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To What Extent Does the Geometry of An Object Affect the Transmission of Sound to the Listener?

Jiachi Xue

Collège Alpin Beau Soleil, Villars-sur-Ollon, Switzerland
Felixxue10@gmail.com

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Abstract: Noise cancellation has become one of the recent technologies that benefit human life. In daily life, people can wear earphones with noise cancellation technology to fully immerse themselves in their works and not to get disturbed by others. With that in mind, I presented an investigation on how the changing geometry (thickness and shapes) of a material affects the effects of noise cancellation. I employed theories such as Fast Fourier Transform, Nyquist Theorem, Constructive and Destructive Interference, and so on to make a hypothesis or strengthen the conclusion. The investigation was completely up to my design, where I sketched how the investigation will be constructed. To increase the accuracy of the results, I asked help from Design and Technology Department at our school to cut materials to their finest. The whole investigation makes use of the same material and same cutting methodology. The testing condition carried out for every measurement is also the same. This investigation eventually guided me to a new understanding of how the effects of noise cancellation can be changed due to its geometry. Eventually, after careful consultation with my research mentor and additional researches on successful experiments conducted by professional researchers, the proposed conclusion will give an idea of future improvement in the noise cancellation field.

1. Introduction

The term Noise Cancellation has come to my life once I get more exposed to electronic devices, including headphones or earphones that contain such technology. When plugging or wearing earphones, the noise emerged from the engines suddenly reduced. This sparked my interest – How did that happen?

Therefore, I came up with a research question to discover further: To what extent does the geometry of an object affect the transmission of sound to the listener?

2. Theoretical Background

Noise Cancellation has been considered beneficial as a tool. It helps the listeners to enjoy music with less noise. For technology companies, they continued to suit more pieces of noise cancellation technology into their designs of headphones. The idea of noise cancellation is to record the background noises and then convert those noises into “anti-noise”. It states that by inverting the polarity of the measured sound wave, it can be approximately canceled for a listener through destructive interference. At the end, when the sound reaches the ear, the noises that were initially generated in the background will be canceled out. (Triggs, 2020) Moreover, there is a terminology called “anti-phase”. If the two waves are identical, have the same amplitude and frequency, they are called “in-phase”. The two waves will then add together and generate louder sounds. (Molina, 2020) In contrast, if the amplitude and frequency do not match between two waves, that is called “out of phase”. The two waves will then subtract and become zero. (Molina, 2020). These features also link to constructive and destructive interference, where two identical waves produce twice the amplitude or completely cancel out. These are pure constructive or destructive interference. However, in the real world, these scenarios will be hard to formalize. Superposition, a phenomenon to describe two or more waves arriving at the same point, will be significantly useful to describe two unidentical waves adding together.

Figure 1 shows that two waves can perform both constructive and destructive interference at the same time, which is, theoretically, what is going to happen during my investigation. (Lumen, n.d.)

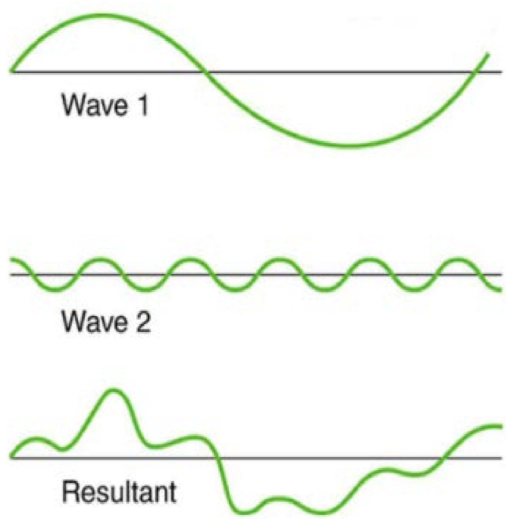

Figure 1: Superposition of non-identical waves

One of the factors that influence the effects of noise cancellation is the thickness of the object. Sound Absorption Coefficient (SAQ) is an index that shows the noise cancellation ability of specific material. (Amares, 2017) The higher the index, the better the noise cancellation.

