoming wave consistently with the experimental value shown in figure 17 above. This is easily achieved taking the difference in 94 dB (1 Pa incoming plane wave magnitude) and each dB value computed from the ANC test above. This correction was applied for the baby control volume (CV) as well as the incubator CV. In this case, the scaling resulted in a variable (function of frequency) downward shift of all simulation results. Note that the transfer function for all simulation results is unaffected since the dB reduction from output to input (ear to external microphone) is the same regardless of shifted value.

The background pressure field in COMSOL creates a plane wave in a specified domain. The equation used is seen below in equation 2.

\[
p_b = p_0 e^{-i k_{eq} (r \cdot e_k)}
\]

\[
k^2_{eq} = \left( \frac{\omega}{c_c} \right)^2 = \text{propogation vector & wave number}
\]

\[
p_b = \text{pressure}
\]

\[
p_0 = \text{pressure amplitude}
\]

\[
e_k = \text{wave direction} \hat{z} - \hat{y}
\]

Eq. 2
By substituting in the appropriate values, the plane wave was generated.

In the poroelastic waves physics, domains are applied to the air space inside the incubator, the mattress and the baby control volume. A poroelastic material defines the mattress domain and any other foam that is added to the model. In the poroelastic material the porous model is an isotropic model where material properties such as the density, Young’s Modulus, poissson’s ratio, permeability, tortuosity, porosity and Biot – Willis Coefficient are referenced from the corresponding material properties. The fluid properties of this are from air which also use properties defined in the materials section. A sound hard boundary is then applied to multiple boundaries. These would include the flat boundaries where the line of symmetry was cut, including the baby’s head and body. A free boundary condition is applied to the all boundaries of the mattress to allow it to move, the opposite of a fixed boundary condition as well as a continuity boundary condition. Initial values are defined for all three domains used in this physics. A pressure acoustics model is defined to represent the air space inside the incubator and the control volume air space. This is defined as a linear elastic fluid model that again references material properties from its corresponding material, air in this case. A symmetry boundary is applied to the side flat boundary of the mattress. This represents where the symmetry plane is recognized. For the original mattress, an impedance value is applied to all sides of the mattress. This value will take into account a piece of plastic being around the mattress. Because acoustic impedance is frequency dependent, a piece of plastic was used in an impedance tube with air on both sides to determine its impedance. These values were determined by Adam Slagle at National Institute of Aerospace and are then displayed appropriately in the corresponding section in the model tree in COMSOL. This impedance value is disregarded for when new foam materials replace the original mattress with the plastic. A boundary pressure is applied to the same five boundaries that was also done in the acoustic – solid interaction.

3.6 Mesh Generation and Resolution Criteria

In finite element modeling, a mesh for a designed model was a direct effect on the accuracy of the results [47]. In the acoustics models, the maximum element size was directly a function of the wavelength, the frequency range of focus and the number of cells [47]. The relationship among these variables is seen in equation 1 below. Since sound was traveling through air, the speed of sound was that of this medium, with a constant value of 343 m/s. When choosing an appropriate frequency range, it should incorporate most of the same range used in the chamber as well as the audible range of hearing, taking into account mesh limitations. When determining the maximum element size, as the frequency increases the wavelength distance decreases. Therefore, the recommendation in number of cells to accurately determine the maximum element size is between 5 and 10 elements [47]. See equation 3 below to show how the maximum number of elements parameter is defined in COMSOL.
To determine if the number of elements should be any number between 5 and 10 a mesh study was performed and can be found in section 4.1.

3.7 Frequency Domain Analysis

For the model design, a frequency domain analysis was performed. The frequency of interest for all tests performed began at 100 Hz and spanned to 1700 Hz. The minimum frequency value did not fall below 100 Hz because the speaker to be used in the experimental results cannot excite white noise below this frequency. In addition, the foam should perform the best in the middle to upper frequencies, so below 100 Hz is out of the range of interest for this thesis. The frequency interval in the specified range was 50 Hz, resulting in 33 independent frequency domain analyses.

Chapter 4. Finite Element Preliminary Studies

4.1 Mesh Density Study

In finite element modeling, a mesh design, including size and growth rate, affects the solution accuracy. A finer mesh will produce more accurate solutions than a coarse mesh, but at significantly increased computation cost (time). An appropriate mesh resolution for a design is considered acceptable when there is minimal change in the solution results of interest. Therefore, a mesh study was performed to determine the effect of cumulative dB over the studied frequency range (100-1700 Hz) when different mesh densities were used. A three inch polyimide mattress at 1300 Hz was computed using a baseline, globally refined and locally refined meshes. These dB levels are computed at the control volume for comparative purposes and can be seen in table 4 found below. The mesh descriptions for each of the three tests are summarized in table 11. Note that column 3 in table 3 is an input parameter to COMSOL that essentially determines the number of elements used to resolve the shape of a full cycle wavelength. The plane wave amplitude was set to 1 Pascal in all mesh tests. With the frequency of 1300 Hz of focus, the wavelength for all mesh tests was 0.264 meters. The globally refined case increases that value from 5 to 7. The locally refined case adjusts the distribution of wavelength resolution from 5 at the outer boundary to 10 inside the incubator where the acoustic interaction is greatest.

<table>
<thead>
<tr>
<th>Mesh Quality</th>
<th>Mesh Location</th>
<th>Number of cells per wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>PML</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Sphere</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Incubator</td>
<td>5</td>
</tr>
<tr>
<td>Globally Refined</td>
<td>PML</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Sphere</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Incubator</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 11. Mesh study tests
Baseline Mesh

The first mesh case performed was a baseline mesh. In this design each section of mesh had 5 elements per wavelength. The 3D view of the meshed geometry can be seen in figure 31 below with its corresponding mesh statistics in figure 32. The mesh statistics are a compilation of the element types and domain element statistics related to that specific study that was performed. This will be displayed for the baseline, globally refined and locally refined mesh qualities.

<table>
<thead>
<tr>
<th>LocallyRefined</th>
<th>PML</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Incubator</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Figure 31. Baseline mesh geometry view
The next set of mesh study was a fine mesh where the number of elements per wavelength increased from 5 to 7 for each domain. This 3D mesh can be seen below in figure 33 with the matching mesh statistics in to follow in figure 34.
Figure 33. Globally refined mesh geometry view

Figure 34. Mesh statistics for globally refined mesh
Locally Refined Mesh

The third test for this study was decreasing the number of elements per wavelength to 5 for the PML, keeping 7 elements for the sphere and increasing the number of elements to 10 for the incubator. This is seen in figure 35 below with the corresponding mesh statistics in figure 36 to follow.

![Locally refined fine mesh geometry view](image)

**Figure 35.** Locally refined fine mesh geometry view
From analyzing the three mesh cases above, using 5 elements per wavelength produced the total number of elements for the baseline design to be 442222 and led to a total mesh volume of 3.182 $m^3$. These values increased for both the globally and locally refined cases to numbers of 1106338 elements with a mesh volume of 3.184 $m^3$ and 1141824 elements with a volume of 3.184 $m^3$, respectively. The two volume meshes are comprised of prism and tetrahedral elements which create the PML and sphere with incubator meshes, respectively. The histogram provides an indication of mesh element quality. A quality value of 1 corresponds to a perfect equilateral element. For the baseline mesh, the average element quality was shown to be 0.7901, the globally refined mesh 0.8013 and 0.7855 for the locally refined mesh. All of these are good representatives of high quality meshes. For each mesh case performed, the SPL for the computed frequency of 1300 Hz was determined. This is seen below with its corresponding dB value in table 12.

Table 12. Total SPL values for each mesh quality

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Number of Elements</th>
<th>$P^2_{rms}$</th>
<th>dB Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>442222</td>
<td>4.03585e-5</td>
<td>50.0386</td>
</tr>
<tr>
<td>Globally Refined</td>
<td>1106338</td>
<td>4.1563e-5</td>
<td>50.1665</td>
</tr>
<tr>
<td>Locally Refined</td>
<td>1141824</td>
<td>4.23354e-5</td>
<td>50.2464</td>
</tr>
</tbody>
</table>

The percent increase if choosing the locally refined mesh over the baseline mesh was only 0.415% increase in SPL. This is a negligible change in sound level for this frequency. Because
this frequency was not affected by refining the 5 or 10 elements per wavelength it is unnecessary to modify to a more globally or locally refined mesh. Note that the computation time increased by a factor of 3 compared to the baseline mesh as well. Therefore, the value of 5 elements per wavelength was used in all mesh domains.

The three different mesh sections for this design are displayed below in table 13. The incubator domain included the thickness of the incubator, the air space inside the incubator, the mattress, baby and control volume. The sphere domain included the air space between the incubator and the sphere and lastly, the PML domain included the PML thickness layer. The total number of elements was not displayed due to its changing value as a function of each case but will vary between 400K and 500K for all tests.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Maximum Element Size</th>
<th>Minimum Element Size</th>
<th>Maximum Element Growth Rate</th>
<th>Resolution of Curvature</th>
<th>Resolution of Narrow Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incubator</td>
<td>343/1700/5</td>
<td>343/1700/10</td>
<td>1.5</td>
<td>0.6</td>
<td>2</td>
</tr>
<tr>
<td>Sphere</td>
<td>343/1700/5</td>
<td>343/1700/10</td>
<td>1.5</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>PML</td>
<td>343/1700/5</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

4.2 Frequency Refinement Study

The next study performed was a frequency refinement investigation to determine an appropriate frequency interval that captures the SPL trend for the frequency range 100-1700 Hz. Ideally, all FE analyses would be performed at one Hz increments to provide highly accurate performance curves, without missing local minimum and maximum peaks. The result presented below in figure 37 illustrates the difference using \( \Delta f = 50 \text{ Hz} \) and \( \Delta f = 5 \text{ Hz} \) over a 1600 Hz (100-1700) range for a three inch polyimide foam mattress with a plane wave pressure amplitude of 1 Pascal for simplicity.
Figure 37. Frequency study showing a $\Delta f = 50$ Hz and $\Delta f = 5$ Hz for polyimide three inch mattress

The significance of this plot was to show that as the frequency increment decreases, more detail is provided on foam performance in terms of sound pressure level. From frequencies 600 Hz to 1200 Hz the peaks are predicted showing small fluctuation in dB value. However, using a $\Delta f = 50$ Hz adequately resolves the trends; hence it will be used for all simulation results. Note that the difference in computational time is reduced by a factor of 10, which correlates to a decrease from 50 hours to 5 hours for each analysis.

Chapter 5. Finite Element Results and Discussion

5.1 Validation Test Studies

The first portion of FE modeling results displays the validation plots. The sound pressure levels of interest are near the baby’s ears. Therefore, the following plots in figures 38 through 54 are the results comparing the baby right ear from the anechoic chamber experiment to the control volume from the FE modeling simulation work. These experimental results will later be discussed in the anechoic chamber results/discussion section. Two plots for each test are displayed that include the transfer function from the ear/control volume to the external microphone and the SPL measured at the ear/control volume. Analysis will be provided in the discussion section.

One must keep in mind some differences between the two that could impact some of the results. There were a few elements to note in the modeling process design that could have affected the FE modeling results when comparing them to the anechoic chamber experimental results for validation purposes. The first one to note was the physical incubator used in the experimental tests. This incubator had two side oval cutouts which could have been opened for nurses to examine the neonate. These were omitted when designing the incubator model due to their minimal effect on the sound pressure level. Additionally, the slanted edge of the incubator was
disregarded when designing the incubator. This allowed a symmetric incubator to be cut in half to decrease the number of total elements and use a maximum frequency for computations. In addition, the number of frequencies being computed for each test was 33. Again, this was limited to the amount of memory and time allowable for each test.

For the anechoic chamber testing there was one microphone in each ear used for the average SPL measured whereas a control volume for the FE model was designed around the baby’s head that was used for comparison. The control volume was appropriate in the regard that there would not be much variation between the control volume and the baby’s ears and the control volume would include the set of ears. This also could be a more realistic case in that not all baby’s when placed inside an incubator will be in the exact location of where the baby from the chamber was lying. The control volume would represent a broader volume of space to compensate for the position of the baby.

![Graph of transfer function](image)

**Figure 38.** Transfer function between baby ear microphone and external microphone for experiment (blue) vs. baby control volume and plane wave (red) for no mattress
Figure 39. Sound pressure level at baby right ear for experiment (blue) compared to sound pressure level heard at baby control volume from simulation (red) for no mattress.

Figure 40. Transfer function between baby ear microphone and external microphone for experiment (blue) vs. baby control volume and plane wave (red) for original mattress.
Figure 41. Sound pressure level at baby right ear for experiment (blue) compared to sound pressure level heard at baby control volume from simulation (red) for original mattress.

Figure 42. Transfer function between baby ear microphone and external microphone for experiment (blue) vs. baby control volume and plane wave (red) for one inch polyimide mattress.
**Figure 43.** Sound pressure level at baby right ear for experiment (blue) compared to sound pressure level heard at baby control volume from simulation (red) for one inch polyimide mattress.

**Figure 44.** Transfer function between baby ear microphone and external microphone for experiment (blue) vs. baby control volume and plane wave (red) for three inch polyimide mattress.
Figure 45. Sound pressure level at baby right ear for experiment (blue) compared to sound pressure level heard at baby control volume from simulation (red) for three inch polyimide mattress

Figure 46. Transfer function between baby ear microphone and external microphone for experiment (blue) vs. baby control volume and plane wave (red) for two inch melamine mattress
Figure 47. Transfer function between baby ear microphone and external microphone for experiment (blue) vs. baby control volume and plane wave (red) for two inch melamine mattress.