Figure 2 (Seddeq, 2009) shows that thickness and SAQ have a directly proportional relationship which signifies that thicker objects can lead to better noise cancellation. However, it is noted that this effect only plays a role when the frequency is lower than 2000 Hz, as the sound waves exceed this value, the thickness will not be as significant as prior before. (Amares, 2017)

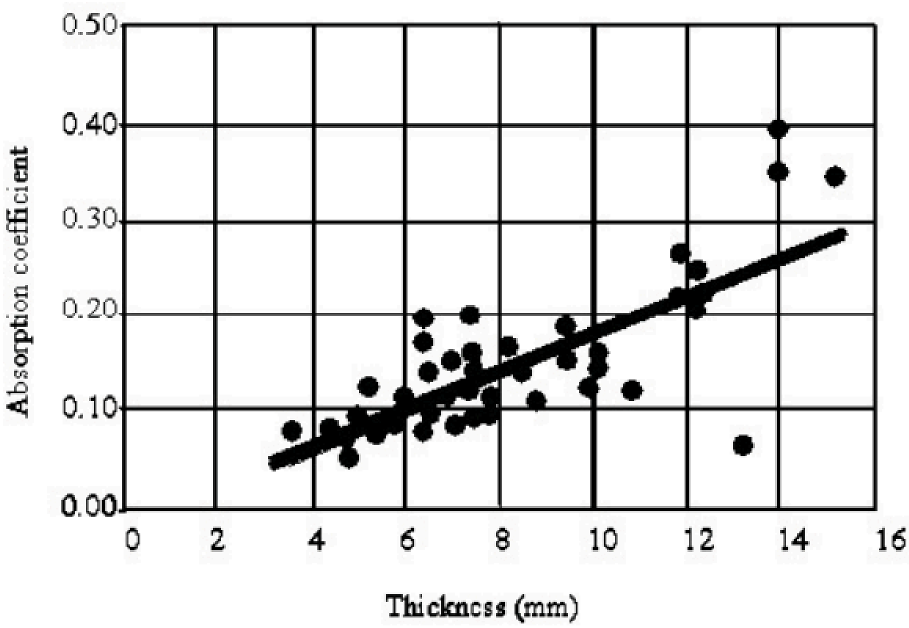

Figure 1: Relationship between Absorption coefficient and thickness

Theoretically, in the noise cancellation field, the thicker the object leads to better noise cancellation. However, it also depends on the cavity of the wall. An empty object cavity can perfectly allow the sound waves to travel through the object, causing no significant effects of noise cancellation. To deal with that, filling insulation materials will be the target. (Dominic, n.d.). There are a lot of materials proven to be soundproofing or having effects of absorbing the sound and preventing some of them to be leaked out. In Design and Technology Department, there is Styrofoam available. This material is a trademark brand of polystyrene and despite not being proven to be soundproofing, it helps to keep the interior noises from leaking out. Therefore, Styrofoam is considered sound resistant, which can therefore be a tool for analyzing noise cancellation.

Sound pressure is described as pressure waves propagating through a consistent pressure level. It is defined as the difference between the actual pressure at any point in a sound wave at any instant and the average pressure at that point. (Merriam-Webster, n.d.)

However, the sound pressure level measured will not play an essential role in determining loudness or how much noise is produced. This means that the average pressure does not contribute to sound, but instead the power transmitted through the pressure waves. Therefore, I decided to use the Root Mean Square to analyze the results obtained from the investigation.

2.1. Fourier Transform

In Fourier transform, there are usually two forms: Continuous Fourier Transform (CFT) and Discrete Fourier Transform (DFT). The former one is less applicable for digital technology since would require continuous functions to describe sound waves instead of discrete samples. Therefore, in real-life situations, we usually encounter Discrete Fourier Transform. The equations describing the CFT are:

$$X(\omega) = \int_{-\infty}^{+\infty} x(t)e^{-j\omega t}$$

And its inverse:

$$x(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} X(\omega)e^{j\omega t}\,d\omega$$

(Cheever, 2005)

The concept of Discrete Fourier Transform is important for us in the digital signal processing field. It enables us to find the spectrum of finite-duration signals. (Arar, 2017)

The DFT is used by converting a sequence of complex numbers to a new sequence of complex numbers through the use of a formula. There are equations for the Discrete-Time Fourier Transform:

$$X_k = \sum_{n=0}^{N-1} x_n e^{-2\pi ikn/N} \ (for\ 0 \le k \le N-1)$$

The inverse equation will be:

$$x_n = \frac{1}{N}\sum_{k=0}^{N-1} X_k e^{\frac{2\pi ikn}{N}}$$

(al., n.d.)

Both the CFT and DFT formulas are invertible, which suggests that taking the Fourier analysis is a complete way to write the same information present in the sound wave.

Fast Fourier Transform has become an effective tool in analyzing the sound file, as it converts waveform data in the time domain into the frequency domain. The Fourier Transform breaks down the original waveform into an individual sinusoidal term. This conversion can make the complicated waveform easier to compute because of the sinusoidal term is more manageable. With the FFT graph, the amplitude plotted will indicate the power spectrum, which is the response of the original waveform in the frequency domain. (DATAQ, n.d.)

In the Noise Cancellation context, the use of Fast Fourier Transform can display the amplitudes of the original waveform. In theory, the greater the amplitude indicated, the worse the noise cancellation will be.

2.2. Practical Application

By implementing the concepts of noise cancellation, several companies have made fascinating earphones and headphones for people's uses. Among these products, the AirPods Pro is one of the most famous and widely-used earphones. Relative to section 2.1, the AirPods Pro has an outward-facing microphone that detects external sounds, and it will then counter it with equal anti-noise, eventually canceling out the external sound before people hear it. It is also mentioned that the noise cancellation is continuously adjusted at the rate of 200 times per second. (AppleCompany, 2019) Next year, after AirPods Pro, Apple Company decided to release the AirPods Max, which makes use of the technology and even cancels out redundant noises more efficiently. Instead of only using one outward-facing microphone in the AirPods Pro, the AirPods Max makes use of six outward-facing microphones with two inward-facing microphones to heighten the performance. (AppleCompany, 2020) Noise cancellation has become a tool that is widely used in the recent world, and because of its widespread popularity, the noise cancellation technology will be further employed for future production.

3. Investigation

The investigation is designed to measure the effects of noise cancellation by measuring the same materials with different thicknesses and shapes. The investigation is performed in the same condition.

3.1. Statement of the Research Question

To what extent does the geometry of an object affect the transmission of the sound to the listener?

3.2. Hypothesis

I hypothesized that the greater the thickness, the better the effects of noise cancellation. This is because when the sound wave passes through an object, it will face more interference when the thickness becomes greater. Moreover, Boston University has developed a noise cancellation material named "acoustic metamaterial". The material is designed to reduce as much sound as possible. The material is a circle shape (Furness, 2019). According to their investigation video, once they removed the material, the amplitude of the waves increased dramatically. (University, 2019) Since it is a circle shape, I formalized a hypothesis that a circle will be the most effective noise cancellation.

3.3. Preliminary Testing

I conducted preliminary testing to reduce the errors that I might face during the investigation. I figured that to measure the sound pressure level more specifically, I need to choose a sound wave that contains no lyrics. Since the lyrics contain different pitches, it affects the results gained from the investigation. Therefore, I chose the sound wave named "Soundwave", and it is being collected in an album called HYPERSPACE MEMORIES from Burnie. (Burnie, 2021)

Moreover, I realized that the testing conditions should be modified. I conducted preliminary testing in which I changed the arrangements in the room. For precision's sake, I decided to investigate with the same arrangement. Also, I realized that the sample rates are too widespread. Since sound waves are measured in minor numbers, taking as many samples as possible will generate more precise results. According to the theory of the Nyquist theorem, it states that the highest frequency measured from the sound wave will be half of the sampling rate. (Oshana, 2006)This suggests that to gain a higher frequency, I will need to increase the sample rates. For example, the frequency of 10kHz will generate less conclusive results than the frequency of 50kHz. Therefore, for the real testing, I decided to increase the sample rates to 50,000 samples per second. This allows me to be able to fully analyze the effects of noise cancellation in different conditions.