Figure 48. Sound pressure level at baby right ear for experiment (blue) compared to sound pressure level heard at baby control volume from simulation (red) for two inch melamine mattress.
Figure 49. Transfer function between baby ear microphone and external microphone for experiment (blue) vs. baby control volume and plane wave (red) for four inch melamine mattress

Figure 50. Sound pressure level at baby right ear for experiment (blue) compared to sound pressure level heard at baby control volume from simulation (red) for four inch melamine mattress
Figure 51. Transfer function between baby ear microphone and external microphone for experiment (blue) vs. baby control volume and plane wave (red) for one inch polyurethane mattress

Figure 52. Sound pressure level at baby right ear for experiment (blue) compared to sound pressure level heard at baby control volume from simulation (red) for one inch polyurethane mattress
The validation plots were computed for eight different tests which were listed in table 8. As previously stated, the transfer functions were determined from the output to input, or baby ear microphone/control volume to external microphone/plane wave. An ANC signal measured at the external reference microphone was applied to the plane wave in the simulation work. The spectral curve for the specific microphone is divided by the spectral curve of the reference microphone and multiplied by 20\log_{10}. The dB values are predominantly negative, primarily because the dB heard at the external microphone is generally louder than what is heard at the baby ear/control volume.
The most important observation to notice for the transfer function plots are the trends between the frequencies. Since there were only 33 frequencies (computed at 50 Hz intervals) for each design, detailed comparisons between the experimental and simulation curves are not seen. If data was collected every 1 Hz, the curves would be more smooth and continuous allowing the variation in performance to be more clearly understood. Hence, the trends will be the primary focus for determining model validation.

For all cases, the TF plots in the frequency range from 100 Hz to 500 Hz follow the same general trend: a decrease to around 200 Hz, then moderate increases and decreases to 500 Hz. Some of the peaks are nearly the same, such as the original one inch mattress at 250 Hz, 450 Hz for the one inch polyurethane, and 200 Hz for two inch melamine. As the frequency increases there is a larger gap in the TF between the two curves although trends still remain consistent throughout most of the higher frequency ranges. For example, the no mattress plot in figure 24, from 500-700 Hz, the peak between 800 Hz and 900 Hz, and the change in the TF dB around 1200-1500 Hz all show the same trend. Similar trends appear for the original mattress and the polyimide three inch mattress. In terms of trend analyses, the simulation model is reasonably validated and shown to predict results consistently with the experiment.

The SPL plots were also shown for each test. The experimental SPL heard at the baby right ear was plotted against the SPL heard at the control volume using the correction factor from the ANC test. Trends were also the main point of focus when analyzing these graphs. The SPL values must also be in a similar range as the experiment to successfully validate the model. It is noticed that for most of these plots, the value at 100 Hz for the simulation was around 7 dB lower than for the experiment. This could be due to the correction factor at 100 Hz used at the external microphone. It is very visible that in the lower frequency range up to 500 Hz the data again matches up in trends very well. As frequency increases, the dB levels do drop up to 15 dB in difference but appear to increase or decrease around the same frequencies. This again could be due to a correction error or a problem in the experiment at higher frequencies. The most noticeable examples of this are the original mattress, polyimide three inch, melamine two inch and the polyurethane one inch foams. It can be concluded that after overall trends in the transfer function and SPL plots that this simulation model is validated and can be used to analyze future designs.

5.2 Passive Noise Control Design Studies in the 0 to 1700 Hz Bandwidth

Once validation plots were confirmed, the next set of results includes different combinations of mattress materials and eight design cases. The main purpose was to determine how sound pressure level was affected by individual shape, position, mattress material and combinations among them. Results are displayed according to purpose of demonstration.

*Comparison of Mattresses with Cases A-H*

The “comparison of mattresses with cases” set of results displays plots showing the effect of each mattress (original, polyimide, melamine, polyurethane) with each case design (A-H). The significance of this section is to show general trends compared to the baseline and how increasing mattress thickness lowers SPL levels in certain frequencies. The baseline for all plots
in this section is the original one inch mattress. There are two types of plots in this section to highlight its purpose. The first type shows only comparisons between mattress materials. This is done for the two thicknesses of each mattress material. For example, the two thicknesses for polyimide will be on one plot as will the two thicknesses for melamine. The second type of plot result shows the baseline plus the specific case design (A-H as previously discussed). As a reminder, the mattress foams when applying the cases only, use the maximum thickness of that material to try and achieve maximum dB reduction. Results show SPL measured at the control volume first followed by SPL heard at the incubator next.

![SPL For Baby Control Volume](image)

**Figure 55.** Comparison among no mattress, original mattress (baseline), polyimide one inch mattress and polyimide three inch mattress at baby control volume
Figure 56. Case A designs for original mattress and three inch polyimide mattress at baby control volume

Figure 57. Case B designs for original mattress and three inch polyimide mattress at baby control volume
Figure 58. Case C designs for original mattress and three inch polyimide mattress at baby control volume

Figure 59. Case D designs for original mattress and three inch polyimide mattress at baby control volume
Figure 60. Case E designs for original mattress and three inch polyimide mattress at baby control volume

Figure 61. Case F designs for original mattress and three inch polyimide mattress at baby control volume
Figure 62. Case G designs for original mattress and three inch polyimide mattress at baby control volume

Figure 63. Case H designs for original mattress and three inch polyimide mattress at baby control volume
Figure 64. Comparison among no mattress, original mattress (baseline), melamine two inch mattress and melamine four inch mattress at baby control volume.

Figure 65. Case A designs for original mattress and four inch melamine mattress at baby control volume.
Figure 66. Case B designs for original mattress and four inch melamine mattress at baby control volume

Figure 67. Case C designs for original mattress and four inch melamine mattress at baby control volume
Figure 68. Case D designs for original mattress and four inch melamine mattress at baby control volume

Figure 69. Case E designs for original mattress and four inch melamine mattress at baby control volume
Figure 70. Case F designs for original mattress and four inch melamine mattress at baby control volume

Figure 71. Case G designs for original mattress and four inch melamine mattress at baby control volume
Figure 72. Case H designs for original mattress and four inch melamine mattress at baby control volume

Figure 73. Comparison among no mattress, original mattress (baseline), polyurethane one inch mattress and polyurethane four inch mattress at baby control volume
**Figure 74.** Case A designs for original mattress and four inch polyurethane mattress at baby control volume

**Figure 75.** Case B designs for original mattress and four inch polyurethane mattress at baby control volume
Figure 76. Case C designs for original mattress and four inch polyurethane foam at baby control volume

Figure 77. Case D designs for original mattress and four inch polyurethane foam at baby control volume
**Figure 78.** Case E designs for original mattress and four inch polyurethane foam at baby control volume

**Figure 79.** Case F designs for original mattress and four inch polyurethane foam at baby control volume
Figure 80. Case G designs for original mattress and four inch polyurethane foam at baby control volume

Figure 81. Case H designs for original mattress and four inch polyurethane foam at baby control volume
Figure 82. Comparison among no mattress, original mattress (baseline), polyimide one inch mattress and polyimide three inch mattress at incubator

Figure 83. Case A designs for original mattress and three inch polyimide foam at incubator
Figure 84. Case B designs for original mattress and three inch polyimide foam at incubator.

Figure 85. Case C designs for original mattress and three inch polyimide foam at incubator.
Figure 86. Case D designs for original mattress and three inch polyimide foam at incubator

Figure 87. Case E designs for original mattress and three inch polyimide foam at incubator
**Figure 88.** Case F designs for original mattress and three inch polyimide foam at incubator

**Figure 89.** Case G designs for original mattress and three inch polyimide foam at incubator
Figure 90. Case H designs for original mattress and three inch polyimide foam at incubator

Figure 91. Comparison among no mattress, original mattress (baseline), melamine two inch mattress and melamine four inch mattress at incubator
Figure 92. Case A designs for original mattress and four inch melamine foam at incubator.

Figure 93. Case B designs for original mattress and four inch melamine foam at incubator.
Figure 94. Case C designs for original mattress and four inch melamine foam at incubator

Figure 95. Case D designs for original mattress and four inch melamine foam at incubator
Figure 96. Case E designs for original mattress and four inch melamine foam at incubator

Figure 97. Case F designs for original mattress and four inch melamine foam at incubator
Figure 98. Case G designs for original mattress and four inch melamine foam at incubator

Figure 99. Case H designs for original mattress and four inch melamine foam at incubator
Figure 100. Comparison among no mattress, original mattress (baseline), polyurethane one inch mattress and polyurethane four inch mattress at incubator.

Figure 101. Case A designs for original mattress and four inch polyurethane foam at incubator.
Figure 102. Case B designs for original mattress and four inch polyurethane foam at incubator

Figure 103. Case C designs for original mattress and four inch polyurethane foam at incubator
Figure 104. Case D designs for original mattress and four inch polyurethane foam at incubator

Figure 105. Case E designs for original mattress and four inch polyurethane foam at incubator
Figure 106. Case F designs for original mattress and four inch polyurethane foam at incubator.

Figure 107. Case G designs for original mattress and four inch polyurethane foam at incubator.
The significance of this section was to demonstrate mattress performance for each case with baseline curves to show that the dB levels should in general, decrease as more foam is added. It can be seen from the previous figures 40 through 87 that the no mattress case has the highest levels inside the control volume and incubator. As foam is added to the incubator, the dB levels decrease from 1 dB up to as many as 20 dB. This mostly occurs in the middle frequencies where the SPLs are at the lowest. After 1000 Hz, the dB values tend to increase up to just less than 50 dB. These values are still below the recommended 45 dB[A], although further investigation needs to be done to understand this trend. The porous mattress material by itself and with the addition of each case shows to be in the top two of the six curves as far as low dB levels are concerned. The original mattress with each design case added does not show much improvement although levels decrease slightly. For some design cases, if the specific foam case does not have much of an effect on the noise levels, the simple foam mattress will perform almost as well which, for example, can be seen in case C for the polyimide three foam and case D for the four melamine foam. The two foam thicknesses for each mattress, (one and three for polyimide, two and four for melamine and one and four for polyurethane) appeared to decrease in cumulative dB value as thickness increased. As more foam was added, the peaks decreased in dB as well. This is more prevalent in the middle frequencies in the control volume. The incubator dBs still have peaks at certain frequencies but are not as dominant.

Comparison of Mattress for Each Design

The next set of plots in the “comparison of mattress for each design” section shows the maximum thickness for each material tested (original mattress, polyimide mattress, melamine mattress, polyurethane mattress) for each case design. The significance of this section is to show how each mattress performs compared to the other mattress materials for each given case. Plots are shown for the SPL measured at the control volume first followed by the SPL measured at the incubator next.

Figure 108. Case H designs for original mattress and four inch polyurethane foam at incubator
**Figure 109.** Case A design for original mattress, polyimide foam, melamine foam and polyurethane foam at baby control volume

**Figure 110.** Case B design for original mattress, polyimide foam, melamine foam and polyurethane foam at baby control volume
**Figure 111.** Case C design for original mattress, polyimide foam, melamine foam and polyurethane foam at baby control volume

**Figure 112.** Case D design for original mattress, polyimide foam, melamine foam and polyurethane foam at baby control volume
Figure 113. Case E design for original mattress, polyimide foam, melamine foam and polyurethane foam at baby control volume

Figure 114. Case F design for original mattress, polyimide foam, melamine foam and polyurethane foam at baby control volume
Figure 115. Case G design for original mattress, polyimide foam, melamine foam and polyurethane foam at baby control volume

Figure 116. Case H design for original mattress, polyimide foam, melamine foam and polyurethane foam at baby control volume
Figure 117. Case A design for original mattress, polyimide foam, melamine foam and polyurethane foam at incubator.

Figure 118. Case B design for original mattress, polyimide foam, melamine foam and polyurethane foam at incubator.
Figure 119. Case C design for original mattress, polyimide foam, melamine foam and polyurethane foam at incubator

Figure 120. Case D design for original mattress, polyimide foam, melamine foam and polyurethane foam at incubator
Figure 121. Case E design for original mattress, polyimide foam, melamine foam and polyurethane foam at incubator

Figure 122. Case F design for original mattress, polyimide foam, melamine foam and polyurethane foam at incubator
The significance of this section was for each case, to show how all the different mattresses compare to one another as a function of cumulative dB value for both the control volume and incubator air spaces. The following tables 14 and 15 to 22 below display the results from the tests performed with just the mattress foam followed by test results with the specific case studies. Each table displays the average $P^2_{rms}$ for both the control volume and incubator and its corresponding mattress material and thickness. The values highlighted in yellow and turquoise
are the best performing mattresses for the control volume and incubator air space for that case of interest.

A simple explanation of how sound pressure levels and the root means squared value, \( P_{\text{rms}}^2 \) were computed is found below.

The original equation for computing sound pressure level is below in equation 4.

\[
SPL = 20 \log_{10}\left(\frac{P_{\text{rms}}}{P_{\text{ref}}}\right) \quad \text{Eq. 4}
\]

Simplifying, leads to equation 5 below.

\[
SPL = 10 \log_{10}\left(\frac{P_{\text{rms}}^2}{P_{\text{ref}}^2}\right) \quad \text{Eq. 5}
\]

Taking equation 5 from above and rearranging leads to the following equation.

\[
P_{\text{rms}}^2 = P_{\text{ref}}^2 \times 10^{\frac{SPL}{10}} \quad \text{Eq. 6}
\]

\[
P_{\text{ref}} = 20 \times 10^{-6} \text{ Pa}
\]

If there are multiple SPL values, equation 6 is slightly modified and can be seen below.

\[
P_{\text{rms}}^2 = P_{\text{ref}}^2 \times 10^{\left(\frac{\text{SPL}_1}{10} + \frac{\text{SPL}_2}{10} + \frac{\text{SPL}_3}{10} + \ldots\right)} \quad \text{Eq. 7}
\]

The first table below is simply the effect of changing the mattress, excluding any additional design added to it.