3.4. Equipment List

1) © LABQUESTS 3 (Data Logger)
2) Vernier Microphone
3) Speaker
4) Styrofoam
5) Soundtrack waves

1. Meter ruler
2. Data reader

3.5. Variables

Table 1 Variables included in the investigation

Independent Variables	Shapes of Styrofoam	-Triangle -Trapezium -Circle -Square -Rectangle
	Thickness of Styrofoam	-0.005m -0.01m -0.015m -0.02m -0.025m
Dependent Variables	Sound Pressure Level	Sound Pressures are measured through the LABQUEST 3, and its company Vernier. The sound is recorded by Vernier Microphone. These devices will help to ensure the accuracy of the data.
Controlled Variables	Materials used for lab	Same materials will ensure the preciseness of each data because if using different materials, it will generate different sound pressures even with same shapes and thickness. The material used for the investigation is Styrofoam.
	Sound Waves	Downloaded from Music App, without any modification
	Times of the collection of the data and samples per take	Same time can ensure the mean value taken will be fair for all takes. Same samples taken per time will guarantee the preciseness of each take
	Distance between Styrofoam, microphone, and player	
	Testing place	
	Surface area of the Styrofoam	All of them will be $0.0016m^2$
	Average Air Pressure	During the measurements, the average air pressure is assumed to be constant. This is because of the same testing condition

3.6. Methodology

To complete the investigation, I place the microphone, Styrofoam, and speaker at a constant distance, and then I ensure there is no more extra sound provided by the environment. Next, I set the duration of the collection of data to 5 seconds, and the samples were taken to 50,000 samples per second. Then, I play the sound wave file and start the recording of the microphone in synchronization. At the end of the collection, the data is read to a computer file, and I make sure there are 8 decimal places to sustain the precision of data.

I repeat the former process for different shapes in the same thickness, and once every shape is done for one thickness, I change the thickness and repeat the former step.

3.7. Explanation of setup

In my following investigation, I employed Styrofoam, a material that does not have a specific Sound Transmission Class rating. However, even it is not specified as a soundproofing material, it can be used to generate better noise cancellation along with the use of other materials. (Anzalone, n.d.) Therefore, I believe that using such material for an investigation will help me to make valid conclusions.

I completed all of the investigations in the same room. Maintaining the day and room constant will ensure the preciseness of the final results. Also, sound pressure level is a subtle measurement. Therefore, I placed measurement to be 50,000 samples per second to allow the microphone to capture precise data happening for every sample.

I kept the surface area of all the shapes to be the same: 0.0016 m^2 This is to eliminate the potential error of different widths and lengths that might influence the investigations' results.

As the distance should be constant, I kept it to be constant with Styrofoam, microphone, and speaker. The distance I set is 0.15m between the Styrofoam and microphone, and between Styrofoam and the player. This is because the thickness I will conduct will be less or equal to 0.025m, which will probably have anomalous results if the distance between the Styrofoam, microphone, and speaker is too big.

To cut the materials to as ideal as possible, I asked for help from the Design and Technology Department in our school. They used a laser-cut machine and pre-entered the length, width, height, or radius for all the shapes. For the surface area of the object, I kept all the surface area of the objects to be equal to 0.0016m^2. Table 2 below demonstrates all the precise measurements for width, height, radius, upper and lower length, and base width.

Table 2 Indexes of the measurement of individual shapes

	Trapezium	Circle	Square	Rectangle	Triangle
Radius(m):		2.25676			
Length(m):			0.04	0.08	0.05,0.05
Width(m):			0.04	0.02	
Height(m):	0.04				0.04
Upper length(m):	0.03				
Lower length(m):	0.05				
Base width(m)					0.08

This approach allowed me to have an equal surface area of materials at the start and further ensures the preciseness of the investigation.

As sound pressure measured by the logger pro will be a minor number, the normal three significant figures will not be enough to perform precise analysis. Therefore, I decided to take 8 significant figures as it allows me to see the discrepancy between data.

Since I used only the ten seconds of the soundtrack of Soundwave from Burnie, it performs a shape more like blue noise, which is a noise that has a higher frequency at the end. (Capritto, 2019) . The characteristic of blue noise helps people who are not sensitive to high-pitched sound to sleep better because it can mask outside noise.

Also, the sound pressure level is not measured along with any unit. The microphone is not calibrated so it is arbitrary. Therefore, I will use Pressure Units (PU) to display the data.

4. Tables and Graphs

By using microphone and data logger to record and measure the data, the figure shows the sample of Styrofoam with circle shape and 0.005 m. Figure 3 demonstrates the time the highest sound pressure is generated.

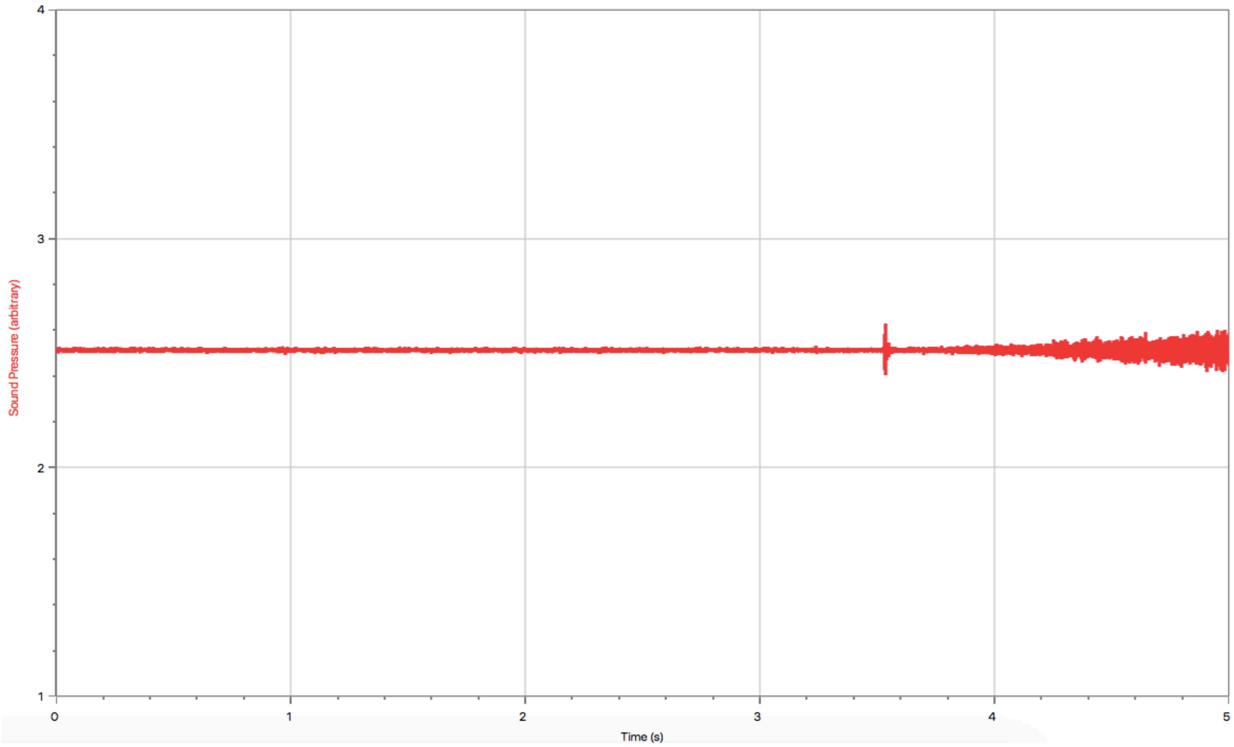

Figure 2 Sample graph obtained by Logger Pro (Circle in 0.005m)

The Logger Pro contains a file that indicates all the values obtained for the sound pressure level. I then extracted all the samples to perform more analysis.

4.1. Processing data and graphs

After the extraction of data from Logger Pro, I used the formula $RMS = \sqrt{\frac{(x_1)^2+(x_2)^2+\cdots+(x_N)^2}{N}}$ to calculate the root mean square of each shape and thickness. Firstly, I evaluate the effects of noise cancellation for shapes.

Decibel is the unit of measuring the sound pressure level, and in this investigation, the decibel can be taken by calculating the standard deviation of the raw data.

The formula of converting sound pressure level (PU) to decibel is: $L_p = 20log_{10}(\frac{p}{p_0})$. The p is the standard deviation of the raw data, and the $p_0$is a constant which is defined as 20uPU. (Zolotkov, 2017)

For example, by taking the triangle with 0.005m as an example. I calculated the standard deviation which gives me the value of 0.0098054 PU, and this is being put into the formula stated above and I obtain the value of 53.8 dBPU. According to the scale of decibel, it stated that the decibel value around

50 is indicating normal conversation. (Zolotkov, 2017)This aligns with the investigation as the soundtrack played was not beyond the sound level of normal conversation.