<table>
<thead>
<tr>
<th>Table 14. Results for mattress only for entire frequency range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mattress Foam</strong></td>
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<tr>
<td>Mattress Material</td>
</tr>
<tr>
<td>No Foam</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Original</td>
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</tr>
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</tr>
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<td></td>
</tr>
<tr>
<td>Polyurethane</td>
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<tr>
<td></td>
</tr>
</tbody>
</table>
Table 15. Results for case A and mattress foam for entire frequency range

<table>
<thead>
<tr>
<th>Mattress Material</th>
<th>Mattress Thickness (in.)</th>
<th>Location</th>
<th>Total $P_{\text{rms}}^2$ (Pa)</th>
<th>Cumulative dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>1</td>
<td>Incubator</td>
<td>1.4216e-005</td>
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</tr>
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<td></td>
<td></td>
<td>CV</td>
<td>1.1732e-005</td>
<td>44.67</td>
</tr>
<tr>
<td>Polyimide</td>
<td>3</td>
<td>Incubator</td>
<td>5.2581e-006</td>
<td>41.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CV</td>
<td>5.6239e-006</td>
<td>41.48</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>4</td>
<td>Incubator</td>
<td>7.2593e-006</td>
<td>42.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CV</td>
<td>9.9596e-006</td>
<td>43.96</td>
</tr>
<tr>
<td>Melamine</td>
<td>4</td>
<td>Incubator</td>
<td>7.3633e-006</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>CV</td>
<td>9.6663e-006</td>
<td>43.83</td>
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</table>

Table 16. Results for case B and mattress foam for entire frequency range

<table>
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<tr>
<th>Mattress Material</th>
<th>Mattress Thickness (in.)</th>
<th>Location</th>
<th>Total $P_{\text{rms}}^2$ (Pa)</th>
<th>Cumulative dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
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<td>Incubator</td>
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<td></td>
<td>CV</td>
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<td>Polyimide</td>
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<td>Incubator</td>
<td>4.1495e-006</td>
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<td></td>
<td>CV</td>
<td>5.5977e-006</td>
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<td>Polyurethane</td>
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<td>Incubator</td>
<td>6.9683e-006</td>
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<td>Melamine</td>
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<tr>
<td></td>
<td></td>
<td>CV</td>
<td>1.2452e-005</td>
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Table 17. Results for case C and mattress foam for entire frequency range

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<tr>
<th>Mattress Material</th>
<th>Mattress Thickness (in.)</th>
<th>Location</th>
<th>Total $P_{\text{rms}}^2$ (Pa)</th>
<th>Cumulative dB</th>
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</thead>
<tbody>
<tr>
<td>Original</td>
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<td>Incubator</td>
<td>1.0512e-005</td>
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<td>CV</td>
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<td>Polyimide</td>
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<td>Polyurethane</td>
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<td></td>
<td></td>
<td>CV</td>
<td>1.2513e-005</td>
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<td>CV</td>
<td>1.1606e-005</td>
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Table 18. Results for case D and mattress foam for entire frequency range
### Case D + Mattress Foam

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<tr>
<th>Mattress Material</th>
<th>Mattress Thickness (in.)</th>
<th>Location</th>
<th>Total $P_{rms}^2$</th>
<th>Cumulative dB</th>
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<tbody>
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<td>7.1446e-006</td>
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<td>CV</td>
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Table 19. Results for case E and mattress foam for entire frequency range

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<tr>
<th>Mattress Material</th>
<th>Mattress Thickness (in.)</th>
<th>Location</th>
<th>Total $P_{rms}^2$</th>
<th>Cumulative dB</th>
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<td>CV</td>
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Table 20. Results for case F and mattress foam for entire frequency range

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<tr>
<th>Mattress Material</th>
<th>Mattress Thickness (in.)</th>
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<th>Total $P_{rms}^2$</th>
<th>Cumulative dB</th>
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<td>Incubator</td>
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Table 21. Results for case G and mattress foam for entire frequency range
Table 22. Results for case H and mattress foam for entire frequency range

<table>
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<tr>
<th>Case H + Mattress Foam</th>
<th>Mattress Material</th>
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For cases A-E for the exception of case D, the polyimide foam plus the design case specified, shows the lowest cumulative SPL at both the baby control volume and the incubator. For case D the original mattress is the best for the control volume while the polyimide is the best for the incubator volume of space. Cases F and H are most useful for the polyurethane foam whereas for case G, both the polyimide and polyurethane foams produce the quietest sounds. Values in the previous tables range in either large or small dB differences among materials for each case. The largest dB difference occurs in case F where it was 8.35 dB for the incubator and 8.44 dB for the control volume. The smallest dB difference occurred in case D where the dB value was 0.86 dB for the incubator and 2.74 dB for the control volume.

Tables 23 and 24 below display the results for each case divided into frequency ranges for the control volume in table 23 followed by the incubator in table 24.

Table 23. Results for control volume for all cases for specified frequency ranges

<table>
<thead>
<tr>
<th>Case</th>
<th>Mattress Material</th>
<th>*Freq. Range</th>
<th>Total $P^2_{int}$</th>
<th>Cumulative dB</th>
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</tr>
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<td>Polyurethane 4 inch</td>
<td>Original Mattress</td>
<td>Polyimide</td>
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<td>Low</td>
</tr>
<tr>
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<td>6.8677E-6</td>
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</table>
From table 23 above for the control volume, the polyurethane one inch and four inch show the lowest cumulative dB value for just mattresses for the low and middle frequency range while the three inch polyimide is the best for the high frequency range. The low frequency range for all cases is dominated by the polyimide foam although the original mattress contributes second most in the lowest cumulative dB value. The polyurethane foam in the middle frequency range shows the lowest cumulative dB value with the exception of case B in which melamine proves to be the best. The high frequency range is also controlled by polyurethane foam for the best dB value for all cases except for case H where melamine holds the lowest dB value. The original mattress as seen in the table is one of the worst mattresses to use even though the levels are below the 45 dB[A]. The plastic covering on this mattress causes little absorption of the mattress when compared to the other porous mattresses and designs that do not have the plastic. There is minimal dB difference among foams in the design cases. For example, for case A for the middle frequencies between melamine and polyurethane, there is less than a 1 dB difference. As the frequencies increase trends appear to show lower dB values with the exception of different cases such as D or G.

Table 24. Results for incubator for all cases for specified frequency ranges

<table>
<thead>
<tr>
<th>Case</th>
<th>Mattress Material</th>
<th>*Freq. Range</th>
<th>Total $\overline{P}_2^{2,\text{max}}$</th>
<th>Cumulative dB</th>
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<td>Middle</td>
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<td>High</td>
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</tr>
<tr>
<td>----------------</td>
<td>---------</td>
<td>------------------</td>
<td>---------</td>
<td>------------------</td>
</tr>
<tr>
<td>Original Mattress</td>
<td>Low</td>
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</table>

**A**

<table>
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**B**

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**C**

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**D**

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<td>----------------</td>
<td>----------</td>
<td>---------</td>
<td>---------</td>
<td>------------</td>
</tr>
<tr>
<td><strong>Original Mattress</strong></td>
<td>1.659E-7</td>
<td>4.4337E-7</td>
<td>26.18</td>
<td>43.11</td>
</tr>
<tr>
<td><strong>Polyimide</strong></td>
<td>2.7520E-6</td>
<td>4.7178E-7</td>
<td>1.8825E-6</td>
<td>38.38</td>
</tr>
<tr>
<td><strong>Melamine</strong></td>
<td>5.2108E-6</td>
<td>2.1212E-6</td>
<td>1.5735E-6</td>
<td>43.11</td>
</tr>
<tr>
<td><strong>Polyurethane</strong></td>
<td>5.4671E-6</td>
<td>2.3801E-7</td>
<td>1.5278E-6</td>
<td>41.36</td>
</tr>
<tr>
<td><strong>Polyimide</strong></td>
<td>6.5515E-6</td>
<td>4.3422E-7</td>
<td>5.6905E-6</td>
<td>42.14</td>
</tr>
<tr>
<td><strong>Melamine</strong></td>
<td>2.6573E-5</td>
<td>3.9269E-7</td>
<td>5.3882E-7</td>
<td>48.22</td>
</tr>
<tr>
<td><strong>Polyurethane</strong></td>
<td>6.2787E-6</td>
<td>1.4040E-7</td>
<td>5.46E-7</td>
<td>39.59</td>
</tr>
<tr>
<td><strong>Polyimide</strong></td>
<td>2.7187E-6</td>
<td>1.5702E-7</td>
<td>5.46E-7</td>
<td>41.96</td>
</tr>
<tr>
<td><strong>Melamine</strong></td>
<td>2.2127E-6</td>
<td>8.0135E-8</td>
<td>3.1821E-7</td>
<td>37.43</td>
</tr>
<tr>
<td><strong>Polyurethane</strong></td>
<td>3.3945E-6</td>
<td>7.2553E-8</td>
<td>5.46E-7</td>
<td>39.29</td>
</tr>
<tr>
<td><strong>Polyimide</strong></td>
<td>4.5702E-6</td>
<td>4.0469E-7</td>
<td>3.46E-7</td>
<td>40.58</td>
</tr>
<tr>
<td><strong>Melamine</strong></td>
<td>1.478E-5</td>
<td>2.8673E-7</td>
<td>3.7069E-7</td>
<td>45.67</td>
</tr>
<tr>
<td><strong>Polyurethane</strong></td>
<td>4.1282E-6</td>
<td>1.2010E-7</td>
<td>2.5082E-7</td>
<td>40.14</td>
</tr>
</tbody>
</table>

*Low Frequency Range: 100-400 Hz
Middle Frequency Range: 400-1000 Hz
High Frequency Range: 1000-1700 Hz

Note: endpoints were shared between frequency ranges.

The incubator cumulative dB value in low frequencies for mattress comparison only, was dominated by a one inch polyimide. For middle and high frequencies, the four inch polyurethane and the three inch polyimide show the best cumulative dB values which was the same for the control volume. For cases A-E, the polyimide shows the best SPL values for the lower frequencies while the polyurethane takes priority in the middle and upper. For Cases F-H polyurethane is responsible for reducing noise levels the most in all ranges except for low frequencies in Case G in which melamine dominates.
Comparison of Design for Each Mattress

The next set of results in the “comparison of design for each mattress” section displays all cases for each mattress to show which design show the lowest SPL levels for that specific mattress. Plots first display the SPL levels measured at the baby control volume followed by the levels measured at the incubator.

![SPL For Baby Control Volume: Original Mattress One Inch](image)

**Figure 125.** All cases for original mattress at baby control volume

![SPL For Baby Control Volume: Polyimide Three Inch Foam](image)

**Figure 126.** All cases for polyimide foam at baby control volume
**Figure 127.** All cases for melamine foam at baby control volume

**Figure 128.** All cases for polyurethane foam at baby control volume
**Figure 129.** All cases for original mattress at incubator

**Figure 130.** All cases for polyimide foam at incubator
Comparison of Design for Each Mattress

The purpose of this section was to be able to say which cases were the best for each mattress. Table 25 below will display results over the entire frequency range followed by tables 26 and 27 which show the best cases for specific ranges of frequencies for each mattress. Results are shown for both the control volume and the incubator. These are based on the lowest overall dB values for all the cases with corresponding mattress. Refer to section 3.3 for case descriptions if necessary.
It is seen from table 25 that case G, vertical hanging blocks treatment (1x3) and case H, top covered angle treatment, show the best results in the four mattresses for both the control volume and incubator. Highlighted in yellow shows the instances where the rank of a case is in the same position for both the control volume and incubator. This occurs at least once for all foam. Each design case is represented at least once and the repetition occurred in every rank except for four. The cases that match up in each rank could correlate to a more even distribution of sound throughout the entire incubator air space for that specific design case. For example, if the infant is not in the exact same position each time, that case design shows an advantage of still being just as effective. Specifically, for the original mattress case H and polyimide and melamine, case G could prove to be a better overall design as opposed to the combination of G and H for polyurethane in rank one.

Tables 26 and 27 below show rankings of the cases for each material over three different frequency ranges for both the control volume and incubator, respectively.