This example aligns with all the other measurements taken in the investigation, which states that the investigation is processed in a good manner.

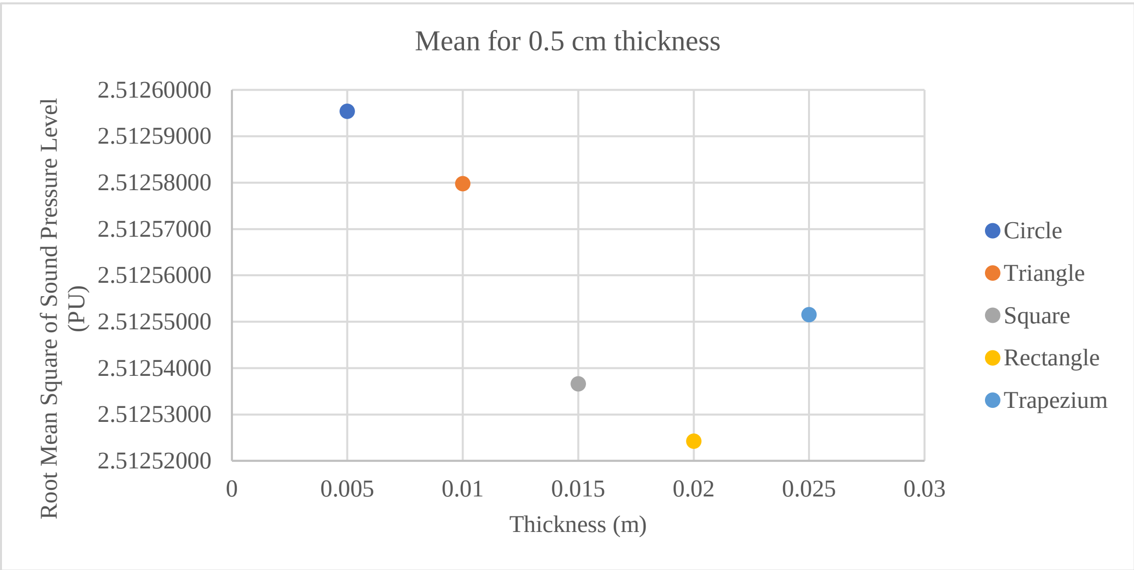

Figure 3 Sample graph of 0.005m thickness for all shapes

Figure 4 demonstrates that, for a thickness of 0.005m, the circle has the highest root mean square for sound pressure. This means that in 0.005m, the circle has the worst effects of noise cancellation. In contrast, the shape of the rectangle has the best effects of noise cancellation.

Table 3 Noise Cancellation Effectiveness Comparison in RMS of sound pressure level

Effectiveness Ranking	Circle	Triangle	Square	Rectangle	Trapezium
1st	1	1	0	2	1
2nd	2	1	1	1	0
3rd	0	0	2	1	2
4th	1	3	0	0	1
5th	1	0	2	1	1
From 5th to 1st	Square	Trapezium	Triangle	Circle, Rectangle	

Table 3 demonstrates how do shapes perform as a whole. This is done by ranking the effects of noise cancellation in every thickness from first to fifth. By looking at the graphs of all the thickness for shapes, I draw this table to indicate how many times the shape has appeared to be "Best", "Second Best" at noise cancellation, and so on. For example, as the circle appeared to be the worst at noise cancellation in 0.005m analysis, the amount of time it appeared to be the worst in the column will be added one. Taking such methodology, the table is then drawn for understanding the effects of noise cancellation through shapes.