Table 26. Best designs for each mattress material over the specified frequency ranges for the control volume

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Original Mattress</th>
<th>Polyimide</th>
<th>Melamine</th>
<th>Polyurethane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Case H</td>
<td>Case G</td>
<td>Case E</td>
<td>Case H</td>
</tr>
<tr>
<td></td>
<td>Case B</td>
<td>Case A</td>
<td>Case G</td>
<td>Case G</td>
</tr>
<tr>
<td></td>
<td>Case G</td>
<td>Case B</td>
<td>Case H</td>
<td>Case F</td>
</tr>
<tr>
<td></td>
<td>Case D</td>
<td>Case E</td>
<td>Case F</td>
<td>Case A</td>
</tr>
<tr>
<td></td>
<td>Case F</td>
<td>Case D</td>
<td>Case A</td>
<td>Case E</td>
</tr>
<tr>
<td></td>
<td>Case C</td>
<td>Case H</td>
<td>Case C</td>
<td>Case B</td>
</tr>
<tr>
<td></td>
<td>Case A</td>
<td>Case F</td>
<td>Case D</td>
<td>Case C</td>
</tr>
<tr>
<td></td>
<td>Case E</td>
<td>Case C</td>
<td>Case B</td>
<td>Case D</td>
</tr>
<tr>
<td></td>
<td>Case H</td>
<td>Case D</td>
<td>Case E</td>
<td>Case G</td>
</tr>
<tr>
<td></td>
<td>Case F</td>
<td>Case F</td>
<td>Case H</td>
<td>Case F</td>
</tr>
<tr>
<td></td>
<td>Case B</td>
<td>Case A</td>
<td>Case D</td>
<td>Case A</td>
</tr>
<tr>
<td></td>
<td>Case H</td>
<td>Case E</td>
<td>Case A</td>
<td>Case E</td>
</tr>
<tr>
<td></td>
<td>Case C</td>
<td>Case C</td>
<td>Case E</td>
<td>Case E</td>
</tr>
<tr>
<td>Middle</td>
<td>Case G</td>
<td>Case G</td>
<td>Case G</td>
<td>Case G</td>
</tr>
<tr>
<td></td>
<td>Case D</td>
<td>Case H</td>
<td>Case B</td>
<td>Case H</td>
</tr>
<tr>
<td></td>
<td>Case F</td>
<td>Case F</td>
<td>Case H</td>
<td>Case F</td>
</tr>
<tr>
<td></td>
<td>Case B</td>
<td>Case B</td>
<td>Case F</td>
<td>Case B</td>
</tr>
<tr>
<td></td>
<td>Case H</td>
<td>Case A</td>
<td>Case D</td>
<td>Case D</td>
</tr>
<tr>
<td></td>
<td>Case C</td>
<td>Case E</td>
<td>Case A</td>
<td>Case A</td>
</tr>
<tr>
<td></td>
<td>Case E</td>
<td>Case C</td>
<td>Case E</td>
<td>Case E</td>
</tr>
</tbody>
</table>
The significance of the result from table 26 above is to show that even though one case is the best for an entire range, it not necessarily is the best for a range of frequencies. This could be true because a higher dB value has a larger contribution to the cumulative dB value even though it may be the only high point in a range. For example, case H, top covered angle treatment, was the best design for the original mattress in the entire frequency range. From table 26 above, case H only dominates in the lower frequency range and is about midway down in the rankings for the middle and high frequencies.

It is clear that designs E, above head block treatment, G and H are the best designs in the low frequency range for all four mattresses. As frequency decreases, wavelength increases, resulting in longer wavelengths. This allows more time for the foam to absorb the sound as the wave passes through the incubator. The middle frequencies are dominated by case G while the best design for high frequencies is either case G or case H. Cases G and H appear to overall perform the best for all foams for the control volume. These top two designs are composed of large pieces of foam that span the width of the incubator either at an angle or simply vertical. When the plane wave enters the incubator much of the sound is absorbed through the wide pieces of foam before continuing to move throughout the incubator. Case A, tetrahedral treatment, has a very small effect in the high range but performs average in the low frequency range. Case B, prism edge treatment, is a decent design for all frequency ranges, especially for the original mattress and polyimide foam. Case D, vertical hanging blocks treatment (3x5), outperforms case C, vertical hanging blocks treatment (1x5), in 67% of the ranges in all foams because it has three rows of foam as opposed to just one. The remaining times in which the single row of foam absorbs more than the case with multiple rows was unexpected and will take further analysis to understand. Table 27 below displays the case rankings for the low, middle and high frequency ranges for all four mattresses.

Table 27. Best designs for each mattress material over the specified frequency ranges for the incubator

<table>
<thead>
<tr>
<th>*Frequency Range</th>
<th>Original Mattress</th>
<th>Polyimide</th>
<th>Melamine</th>
<th>Polyurethane</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low</strong></td>
<td>Case B</td>
<td>Case A</td>
<td>Case G</td>
<td>Case H</td>
</tr>
<tr>
<td>Case H</td>
<td>Case N</td>
<td>Case F</td>
<td>Case G</td>
<td></td>
</tr>
<tr>
<td>Case G</td>
<td>Case G</td>
<td>Case H</td>
<td>Case F</td>
<td></td>
</tr>
<tr>
<td>Case D</td>
<td>Case E</td>
<td>Case A</td>
<td>Case A</td>
<td></td>
</tr>
</tbody>
</table>
From table 27 above, cases G and H are the best designs when the middle or high frequencies are of interest for each mattress. Cases B, A, G and H are the best for low frequencies for each mattress. Case A tends to be a better design for lower frequencies only while designs B and C are average in each range. Case F shows a low dB cumulative number because the foams stick out horizontally to the plane wave coming in and because there are five rows with three vertical pieces of foam in each, the foam is able to capture more sound as it moves throughout the incubator. Case E had minimal effect because even though the foam was located above the infant’s head, there was no direct contact with the foam when the wave entered the incubator. Case D provided good SPL levels in the high frequency range but fluctuated a lot in the lower and middle depending upon the mattress material.

5.3 Passive Noise Control Design Studies in the 0 to 600 Hz Bandwidth

This section will focus on a bandwidth from 0 to 600 Hz which includes the targeted range where the highest sound levels were measured in the actual hospital tests. The purpose is (1) to demonstrate good agreement between the experimental and numerical results in the lower frequency range of interest and (2) to apply the numerical modeling to improve the incubator SPL in the NICU environments in the above frequency range. This includes the ventilator pump which was the largest contributor to noise levels, in the 30 to 150 Hz range. Since the validated FE model is very accurate in the lower frequency range, the likelihood of the porous mattress materials reducing ventilator pump noise is very plausible. For completeness, the validation plots from section 5.1 are shown below over the reduced frequency range from 0 to 600 Hz.
Figure 133. Transfer function between baby ear microphone and external microphone for experiment (blue) vs. baby control volume and plane wave (red) for no mattress

Figure 134. Sound pressure level at baby right ear for experiment (blue) compared to sound pressure level heard at baby control volume from simulation (red) for no mattress
From looking at figures 133 and 135 above, from 100 to 200 Hz the simulation data is slightly under predicted as compared to the experimental data. In figure 134 and 136, some peaks are near the same dB level between the experimental and simulation data, occurring at frequencies of 250 Hz for both the no mattress case and the original mattress case.
Figure 137. Transfer function between baby ear microphone and external microphone for experiment (blue) vs. baby control volume and plane wave (red) for one inch polyimide mattress

Figure 138. Sound pressure level at baby right ear for experiment (blue) compared to sound pressure level heard at baby control volume from simulation (red) for one inch polyimide mattress
Figure 139. Transfer function between baby ear microphone and external microphone for experiment (blue) vs. baby control volume and plane wave (red) for three inch polyimide mattress.

Figure 140. Sound pressure level at baby right ear for experiment (blue) compared to sound pressure level heard at baby control volume from simulation (red) for three inch polyimide mattress.

In figures 137 and 139 above the simulation data is under predicted throughout the frequency range from 100 to 500 Hz. This could be due to a correction factor that was applied at a certain frequency. Surpassing 500 Hz, the experimental data is higher than the simulation data in dB.
level. In figures 138 and 140, from 200 to 230 Hz the simulation data is higher in SPL than the experimental data, but as frequency increases, there is more variation in which data set is higher in dB level.

Figure 141. Transfer function between baby ear microphone and external microphone for experiment (blue) vs. baby control volume and plane wave (red) for two inch melamine mattress

Figure 142. Sound pressure level at baby right ear for experiment (blue) compared to sound pressure level heard at baby control volume from simulation (red) for two inch melamine mattress
Figure 143. Transfer function between baby ear microphone and external microphone for experiment (blue) vs. baby control volume and plane wave (red) for four inch melamine mattress

Figure 144. Sound pressure level at baby right ear for experiment (blue) compared to sound pressure level heard at baby control volume from simulation (red) for four inch melamine mattress

When analyzing the transfer function plots in figures 141 and 143 above, there are similarities between the two inch melamine mattress and the four inch melamine mattress. Throughout the frequency range, the simulation data is lower in dB level with the exception of 200 Hz where
there is a 4 dB difference in the two data sets for the four inch melamine mattress. In figures 142 and 144, there are similar comparisons. At 200 Hz, the SPL dB level for the four inch melamine is 10 dB whereas it is 5 dB for the two inch melamine mattress. As frequency surpasses 400 Hz, the trends between the data sets for the two thicknesses of melamine are consistent, with the experimental data levels higher in dB.

Figure 145. Transfer function between baby ear microphone and external microphone for experiment (blue) vs. baby control volume and plane wave (red) for one inch polyurethane mattress
Figure 146. Sound pressure level at baby right ear for experiment (blue) compared to sound pressure level heard at baby control volume from simulation (red) for one inch polyurethane mattress.

Figure 147. Transfer function between baby ear microphone and external microphone for experiment (blue) vs. baby control volume and plane wave (red) for four inch polyurethane mattress.
Figure 148. Sound pressure level at baby right ear for experiment (blue) compared to sound pressure level heard at baby control volume from simulation (red) for four inch polyurethane mattress

From figures 145 and 146 above, the trends and magnitudes are in good agreement for the one inch polyurethane cases. For the four inch polyurethane case, again at 200 Hz, there is a jump in dB level for the simulation data when compared to the experimental data. At 500 Hz, the simulation data under predicts the SPL levels measured in the experiment.

Case designs A, the tetrahedral treatment, and B, the prism edge treatment, are good design candidates for reducing dB levels in the low frequencies using porous mattress materials. These designs are shown below.

Figure 149. Geometric view of Case A
Table 28 and 29 below show the new cumulative dB values in the range 0-600 Hz for cases A and B designs for all mattress materials.

Table 28. Results for case A and mattress foam for frequency range 0-600 Hz

<table>
<thead>
<tr>
<th>Mattress Material</th>
<th>Mattress Thickness (in.)</th>
<th>Location</th>
<th>Total $p_{rms}^2$ (Pa)</th>
<th>Cumulative dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>1</td>
<td>Incubator</td>
<td>1.188E-5</td>
<td>44.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CV</td>
<td>1.0017E-5</td>
<td>43.99</td>
</tr>
<tr>
<td>Polyimide</td>
<td>3</td>
<td>Incubator</td>
<td>2.6421E-5</td>
<td>48.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CV</td>
<td>4.353E-6</td>
<td>40.37</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>4</td>
<td>Incubator</td>
<td>4.916E-6</td>
<td>40.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CV</td>
<td>8.9187E-6</td>
<td>43.48</td>
</tr>
<tr>
<td>Melamine</td>
<td>4</td>
<td>Incubator</td>
<td>4.7111E-6</td>
<td>40.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CV</td>
<td>8.5307E-6</td>
<td>43.29</td>
</tr>
</tbody>
</table>

Table 29. Results for case B and mattress foam for frequency range 0-600 Hz

<table>
<thead>
<tr>
<th>Mattress Material</th>
<th>Mattress Thickness (in.)</th>
<th>Location</th>
<th>Total $p_{rms}^2$ (Pa)</th>
<th>Cumulative dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>1</td>
<td>Incubator</td>
<td>4.5209E-6</td>
<td>40.53</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CV</td>
<td>5.4566E-6</td>
<td>41.35</td>
</tr>
<tr>
<td>Polyimide</td>
<td>3</td>
<td>Incubator</td>
<td>2.7817E-6</td>
<td>38.42</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CV</td>
<td>4.8068E-6</td>
<td>40.80</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>4</td>
<td>Incubator</td>
<td>6.0301E-6</td>
<td>41.78</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CV</td>
<td>1.1532E-5</td>
<td>44.60</td>
</tr>
<tr>
<td>Melamine</td>
<td>4</td>
<td>Incubator</td>
<td>6.1701E-6</td>
<td>41.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CV</td>
<td>1.850E-5</td>
<td>46.65</td>
</tr>
</tbody>
</table>

From tables 28 and 29 above, the lowest values for the cumulative dB level in the incubator and control volume are highlighted. For case A, the melamine and polyimide have the lowest values.
for the incubator and control volume respectively, while for case B, the polyimide foam dominates both categories. With these low cumulative dB values, the foam designs A and B could provide a large decrease in dB values if the foam was used in the hospital environment incubator. For future work, these two foam designs will be applied with a focus of reducing the ventilator pump noise.

5.4 Decibel A Weighted Filter Comparison

The comparison of the dB values if converted to dB[A] from the case design results cannot be directly compared to the hospital results in dB[A] because the outside sources are not the same. A speaker would have to be used in the NICU with the same amount of excited white noise going in the same direction as it was in the anechoic chamber. If the same set up was performed in the hospital, then it is safe to assume that the dB[A] values would decrease the same amount over a set of frequency bands as they did in the simulation tests. Then the statement can be made if levels were successfully below the recommended 45 dB[A]. If simply the design cases were implemented into the hospital incubator without taking into account the noise source, then the design cases might produce different effects. For example, the hospital environment might introduce a low signal in low frequencies or in a natural setting constantly vary in which the foam might not have any effect or constantly be changing. Another difference is that in the hospital, in addition to the outside noise source (background noise, ventilator pump, fan etc.) there was also the air noise coming out of the tube or lungs in the incubator. The simulation model did not generate an “inside” noise source. This would also have to be modeled correctly in order to allow for a more appropriate comparison set up.

Taking the best design, case G, with the best mattress over the whole frequency range and computing the dB[A] values will show the dB[A] levels. This is shown below in figure 151.

![Figure 151: Correction factor applied from dB to dB[A]](image-url)
The cumulative dB value is 40.06 for this design for the three inch polyimide. The cumulative dB\([\text{A}]\) value is 32.26 dB\([\text{A}]\), below the recommended 45 dB\([\text{A}]\). This is simply a demonstration to show the corresponding dB\([\text{A}]\) values using the outside source signal that was used, in an incubator what the levels would look like. Because the correction factor from dB to dB\([\text{A}]\) is a function of frequency and irrelevant of the type of test being performed, noise source etc., this correction factor can be applied to any of the previous cases.

5.5 Data Visualization

The following figures display 3D viewings comparing the original mattress and the four inch polyurethane mattress for case H at 1300 Hz. The original mattress was also plotted at 200 Hz to show the comparison in isosurface and sound pressure level inside the sphere and incubator. These parameters were chosen because case H showed a significant change in dB level in the upper frequency range between the original mattress and the foam mattresses. Polyurethane was the lowest at the frequency of 1300 Hz which is why it will be a good representation of this difference. It is necessary to show the original mattress as the baseline, when comparing to see how the porous materials affect the sound pressure levels heard at the baby control volume.

*Note:* the plane wave pressure magnitude was set to 1 Pascal (94 dB) for convenience in interpreting the results.

![Figure 152. Sound pressure level for original mattress, case H at 200 Hz](image)
The three legends displayed in the figures 152-154 above represent the following, from left to right: the foam slice legend which includes the mattress and any other foam case design that was used in that model. For the three previous plots, this refers to case H, the Top Covered Angled Treatment. The middle legend is associated with the interior incubator slice legend. This included the air space and the control volume air space. The third legend shown the furthest to
the right is the exterior sphere slice legend that includes everything exterior to the incubator, namely the sphere air space. For all three figures 152-154, the exterior sphere slice legend has a higher maximum dB level than the other two legends. This is due to the 1 Pascal amplitude plane wave originating in the sphere domain. When the wave passes through the incubator, the SPL values decrease.

One can see many differences in figures 153 and 154 above when comparing the sound pressure levels for the original mattress and polyurethane mattress at 1300 Hz. The plane wave was initiated at the left center side of the sphere and continues to move to the right, into the incubator and out. With a plane wave of 94 dB, one can see the correct amplitudes for the wave when it enters the incubator. Once the wave is inside the incubator, the foam begins to absorb. It is clearly noticeable that in figure 154 it is much quieter inside than in figure 153 where the original mattress is used. In the original mattress case it appears that the mattress is absorbing minimally, for the sound pressure level is consistent with the wave when it hits the mattress. Contrastingly, in the polyurethane plot, when the wave reaches the mattress, the polyurethane is absorbing sound and as a result, decreasing the sound levels heard in the incubator. It is apparent in the polyurethane plot that the SPL inside the control volume is lower than the one with the original mattress. When analyzing the foam hanging at an angle in both plots, the wave tends to deform according to the foam layout. For future research this is informative so one can create and assign foam designs based on the wave form, shape etc.

When comparing figure 152 and figure 153, it is apparent that the plane wave for the 200 Hz frequency is quite different than at 1300 Hz. When the frequency is lower, the wavelength is longer. In the case of 200 Hz, the wavelength is \[ \frac{343 \text{ m/s}}{200 \text{ Hz}} = 1.715 \text{ m} \]. This is longer than the length of the incubator which is why there is only one visible wave coming through, near the center of the incubator.

An isosurface is defined as a 3D surface that represents points of a constant value. Therefore these three plots show the shape of the SPLs and provides insight with the wave when it interacts with the configurations, such as the mattress, baby etc. In the following figures 155 through 157, the isosurface plots for the same case and materials are plotted inside the incubator and baby control volume.
Figure 155. Isosurface plot for original mattress, case H at 200 Hz

Figure 156. Isosurface plot for original mattress, case H at 1300 Hz
When comparing figures 155 and 156 at the two different frequencies, the single wave is almost centered in the incubator and reaches levels in the low 30 dBs. After the wave has continued moving through the incubator as it gets towards the back side, the wave starts to curve up as a result of the shape of the angled foam. Taking this into consideration for future foam designs could lead to a more detailed explanation of how the wave interacts with different placed foams. When examining the incubator, it is notable that in figure 156 the sound levels throughout that air space are louder than the ones seen in figure 157 where the polyurethane foam is used. These values range from approximately 10 – 67 dB for the original mattress and 0 to 60 dB for polyurethane. In the control volume air space it is quieter inside for the polyurethane foam than the original mattress. Additionally, the mattress is absorbing sound which is again visibly seen inside and around the mattress.

Figure 158 below shows the isosurface at the baby control volume for the polyurethane foam case H at 1300 Hz.
Figure 158. Isosurface plot for polyurethane mattress at baby control volume case H at 1300 Hz.

From figure 158 above the sound pressure levels in the volume of air around the baby’s head has a range of values beginning around 7 dB and increasing to 52 dB. From observation, the levels inside are mostly in the upper ranges where it should be close to 50 dB. This value would match up with the SPL heard at 1300 Hz polyurethane foam once the correction factor is applied to the 1 Pascal for that frequency. Also from this figure the sound hard boundary is demonstrated because the wave is not penetrating through the baby. Furthermore, the loudest area in the control volume is near the top of the baby’s head whereas the quietest area is behind the baby’s neck.

5.6 Conclusions

Finite element analyses were successfully performed using COMSOL to determine the acoustic performance of several design concepts using passive treatments in incubator applications. Following the approach defined above, all of the project aims were addressed and the following conclusions are drawn.

- FEA modeling approach was successfully used to model 8 different foam design cases and 4 different mattresses to quantify SPL.
- Validation plots were acceptable due to their similarity in trends and in the appropriate ranges in SPL values.
- The top design, case G, for polyimide foam had a cumulative dB[A] level of 32.36 dB[A], well below the recommended 45 dB[A], when using the previous design conditions.
- The best performing single mattress over the whole frequency range was three inch polyimide for the control volume and incubator.
• The top designs based on dB reduction across the entire frequency range tested for the control volume are ranked as follows:
  - Case G: Vertical Hanging Blocks Treatment (1x3)-Polyimide
  - Case H: Top Covered Angle Treatment-Polyurethane
  - Case B: Prism Edge Treatment-Polyimide
  - Case A: Tetrahedral Treatment-Polyimide
  - Case E: Above Head Block Treatment-Polyimide
  - Case C: Vertical Hanging Blocks Treatment (1x5)-Polyimide
  - Case F: Horizontal Hanging Blocks Treatment (3x5)-Polyimide
  - Case D: Vertical Hanging Blocks Treatment (3x5)-Original Mattress

• The top designs based on dB reduction across the entire frequency range tested for the incubator are ranked as follows:
  - Case G: Vertical Hanging Blocks Treatment (1x3)-Polyurethane
  - Case H: Top Covered Angle Treatment-Polyurethane
  - Case F: Horizontal Hanging Blocks Treatment (3x5)-Polyimide
  - Case B: Prism Edge Treatment-Polyimide
  - Case E: Above Head Block Treatment-Polyimide
  - Case C: Vertical Hanging Blocks Treatment (1x5)-Polyimide
  - Case A: Tetrahedral Treatment-Polyimide
  - Case D: Vertical Hanging Blocks Treatment (3x5)-Polyimide

• For all cases analyzed, the best performing mattress material at low frequencies is polyimide for the control volume.
• For all cases analyzed, the best performing mattress material at middle and high frequencies is polyurethane for the control volume.
• For all cases analyzed, the range in dB for the entire frequency range for the control volume was between 40.06 dB and 50.40 dB.
• For all cases analyzed, the range in dB for the entire frequency range for the incubator was between 36.69 dB and 48.34 dB.
• Cases G and H show the most dB reduction due to foam placement within the incubator. Case G included three hanging (vertical) pieces of foam at full incubator width. This foam design captured sound effectively due to its high foam volume as well as its perpendicular orientation to the wave. Recall that the case H design was based on angled foam which increases its relative thickness to the incoming plane wave resulting in higher sound absorption.
• The three-walled corner design A and the prismatic edge design B showed promise in the lower frequency range (100-400 Hz). An important design benefit shared by both A and B is that they introduce minimal visibility concerns inside the incubator.
• FE modeling was effectively used to model the acoustic interaction between porous material and pressure acoustics.
• For this study, a Δf of 50 Hz was used to determine all results. Smaller Δf intervals would provide more performance details for the given range analyzed.
• Effective use of isosurface rendering of SPL values within the incubator and through the porous material was shown to provide insight into pressure wave shape.
• Cutting plane rendering of SPL was also shown to provide improved understanding of SPL distribution.
Mesh densities based on wavelength divided by 5 was shown to be within 5% of the computed values using a mesh based on frequency divided by 8

Chapter 6. Anechoic Chamber Testing

6.1 Anechoic Chamber Experiment

A variety of tests were performed on a Drager 8000 SC incubator in the anechoic chamber at Virginia Tech. This incubator was acceptable when directly comparing results to the incubators in the NICU due to a similar structure and therefore will produce comparable acoustic responses [7]. This chamber from wedge tips to wedge tips has dimensions of 5.4 m x 4.1 m x 2.4 m, a cutoff frequency of 100 Hz and is usually used when conducting experiments in the “free field” condition. This means that there are no reflective surfaces and obstructions in all directions.

The objective of this study was to find a comparative measure of the noise reduction using different mattresses. Because the inside of the incubator was low in acoustic damping, adding different acoustic foam to increase the sound damping will contribute to the overall decrease in SPL heard in the interior of the incubator. The current experiment involved exciting the incubator in one angle of incidence with a speaker in an anechoic chamber. The noise was compared inside and outside of the incubator at two positions, baby right and left ears, using the transfer function.

6.2 Test Setup and Conditions

A baby doll about the size of a premature newborn was used for the representation of an actual baby. Quarter inch Brüel & Kjaer (B&K) microphones in the baby’s ears will approximate acoustic diffraction around the baby. Figure 159A shows the baby left ear microphone. Expanding foam filled the inside of the baby up in order to have a non-hollow object and provided the baby with more weight to take into account an actual newborn’s size. The baby was placed in the incubator with its feet towards the noise source speaker and remained in the same location for all tests that followed. A JVC speaker was used with dimensions of 6.5 in. x 9.25 in. x 10.5 in. which was driven to produce broadband white noise and excite the incubator in one direction. This is seen in figure 140A below. The loudspeaker was located approximately 5 feet from the incubator and supported 3 feet off the ground. Internal and external half inch B&K microphones were also used. The internal microphone was located in the incubator where a wire for microphone support was positioned behind the infant’s head. Figure 159B below displays the microphone and wire. The external one was used as the reference microphone and was located within a foot from the end of the incubator, between that and the speaker. Figure 159A below shows the external microphone location.
The original mattress in the incubator was a one inch thick mattress and constructed from polyurethane foam [15]. Although this is a sound absorbing foam, it was covered with a waterproof plastic that prevents any acoustic absorption from occurring [15]. There has been much research on replacing this mattress with poroelastic foams for a quieter environment. As a result, three different acoustic foams were chosen with varying thicknesses to use as possible replacement mattresses. These can be seen in table 30 below.

Table 30. List of mattress foams and thicknesses used in experiment

<table>
<thead>
<tr>
<th>Mattress Material</th>
<th>Thickness (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>1</td>
</tr>
<tr>
<td>Melamine</td>
<td>2, 4</td>
</tr>
<tr>
<td>Polyimide</td>
<td>1, 2, 3</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>1, 2, 3, 4</td>
</tr>
</tbody>
</table>

The variety of sound absorbing materials and choices of thicknesses were based on individual preference and similar in sizes relevant to a realistic incubator setting. In reality, the presence of pure foam in an incubator for an infant is unfeasible, so another option for a covering over the foam was needed. Tyvek is a very strong material composed of high – density polyethylene fibers and is both an acoustically – transparent and waterproof covering. Tyvek is not perforated with holes that can reduce the effectiveness of its function [48]. The microfibrous, non-perforated structure also allows “breathing” while providing a highly effective water barrier [48]. This is beneficial when applying it as a mattress covering and protectant for the infants to lie on because of light, durable and outstanding chemical resistance characteristics. Furthermore, water and highly polar solvents have very little effect on the properties of Tyvek [49]. This material will be used in several tests as well. Table 31 below displays the tests performed in the chamber.
Table 31. Display of tests performed in chamber

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (in.)</th>
<th>Incubator Top</th>
<th>Tyvek/Plastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>1</td>
<td>Closed</td>
<td>Plastic</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Open</td>
<td>Plastic</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Half – open</td>
<td>Plastic</td>
</tr>
<tr>
<td>Melamine</td>
<td>2</td>
<td>Closed</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Closed</td>
<td>Tyvek</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Closed</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Closed</td>
<td>Tyvek</td>
</tr>
<tr>
<td>Polyimide</td>
<td>1</td>
<td>Closed</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Closed</td>
<td>Tyvek</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Closed</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Closed</td>
<td>Tyvek</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Closed</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Closed</td>
<td>Tyvek</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>1</td>
<td>Closed</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Closed</td>
<td>Tyvek</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Closed</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Closed</td>
<td>Tyvek</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Closed</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Closed</td>
<td>Tyvek</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Closed</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Closed</td>
<td>Tyvek</td>
</tr>
</tbody>
</table>

6.3 Experimental Procedure

In setting up the experiment for data collection, a variety of equipment was needed to produce successful results. The flow chart displayed below shows how microphones and BNC cables were connected in order to gather data.
Figure 160. Display of equipment set up inside and outside anechoic chamber

As seen above in figure 160 three interior incubator microphones were used and are defined as A, B and C. “A” represents the internal microphone whereas B and C represent the right and left ear microphones, respectively. The one external microphone was mounted outside the incubator and can be seen directly to the right of the incubator. All microphones were connected to a signal conditioning box using BNC cables and then connected to a laptop. Signal conditioning is needed for filtering, converting, range matching and any other processes to make sensor output suitable for analog-to-digital conversion and read by computerized devices [45]. In this research, the conditioning box was used to power the microphones, apply gains to the microphones, and filter the frequency output (measured in Hertz). A white noise generator was connected to an amplifier and then routed to a loudspeaker to produce white noise. The amplifier uses energy from a power supply and controls the output the match the input signal shape but with a larger amplitude, hence modulating the output of the power supply [46].

The same data acquisition process that was defined using the Graphical User Interface tool in the hospital was used in the chamber. The same parameter inputs were used in the chamber that was defined in the hospital.
Additional values were needed in a new MATLAB code used to compute the outputted plots for the chamber tests. In the chamber tests, the input was from the external microphone. In the hospital data collection, channels 1 and 2 had 0 dB while channels 3 and 4 had gains of 40 dB. The baby right and left ear microphones had calibration factors of 2.7378 V/Pa and 2.4062 V/P respectively, 2.5366 V/Pa for the internal microphone and external microphone was 0.4476 V/Pa.

**Chapter 7. Anechoic Chamber Results and Discussion**

The results from the anechoic chamber are displayed below. With the external microphone representing the reference location, three different possibilities for the sound pressure level locations were available: baby right ear, baby left ear and internal microphone. Results are shown representing one or more of the three locations. It can be assumed that the results for the baby left and right ear will display similar trends. The transfer function will represent the relationship between one of the microphones inside the incubator and the external microphone. See appendix B for further in depth analysis involving transfer functions. Other results are displayed in 1/3rd octave while others are shown in dB[A] representation. The proper form will be displayed according to the purpose of what is trying to be displayed. Please note that the width of the bars for 1/3rd octave are chosen for clarity purposes.

### 7.1 Plexiglass Canopy Study

The first two plots, figures 161 and 162 displayed below are shown to demonstrate the effect of the plexiglass enclosure being open, partially open or closed.

![Figure 161. Broadband (top graph) transfer function and 1/3rd octave (bottom graph) transfer function between baby right ear microphone and external microphone with plexiglass enclosure closed (blue) and half opened (red) with original mattress](image-url)

Figure 161. Broadband (top graph) transfer function and 1/3rd octave (bottom graph) transfer function between baby right ear microphone and external microphone with plexiglass enclosure closed (blue) and half opened (red) with original mattress
The top broadband plot above shows that both sets of line curves have modes appearing throughout the frequency spectrum, specifically in the range from 700 Hz to 10000 Hz. When the enclosure is half open, the resonance of the modes present is not as severe as those when the enclosure is fully closed. Throughout the entire frequency range except at certain frequency ranges between 100 and 150 Hz, it is quieter inside the incubator when the enclosure is closed, where the dB difference between the enclosure open and closed is between 1 and 8 dB.

![Graph showing broadband transfer function and 1/3rd octave transfer function](image)

**Figure 162.** Broadband (top graph) transfer function and 1/3rd octave (bottom graph) transfer function between baby right ear microphone and external microphone with plexiglass enclosure closed (blue) and opened (red) with original mattress

When analyzing the top broadband plot, many modes are appearing when the enclosure is closed, which was caused by the resonances of the incubator due to an enclosed air space. Hence, the peaks reveal the modal nature of the volume of air enclosed in the incubator. It might be reasonable to assume that the plexiglass would act as a noise barrier, but from the bottom graph the dB values are consistent around the same values with each other for both top open and top closed over the frequency range. When the plexiglass is open, the dB level doesn’t fluctuate nearly as much as it does when the plexiglass is closed from the broadband graph. This is because when the plexiglass enclosure is closed the reflection from the sound is restricted to an enclosed spaced so the dB level varies constantly whereas when the top is open noise can escape the volume of space. At frequency values up to 300 Hz, the plexiglass does not attenuate noise level but at frequencies greater than 300 Hz, sound decreases in the incubator. Specifically, from 100 Hz to 300 Hz, the sound levels have decreased 3 to 7 dB when the enclosure is open. This shows that the reverberance in the interior space of the closed incubator at low frequencies leads to increased sound levels due to the lack of effective acoustic damping. Furthermore, it is assumed here that the physical transmission loss of the sides of the incubator is negligible at low frequencies.
7.2 Tyvek Mattress Cover Study

It is important to demonstrate Tyvek’s effect on the dB level when considering it a possible mattress cover. The following figures will present these findings.

Figure 163. Broadband (top graph) transfer function and 1/3rd octave (bottom graph) transfer function between internal microphone and external microphone melamine without (blue) and with Tyvek (red)

Throughout the whole frequency range there is consistency in both 1/3rd octave transfer function values for with and without Tyvek. This shows that Tyvek doesn’t affect absorption while still serving its purpose of a waterproof and acoustically transparent material.
Figure 164. Broadband (top graph) transfer function and 1/3rd octave (bottom graph) transfer function between internal microphone and external microphone polyimide without (blue) and with Tyvek (red)

The second graph, when looking at the transfer function in 1/3rd octave, shows that the Tyvek appears to not make much of a difference for a three inch thickness at frequencies from 100 Hz to 3000 Hz. Around 800 Hz and 2500 Hz Tyvek helped reduce noise by 2 dB and in the higher frequency range, doesn’t appear to cause any change in noise reduction. Thus Tyvek is considered an appropriate covering for the mattresses because of its micro-porous structure and its little effect on dB reduction.

7.3 Mattress Thickness Study

It is assumed that the more foam, the more sound is absorbed through this material. Therefore, as thickness increases for each foam, the sound should decrease at most frequencies. Depending upon the porous material’s independent characteristics can affect exactly how much sound is being absorbed such as its porosity or speed of sound. The following three figures below represent how sound pressure level can be a function of thickness.

The first set of graphs below compares the dB levels for the three difference mattress thicknesses for polyimide.
Figure 165. Broadband (top graph) transfer function and 1/3rd octave (bottom graph) transfer function between baby right ear microphone and external microphone with polyimide one (blue), two (red) and three (green) inch foam.

From figure 165 above one can see from the 1/3rd octave plot that at low frequencies from around 100 Hz to 400 Hz there isn’t much difference between the dB level as a function of thickness. This could be due to the fact that passive noise control doesn’t serve much significance in sound reduction at lower frequencies [14]. In frequencies from around 500 Hz to the end of the frequency range, comparable trends start to become noticeable. As thickness increases, the SPL level decreases, with the greatest dB differences occurring in the frequency range 700 – 900 Hz for a one inch and two inch mattress and a frequency of 4000 Hz for a one inch and three inch mattress. These dB levels are 10 dB and 9 dB respectively. For all thickness comparisons it is shown that the larger the thickness the more absorption. The thickness must be kept to a reasonable value in order to accommodate the infant in the incubator.

Shown below in figure 166 are the two thickness comparisons for melamine.
Figure 166. Broadband (top graph) transfer function and 1/3rd octave (bottom graph) transfer function between baby right ear microphone and external microphone with melamine one (blue) and two (red) inch foam.

From figure 166 above similar trends for sets of frequencies occur as compared to those from the polyimide in figure 129. From 100 Hz to 400 Hz the mattress thickness increase doesn’t appear have an effect on the sound reduction. At 500 Hz, the foam absorbs more sound for the four inch melamine than the one inch, producing about a 10 dB noise reduction. As frequency increases the foam thickness has a larger impact on the noise reduction level, ranging from 1 dB to 10 dB reduction, with a large reduction occurring again around 4000 Hz.

The next plot displays the dB levels using polyurethane foam mattresses.
From figure 167 above in the lower frequency range from 100 Hz to 300 Hz, similar results again are shown compared to the polyimide and melamine results. There is not much variation in dB fluctuation among the foam thicknesses as well as their dB change over the lower frequency range. For the remaining frequencies, as the thickness increases, with the exception of a few frequencies, when comparing the one inch foam to the other thicknesses, the dB level significantly decreases. Specifically, at frequency of 500 Hz the four inch polyurethane helped decrease the sound pressure level by almost 16 dB. Additionally, from 3000 Hz to 10 kHz there is consistent decrease in dB value as thickness increases.

7.4 Mattress Material Study

The significance of the next results will show the effects of the material used. These plots will indicate that some of foam may produce better results depending on the thickness used.

The following figure will compare the one inch results. The baseline curve will be the original mattress in each plot.
Figure 168. Broadband (top graph) transfer function and 1/3rd octave (bottom graph) transfer function between baby right ear microphone and external microphone with original one inch mattress (blue), polyimide one inch (red) and polyurethane one inch foam (green).

From figure 168 when looking at the third octave plot, it is seen that at some lower frequencies from 100 Hz to 200 Hz there is minimal change in dB fluctuation. Beginning around 300 Hz to the end of the frequency range, it is very noticeable that when compared to the original mattress, the one inch polyimide and polyurethane reduce dB levels ranging from 2 dB to 8 dB. At frequency ranges from 1000 Hz to 10 kHz it was loudest at the baby right ear for no mattress than any of the other three mattresses. At these specific frequencies they are most affected by any sort of mattress and can be targeted when wanting to decrease the noise level even further.

Figure 169 below shows the results of different foams for a two inch mattress.
Figure 169. Broadband (top graph) transfer function and 1/3rd octave (bottom graph) transfer function between baby right ear microphone and external microphone with original mattress on inch mattress (blue), polyimide two inch (red), melamine two inch (green) and polyurethane two inch foam (magenta).

Figure 169 demonstrates that as thickness increased to two inch foam mattresses, in the middle to higher frequencies there becomes a larger dB decrease. This is an improvement as compared to the results with all one inch mattresses. Beginning around 1000 Hz to the end of the frequency range, each of the three foams decrease dB level compared to the original mattress by 3 to 10 dB. The largest dB reduction for the polyimide foam occurred around 1600 Hz, for melamine foam around 5000 Hz and 3000 Hz for polyurethane.

The following figure shows the three inch foams compared to the original one inch mattress.
Figure 170. Broadband (top graph) transfer function and 1/3rd octave (bottom graph) transfer function between baby right ear microphone and external microphone with the original one inch mattress (blue), polyimide three inch (red) and polyurethane three inch foam.

Figure 170 above proves that there is again, a large decrease again in dB attenuation over the majority of the frequency range. Specifically, from frequencies 1000 Hz and up, both the polyimide and polyurethane show drastic differences in dB level compared to the original mattress. At frequency 1600 Hz the dB level has decreased about 11 dB which is a large improvement in the noise reduction.

The comparison between the original mattress and a four inch melamine mattress and a four inch polyurethane is presented below in figure 171.
Figure 171. Broadband (top graph) transfer function and 1/3rd octave (bottom graph) transfer function between baby right ear microphone and external microphone with melamine four inch (blue) and polyurethane four inch foam (red)

From figure 171 both the melamine and polyurethane foam show significant decrease in dBs throughout the entire frequency range with the exception of frequency at 200 Hz. There is improvement from the previous thicknesses of one, two and three inch mattresses the most in the upper frequencies. In the lower and upper frequencies the polyurethane tends to show the most progress in the dB reduction but only by 3 dB difference whereas in the middle frequencies, the melamine shows the most significant reduction in dB levels.

After executing the anechoic chamber experimental tests, discussion among the results is provided. Before understanding how SPL was affected by different porous materials, a concept of basic noise performance was tested. The foundation for this experiment was the argument that simply closing the plexiglass enclosure would reduce sound pressure level inside the incubator, to block out the noise from the outside environment. When analyzing the effect of Tyvek, there was consistency in the dB levels between those foams with and without this material. Because of its waterproof and acoustically transparent behavior, this material serves its purpose as both a mattress covering for the infant as well as its minimum contribution to the dB levels heard in the incubator at the baby’s ears. Data was then measured comparing the thicknesses of each mattress individually.

The following table displays for each material, which thickness proved to be the best in reducing dB with the baseline against the minimum thickness of that material. Note: Not all foams were tested at the same thickness.
Table 32. Results comparing the effect of thickness for each mattress

<table>
<thead>
<tr>
<th>Material</th>
<th>*Frequency Range</th>
<th>Thickness (in.)</th>
<th>Reduction Range dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyimide (1”,2”,3”)</td>
<td>Low</td>
<td>3</td>
<td>0.5 – 1</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>2</td>
<td>1 – 5</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>3</td>
<td>0.5 – 9</td>
</tr>
<tr>
<td>Melamine (2”,4”)</td>
<td>Low</td>
<td>4</td>
<td>0.5 – 2</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>4</td>
<td>0.5 – 5</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>4</td>
<td>0.5 – 11</td>
</tr>
<tr>
<td>Polyurethane (1”,2”,3”,4”)</td>
<td>Low</td>
<td>4</td>
<td>0.5 – 6</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>4</td>
<td>0.5 – 11</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>4</td>
<td>0.5 – 12</td>
</tr>
</tbody>
</table>

*Low Frequency: 100 – 400 Hz  
Middle Frequency: 401 – 2000 Hz  
High Frequency: 2001 – 10000 Hz

One can note from the table above that in all frequency ranges for each material the maximum thickness proves to decrease dB level the most. The dB reduction range is highest for the polyurethane foam followed by the melamine then the polyimide. It therefore can be assumed that the thicker the mattress, the more sound is absorbed.

The next set of results compared individual thicknesses to analyze foam performance. The following table displays for each thickness, the best material in reducing dB compared to the original mattress. Note: Not all foams were tested at each thickness.

Table 33. Results comparing the effect of material at each thickness

<table>
<thead>
<tr>
<th>Thickness (in.)</th>
<th>*Frequency Range</th>
<th>Material</th>
<th>Reduction Range dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low</td>
<td>Polyurethane</td>
<td>1 – 2</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>Polyimide</td>
<td>0.5 – 5</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>Polyurethane</td>
<td>2 – 10</td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
<td>Polyurethane</td>
<td>0.5 – 2</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>Polyimide</td>
<td>4 – 8</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>Polyurethane</td>
<td>5 – 10</td>
</tr>
<tr>
<td>3</td>
<td>Low</td>
<td>Polyurethane</td>
<td>0.5 – 5</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>Polyimide</td>
<td>1 – 10</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>Polyurethane</td>
<td>3 – 9</td>
</tr>
<tr>
<td>4</td>
<td>Low</td>
<td>Polyurethane</td>
<td>0.5 – 8</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>Melamine</td>
<td>1 – 13</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>Polyurethane</td>
<td>3 – 8</td>
</tr>
</tbody>
</table>

*Low Frequency: 100 – 400 Hz  
Middle Frequency: 401 – 2000 Hz  
High Frequency: 2001 – 10000 Hz

It can be noted from the table above that polyurethane tends to impact the dB reduction level for the lower frequency range for all thicknesses. For the middle frequencies, polyimide is the best
representation of noise reduction with the exception of 4 inches, in which melamine dominates. The best dB reduction in any range for any thickness was the four inch melamine for middle frequencies, although all dB reductions for the best range are very similar in value.

7.5 Conclusions

The thickest mattress material provided the greatest sound absorption, resulting in the largest decrease in dB level. These thickness values correspond to the polyimide, melamine and polyurethane are 3, 4 and 4 inches respectively. When comparing materials to a relative thickness, polyurethane is the recommended material for a low and high frequency range whereas polyimide is suggested for middle frequencies. If these tests were to be repeated, the same thickness for each material would be used in order to have a sufficient and accurate conclusion when all foams are taken into account representing each thickness. Tyvek is considered an appropriate covering for the mattress because of its waterproof and acoustic transparency as well as its little effect on the dB level.

The primary focus of this research was aimed to reduce sound pressure levels in a neonatal incubator by application of simulation and experimental work. The dual use of both approaches has resulted in improvements in sound absorbing potential for existing incubator designs as well as creating insight for additional research in passive noise control techniques. Continued work in the previous studies for finite element modeling and experimentation can be expanded further below.

Chapter 8. Overall Summary and Conclusions

The main objective of this research paper was to use Finite Element Analyses to design passive noise control treatments to reduce SPL in incubators. The first step was to effectively understand current sound pressure levels and noise sources inside incubators within a NICU hospital environment by collecting and analyzing data. Once this was performed, a finite element model was successfully developed using COMSOL and demonstrated the ability to predict pressure acoustics. Experimental tests were executed in an anechoic chamber on an incubator using sound absorbing porous materials. The Finite Element model was validated using the chamber experimental results. The validated model was used to successfully design and analyze novel passive noise treatments that further reduced interior incubator noise. An overall summary of the conclusions is as follows:

- The ventilator pump is the most substantial contributor to the overall SPL in the frequency range up to 150 Hz.
- When comparing high and low pressures of the ventilator pump, the levels heard at all microphones were lower in SPL for the lower pressure cases.
- When the ventilator pump is located on the outside of the incubator the noise levels measured inside in incubator are only slightly quieter by less than 1 dB.
- Broadband sound also adds to the SPLs for frequencies greater than 150 Hz.
• The top design for polyimide foam had a cumulative dB[A] level of 32.36 dB[A], well below the recommended 45 dB[A], when using the previous design conditions.
• The best performing single mattress over the whole frequency range was three inch polyimide for the control volume and incubator.
• For all cases analyzed, the best performing mattress material at low frequencies is polyimide for the control volume.
• For all cases analyzed, the best performing mattress material at middle and high frequencies is polyurethane for the control volume.
• Mesh densities based on wavelength divided by 5 was shown to be within 5% of the computed values using a mesh based on frequency divided by 8.
• The top two designs based on dB reduction across the entire frequency range tested for the control volume are:
  
  Case G: Vertical Hanging Blocks Treatment (1x3)-Polyimide
  
  Case H: Top Covered Angle Treatment-Polyurethane
• The top two designs based on dB reduction across the entire frequency range tested for the incubator are:
  
  Case G: Vertical Hanging Blocks Treatment (1x3)-Polyurethane
  
  Case H: Top Covered Angle Treatment-Polyurethane
• Thickest mattress provided the greatest sound absorption in the anechoic chamber, resulting in the largest decrease in dB level
• Polyurethane is the recommended material for a low and high frequency range
• Polyimide is the recommended material for middle frequencies
• Tyvek is considered an appropriate covering for the mattress because of its waterproof, micro-porous and acoustic transparency

Chapter 9. Future Research Directions

9.1 Additional Modeling

Numerical simulation has been shown to be a useful design tool when properly validated against experimental testing. The ease and simplicity of applying various combinations of foam designs, size and material make the feasibility for new tests practical and time efficient. There were eight additional foam designs created inside the incubator and three different foam materials, all of varied thicknesses. However, for each test both the mattress and interior foam treatment were fabricated form the same foam material. To build on this approach, different shapes and materials used in this research could be combined to create new designs to reduce sound pressure levels inside the designated space. For instance, case B, the prism edge treatment, could be
expanded to applying vertical triangular prisms along multiple edges of the incubator including
the top. Additionally, using multiple foam materials throughout tests for both the mattress and
the foam designs might provide a different set of outcomes, with the possibility of better material
absorption with differing location. The foam dimensions alone would produce dissimilar results.

Modifying the acoustic source location can become an important factor when determining the
true effect of the foam inside the incubator. For future tests the background plane wave can be
positioned in locations more representative of common hospital environments and the acoustic
performance determined. Creating an inside noise source that replicates the air tube (as seen in
hospital incubators) would also add a small degree of improvement to the model accuracy.
Although it was created to show diffraction around its body, defining an impedance for the baby
as well as implementing additional human features could show more of an illustration of its
affect. SPL sensitivity to control volume design at the ears should also be studied.

9.2 Hospital Testing

One of the most important factors in finalizing the effect of foam is to demonstrate its
performance in the hospital environment. Because noise is produced from the operating
equipment and nurses are consistently moving around the NICU, this is a proper and appropriate
location for testing. The three different combinations of foam materials and thicknesses can be
tested in a hospital incubator to see if they will absorb a similar amount of sound when actual
hospital noise is in the surroundings, with the appropriate noise sources initially followed by the
actual noise levels heard. The additional case designs modeled in finite element can also be
physically created and implemented to see their direct effect. Adding panels of foam to the
ceilings of the rooms in the NICU could broaden the range of noise reduction to the entire
enclosure space. This will further minimize the amount of noise that travels to the inside of the
incubator. The time span for collection of data was originally 60 seconds and will be expanded to
allow for more accurate readings. When collecting data in the future, a room with multiple
incubators will be more sufficient in understanding the overall problems with the contributing
noise factors as opposed to only having data from an isolated room with one incubator.

9.3 Anechoic Chamber Testing

Experimental work is also a significant factor for post processing additional tests. The additional
foam designs previously created in the finite element model can be recreated in the anechoic
chamber. This would include the additional foam designs with the original baby mattress and
those in combination with a porous mattress material. Attaching foam to the outside of the
incubator could also further reduce noise near the baby’s ears. This could be replicated in the
hospital environment. The loudspeaker used to represent the source can also be relocated to new
positions as well and possibly incorporate noise levels heard in the hospital to use as the input,
such as the ventilator pump.

Investigating noise control at low frequencies might be a future point of focus. By applying this
to the lower frequency range with the addition of the passive noise control techniques, the overall
sound pressure levels should decrease throughout the entire frequency range.
9.4 Reverberation Chamber

The purpose of a reverberation chamber is to create a random incidence sound field. This allows for a uniform distribution of acoustic energy and random direction of sound incidence over a short period of time [50]. Multiple microphones hanging from all directions throughout the chamber and the incubator could be arranged. The combination of many microphones will allow an estimate of acoustic power inside and outside the incubator. It would also provide a more accurate reading of the sound that is heard throughout the incubator’s environment to get a more averaged noise reduction reading. Compared to the anechoic chamber where white noise was distributed in one direction, this technique will be more accurate with multiple microphones. As a result, the transfer function trends should output curves with less noise variation.

9.5 Helmholtz Resonator

Additional tests to be proposed would include using a Helmholtz resonator and placing it either under the mattress once it is elevated or underneath the incubator. The way a Helmholtz resonator works is the following: Air is forced into a cavity, resulting in a pressure increase [51]. When the external force pushing the air into the cavity is removed, the pressure of the air inside the incubator will flow out [51]. The cavity is then left at a pressure lower than the outside, causing the air to be drawn back in. Each time the process repeats, the magnitude of the pressure changes [51]. If trying to attenuate a certain tone, this is of good use since the resonator is tuned at one isolated resonant frequency and no other resonances below approximately 10 times that frequency value. Some of the tests have one frequency where the SPL is high, such as 1600 Hz, which occurs in many of the simulation tests. To achieve this frequency value ($f$), the following equation is solved for the resonator volume ($V$), length ($L$) and area of its neck ($A$). $S$ is defined as the speed of sound, particularly 343 m/s.

$$f(Hz) = \left(\frac{S}{2\pi}\right) \sqrt{\frac{A}{LV'}}$$

Eq. 8

This resonator’s function would benefit the overall root mean square pressure value throughout that designated volume of space and decrease the sound pressure level only at the tuned frequency [52].

One benefit of using a Helmholtz resonator is that the neck can be easily varied to produce different tones [53]. For instance, a small neck area might produce a deep bass tone. Furthermore, increasing the area of the neck increases the inertia of the air proportionally, but also decreases the velocity at which the air rushes out [53]. The resonators can be used in architectural acoustics to reduce undesirable low frequency sounds or used to build acoustic liners for reducing the noise of aircraft engines [53].

Based on the results from this research, it has been conclusively shown that the design and analysis of passive noise control devices using numerical and experimental techniques can result in acoustic treatment products that reduce SPL in incubator environments. The potential is a
family of material shapes and sizes that can be combined to produce products that decrease short and long term hearing loss as well as psychological damage of the premature infant.
References


[34] U. o. R. I. D. o. E. a. C. Engineering, "FFT Tutorial".


[64] Extra2. [Online].


[76] I. P. Iddamalgoda and R. V. Coorey, "Study of Non - Linear Stress - Strain Curves of Locally Available


Appendix A Finite Element Analysis Theory

This appendix provides a high level discussion on finite element (FE) theory followed by a summary of COMSOL’s approach to using FE to solve multi-physics applications.

Finite element analysis is a method of analysis in which the field equations of mathematical physics are approximated over simple regions and then assembled together so that the equilibrium or continuity is satisfied at the interconnecting nodal points of the domains [41]. When understanding present day notation of the FE Method, a simple polygon formulation is most often considered where each side of the polygon can be called a “finite element.”

A common derivation for the FE equations uses a weighed residual method, for example the Galerkin method or least squares approach, which led to interest among applied mathematics in applying the FEM for the solution of linear and nonlinear differential equations [54]. A similar procedure is understood when choosing a mesh to apply over a boundary or domain. As the number of elements increases, the chances of improving the results by converging to more exact answers are attained.

Three primary steps in a finite element analysis description include preprocessing, analysis and post processing. In preprocessing, the user constructs a model of the part to be analyzed where the geometry is divided into a number of discrete subregions and are connected at discrete points called nodes [55]. In this step physics are chosen, boundary conditions are applied, meshes are implemented, loads are defined and any other necessary condition is applied. Some of these preprocessors can overlay a mesh on a preexisting CAD file so that FEA can be done in a convenient way as part of the computerized drafting-and-design process [55]. In the analysis step, the preprocessor prepares the dataset for input to the finite element code which builds and solves a system of linear or nonlinear sets of equations. The last step is post processing which consists of using graphical displays to assist in visualizing results. For instance, colored contours representing stress levels for deformed structures, isosurface plots showing sound pressure levels for acoustic analyses, or streamline plots of displacement of a beam are some examples of using visualization tools to understand the (physics) results.

COMSOL FEA Theory

This section of Appendix I follows the FE approach as described in [56]. When using COMSOL for performing FE analyses, there are two different aspects of the modeling that must be correctly understood and applied: the mathematical portion and the finite element portion. The mathematical problem includes the three steps below.

1. Partial differential equation representing the physics
2. Geometry on which to solve the problem
3. Boundary conditions (for static or steady state problems) and initial conditions (for transient problems)

The independent variables are space and time and are represented by (x, y, z, t). The displacement field variables (u, v, w) are the dependent variables. In order to solve the
mathematical problem, the proper boundary conditions must be applied on each boundary based and typically consists of one of the following types.

1. The dependent variable itself. This could include “Essential Boundary Condition” or “Dirichlet Boundary Condition”
2. The derivative of the variable itself. This might include “Natural Boundary Condition” or “Neumann Boundary Condition”
3. The relationship between the dependent variable and its normal derivative [56]

The finite element part of the basic COMSOL Multiphysics application includes the following four steps.

1. Discretization of the computational space
2. Choice of element type-shape, number of nodes, shape function
3. Choice of solver (direct, iterative, preconditioning)
4. Post processing

The basic steps that were followed to perform all of the FE analyses in this thesis using COMSOL are provided below in Table 34.

Table 34. FE modeling design steps

<table>
<thead>
<tr>
<th>Step Number</th>
<th>Step Process</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Physics model selection</td>
<td>3D, Acoustics, Fluid Flow, Heat Transfer, Structural Mechanics, Frequency domain, Time dependent, etc.</td>
</tr>
<tr>
<td>2</td>
<td>Geometry definition</td>
<td>Units, Ellipsoid, block, cone, point, curve, Boolean tools, etc.</td>
</tr>
<tr>
<td>3</td>
<td>Material properties specifications</td>
<td>Implement built in material, create own material, add specific properties, define materials to geometry</td>
</tr>
<tr>
<td>4</td>
<td>Boundary conditions and initial conditions assignments</td>
<td>Sound hard boundary, symmetry, pressure acoustics, porous material, fixed constraint, impedance, define source etc.</td>
</tr>
<tr>
<td>5</td>
<td>Element type selection and mesh generation</td>
<td>Physics/User controlled mesh, tetrahedral, swept, mapped, triangular</td>
</tr>
<tr>
<td>6</td>
<td>Equation solver selection</td>
<td>Direct (full matrix conversions), indirect</td>
</tr>
<tr>
<td>7</td>
<td>Post process results</td>
<td>Derived values, isosurface plots, stress plots, multislice, particle tracing, streamline plots</td>
</tr>
</tbody>
</table>

Depending on the design objectives of the study, the FE analyses can be performed in either the frequency domain or the time domain. A few common examples that are performed in the frequency domain are provided below:

1. Solving for steady state pressure at a single frequency (Solutions to the Helmholtz).
2. Determining the acoustic modes of a structure typically referred to as an Eigenfrequency study.
3. Pressure acoustics analyses to determine SPL levels throughout a volume. Since this analysis approach was used to satisfy the aims in this research, further discussion follows.

The Pressure acoustics physics model within COMSOL solves the Helmholtz equation for the complex acoustic pressure. The Helmholtz equation is shown below in equation 9.

\[ \nabla \cdot \left( \frac{1}{\rho_0} \nabla p \right) + \left( \frac{1}{\rho_0} \frac{\omega}{c} \right)^2 p = 0 \]  \hspace{1cm} \text{Eq. 9}

For constant density, the equation from above reduces to the following equation below.

\[ \nabla^2 \cdot \left( \frac{\omega}{c} \right)^2 p = 0 \]  \hspace{1cm} \text{Eq. 10}

The most common boundary conditions (BC) required to solve Eq. 9 used in this research are the following:

1. **Sound hard boundary condition.** This BC is applied on all acoustically rigid surfaces and enforces the Neumann condition where the normal velocity, \( \frac{dp}{dn} = 0 \). Physically smooth boundaries are necessary for the normal derivative to exist. Corner points, for example, can cause irregularities in the solutions since the normal vector is not well defined. The geometric symmetry of the incubator allowed for modeling ½ of the incubator structure and as such required the use of Sound hard boundary along the symmetry plane, see also Item 4. Sound hard boundaries were also applied for the baby.

2. **Impedance condition.** This BC is used to approximate an absorbing panel. The plastic covering from the original mattress in the FE model design was represented and modeled by its complex impedance value.

3. **Perfectly matched layer.** This BC will not reflect normally incident plane waves, cylindrical waves or spherical waves. Its primary use is to approximate an infinite space without physically having to model it. This was used extensively in this research by creating an “outer boundary” that was in close proximity to the incubator.

4. **Background pressure field.** Defines a plane wave over a domain in the geometry.

5. **Symmetry condition.** If the physical system to be modeled is a geometrically symmetric system, the symmetry boundary can be applied and it will act like a rigid wall; the derivative of pressure will be zero on the symmetry boundary. A major benefit is a significant reduction in computational time, since only ½ of the problem needs to be modeled.

6. **Other BC’s not used in this research include:** Acceleration boundary condition that produces sound through the vibration of the boundary; a plane wave/ spherical wave radiation boundary condition which accounts for reflections and refraction; point sources, either volume flow source or monopole source that radiates as a sphere or monopole distribution.
Lastly, choosing a solver is important and is largely influenced by the mesh geometry, structural non-linearities, and computational resources. For most applications, the direct solvers tend to be more robust (likely to converge) but require more memory. [56] There are several parameters that control the solver; however, the default values were successfully used in this research.
Appendix B Digital Data Acquisition and Spectral Analysis

Data Acquisition Systems

Data acquisition is defined as the process of sampling signals that measure real world physical conditions and converting the resulting samples into digital numeric values that can be manipulated by a computer [57]. Typical components of a data acquisition system include the following (taken from [57]):

- Sensors that convert physical parameters to electrical signals
- Signal conditioning circuitry to convert sensor signals into a form that can be converted to digital values
- Analog-to-digital converters, which convert conditioned sensor signals to digital values

The primary elements in a Data Acquisition System that include data collection, measurement, timing and triggering, a real-time clock, system control, data communication and data archiving [58]. Data acquisition begins with the physical property to be measured. Properties are measured using transducers (sensors) which transform data into a form that can be sampled by a data acquisition system. Because the signal from the transducer needs to be filtered, it is passed through the signal conditioning box. Once digitized, the signal can be encoded to reduce and correct transmission errors [57].

The sample rate and number of samples are two important criteria when determining inputs to achieve a digital signal of the data. The sample rate equation and total sampling time are seen below in Eqs 11 and 12, respectively.

\[
f_s = \frac{1}{\Delta t} \quad \text{Eq. 11}
\]

\[
\Delta t = \text{time between samples} = \frac{\text{samples}}{\text{second}}
\]

\[
\text{Total length of time} = (N - 1) \times \Delta t \quad \text{Eq. 12}
\]

\[
N = \text{number of samples}
\]

The faster the sample rate, the more closely the analog waveform may be described [59]. If the sample rate is too low, the amount of information per unit time describing the signal decreases and errors could occur and the nature of the waveform could be misrepresented. As a rule of thumb, the sample rate should be at least twice the maximum frequency component of the analog signal [59].

There are two different kinds of digital data acquisition systems. The first consists of a computer with a specialized plug-in board that performs analog-to-digital (A/D) and digital-to-analog (D/A) conversion. The second, which was the one used in this study, is a digital measurement system that consists of a computer with an interface board that communicates with external digital instruments, such as function generators.
**Fast Fourier Transform**

A Fast Fourier transform (FFT) is an algorithm that is used to compute the discrete Fourier transform (DFT) \([60]\). FFT’s are used in a wide variety of applications that include digital signal processing and solving partial differential equations. To understand how an FFT works, the explanation of a discrete Fourier transform is necessary. A DFT converts a finite list of equally spaced samples of a function into the list of coefficients of a finite combination of complex sinusoids, ordered by their frequencies, that has those same sample values \([61]\). The output sinusoids of the frequencies are integer multiples of a fundamental frequency. A DFT is defined by the following formula seen in equation 13 below.

\[
X_k = \sum_{n=0}^{N-1} x_n e^{-i2\pi kn/N}
\]

\(k = 0 \ldots N-1\) complex numbers

Direct evaluation of this expression is an \(O(N^2)\) operation, which is computational expensive for increasing \(N\). An FFT can compute the same results in \(O(N\log N)\) operations. The most commonly used FFT is the Cooley-Tukey algorithm. This algorithm is a divide and conquer algorithm that recursively breaks down a DF of any composite size \(N = N_1N_2\) into many smaller DFTs of sizes \(N_1\) and \(N_2\) along with \(O(N)\) multiplications of complex roots of unity. \([60]\) FFT’s were applied extensively in this work for the analysis of sound. It is

**Third Octave Frequency Band**

When representing a frequency domain plot, frequencies can be split up into sections or bands, depending on the information needed in a frequency range. The bands usually have a bandwidth of one octave or one third octave. An octave band is a frequency band where the highest frequency is twice the lowest frequency, whereas a third octave has a width 1/3rd of that of an octave band. The 1/3rd band is more representative of the human ear perception. See equations *14-16 below for calculating frequencies for octave and third octave bands.

Geometric Mean (same for octave & 1/3rd octave):

\[
f_c = (f_1f_2)^{1/2}
\]

Octave Band:

\[
f_2 = 2f_1
\]

1/3rd Octave Band:

\[
f_2 = 2^{(1/3)}f_1
\]

\(f_1 = \text{lower frequency band limit}\)

\(f_2 = \text{upper frequency band limit}\)

\(f_c = \text{center frequency} = \text{geometric mean}\)

For example, the relationship between a one octave band and the three adjacent one-third octave bands that belong to one octave band can be seen in Figure 172.
Frequency Response Function/Transfer Function

A frequency response function (FRF) is a transfer function that is expressed (in the frequency domain) as a complex function with real and imaginary components. These components are represented in terms of magnitude (usually in dB) and phase (usually in radians vs. frequency (Hz)) and represent the structural response to an applied force as a function of frequency. Estimating the frequency response for a physical system usually involves exciting the system with an input signal, measuring both the input and output time histories and comparing the two through the FFT process [64]. It is important to note that the frequency content of the input signal must cover the frequency range of interest or else the results will not be valid for the portion of the frequency range that is not covered.

A transfer function (TF) is a mathematical representation of the relation between the input and output of a linear time-invariant system. TF’s are most commonly used in the analysis of systems such as single-input single-output filters, usually in the fields of signal processing and control theory [65]. A typical transfer function equation is represented below in equation 17.

$$H(s) = \frac{Y(s)}{X(s)} = \frac{\mathcal{L}\{y(t)\}}{\mathcal{L}\{x(t)\}}$$  \hspace{1cm} \text{Eq. 17}$$

Where \(x(t)\) is a continuous-time input signal and \(y(t)\) is the output. The transfer function \(H(s)\) is the linear mapping of the Laplace transform of the input, \(X(s) = \mathcal{L}\{x(t)\}\), to the Laplace transform of the output \(Y(s) = \mathcal{L}\{y(t)\}\).

Power Spectral Density

In signal processing, the spectrum of a signal is a function of a frequency which has dimensions of power per hertz (Hz) or energy per hertz. A power spectral density (PSD) measured in watts per hertz describes how the power of a signal is distributed over the different frequencies. In physics, the signal is usually a wave, such as an acoustic wave. The spectral density of the wave, when multiplied by an appropriate factor will give the power carried by the wave, per unit
frequency, known as the PSD of the signal. The total power of a signal is provided below in equation 18.

\[
P = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} x(t)^2 \, dt
\]

\[x(t) = \text{signal}\]

\[T = \text{continuous time}\]

The power of a signal in a given frequency band can be calculated by integrating over positive and negative frequencies. See this in equation 19 below.

\[
\int_{\omega_1}^{\omega_2} S_{xx}(\omega) + S_{xx}(-\omega) \, d\omega
\]

\[= F(\omega_2) - F(-\omega_2)\]

\[F = \text{integrated spectrum}\]
Appendix C Microphone Calibration

Each microphone in the experiments was calibrated. In order to take a scientific measurement with a microphone, its sensitivity must be known in volts per Pascal. These values were stated in chapters 2 and 6 for the NICU environment preliminary studies and anechoic chamber testing, respectively. All microphone calibration was traceable to primary standards at a National Measurement Institution [66]. Laboratory standard microphones calibrated using this method were used in turn, to calibrate other microphones using comparison calibration techniques, referencing the output of the ‘test’ microphone against that of the reference laboratory standard microphone [66].

A comparison calibration method determines a microphone's sensitivity by comparing its electrical response to a sound field against that of a previously calibrated microphone. If the two microphones are exposed to the same stimulus, the responses can be directly compared [66]. Therefore, by facing the two microphones towards each other closely spaced, the pressure on both of the microphones’ diaphragms can assumed to be equal at the frequencies of interest [66]. Both microphones are subjected to a broadband noise signal from a loudspeaker and the frequency response computed. The ratio of sensitivities of the two microphones was multiplied by the known sensitivity of the calibrated referenced microphone in order to obtain sensitivity of the test microphone. Comparison calibration can be carried out depending on the application of the microphone. For the experimental testing in this thesis, the free-field anechoic chamber environment was used. See equations 20 and 21 for a sample used to produce the calibration factors for the baby right and left ears in the chamber testing.

\[
\frac{2.5373}{1.1971} \times 1.2917 \times \frac{V}{Pa} = 2.7378 \times \frac{V}{Pa}
\]

Eq. 20

\[
\frac{2.5833}{1.1974} \times 1.1153 \times \frac{V}{Pa} = 2.4062 \times \frac{V}{Pa}
\]

Eq. 21

Another way of calibrating microphones is using pistophones and sound calibrators. A pistophone is an acoustical calibrator (sound source) that uses a closed coupling volume to generate a precise sound pressure for the calibration of measurement microphones [66]. A piston is mechanically driven to move at a specified cyclic rate, pushing on a fixed volume of air to which the microphone under test is coupled [66]. These pistophones are very dependent on ambient pressure and are used to reproduce low frequencies. Several of the commercial pistophones are not calculable devices and therefore must be calibrated using a calibrated microphone if the results are to be traceable. Sound calibrators are similar to a pistophone except they work electronically and use a low impedance source to yield a high degree of volume independent operation [66]. These usually generate a 1 kHz sine tone and should be calibrated regularly at a nationally accredited calibration laboratory to ensure traceability [66].

A third method of calibration is reciprocity calibration and can be carried out either using an acoustical coupler or implemented in a free field. The reciprocal technique exploits the reciprocal nature of certain transduction mechanisms; measurement microphones are usually capacitor microphones which exhibit this behavior [66]. The acoustical coupler method is used to give the microphone’s pressure response, while the free field is used to give the free field response. For
the acoustical coupler technique, three sensitivity product measurements allow the individual microphone sensitivities to be deduced by solving three simultaneous equations [66]. This process provides a measurement of the sensitivity of a microphone without the need for comparison with another previously calibrated microphone and is instead traceable to reference quantities such volts or ohms [66]. This free field process is different from the coupler way in that it is more difficult to implement. Instead of applying this technique, one could use the coupler process and then apply a correction factor to account for the free field condition.