After the conclusion drawn from analyzing the effects of noise cancellation by shapes, I analyzed the average of the sound pressure of each thickness. I took the average of the thickness since I want to make sure that the investigation is performed in the same strategy. The calculation is done by taking the average of all the five values taken in one thickness. For example, Table 4 shows the RMS average of 0.005m thickness:

Table 4 RMS of 0.005m thickness

Root Mean Square for 0.005m (Pa)
2.51259538
2.51257980
2.51253658
2.51252421
2.51255153

Then, by taking the mean for all the values, it gives a final value of 2.51255750. By doing the same calculation for every thickness, Table 5 is drawn as followed:

Table 5 All the sum of RMS of sound pressure for thickness

Average for 0.005m	Average for 0.01m	Average for 0.015m	Average for 0.02m	Average for 0.025m
2.51255750	2.51264534	2.51255464	2.51258140	2.51254458

To evaluate the effects of noise cancellation by thickness, I plotted the graph through the use of Excel.

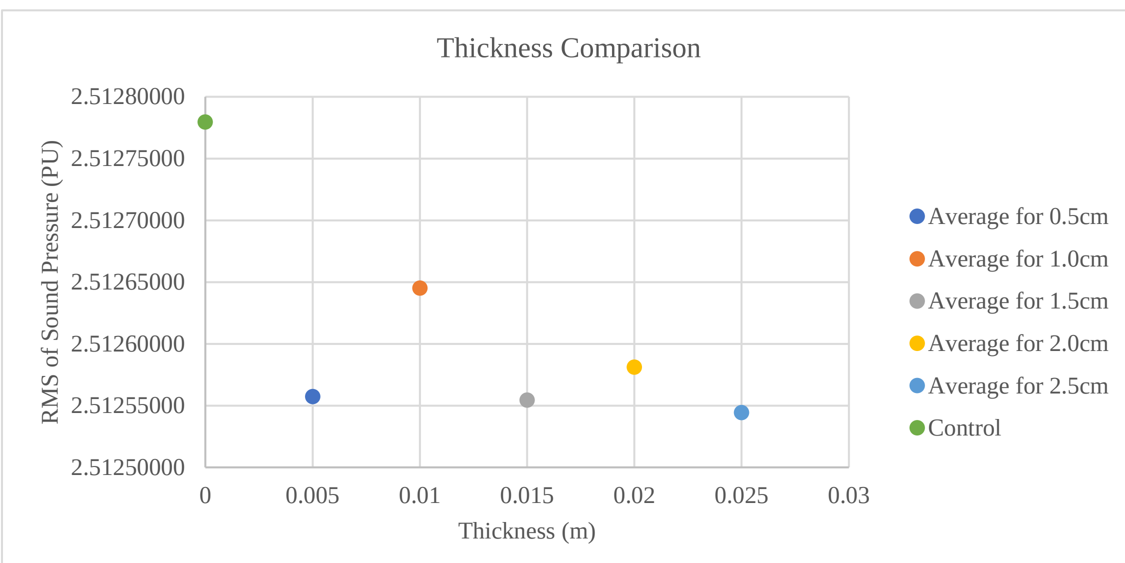

Figure 4 Graph of average of sound pressure for all the thickness

From Figure 5, it can be concluded that the average of 0.01m has the worst effects of noise cancellation. In contrast, the average of 2.5cm has the best effects of noise cancellation.

By taking the RMS of the sound pressure level without any Styrofoam, the RMS value obtained is 2.51277963. In Figure 3, the control one is also drawn, and it shows that this point exceeds any other average points with Styrofoam involved. It also suggests that even by placing a Styrofoam with small thickness, the noise cancellation effects will be better than the time when I did not place any Styrofoam.

4.2. Conclusion and Errors

To conclude from the analysis of shapes and thickness, the result shows that 0.025m has the best effects of noise cancellation among all the thicknesses. This corresponds to the hypothesis that the thicker the Styrofoam becomes, the greater the effects of noise cancellation will be. However, the result shows that 0.01m has the worst effect of noise cancellation. This is not corresponding to the hypothesis. From the graph, it can be seen that 0.01m creates a discrepancy with other thicknesses. Therefore, it is reasonable to hypothesize that this result may contain errors such that during the investigation, there might be temporary sound coming from outside of the room to interfere with the results. Moreover, I hypothesized that the circle will be a great shape for noise cancellation. Through results, I can conclude that circle and rectangle have the best effects of noise cancellation among all the five shapes, which proved my hypothesis. This is also why mostly every headphone is designed to be in the shape of circle. Not only does it fit the ears, but also does help to conduct noise cancellation.

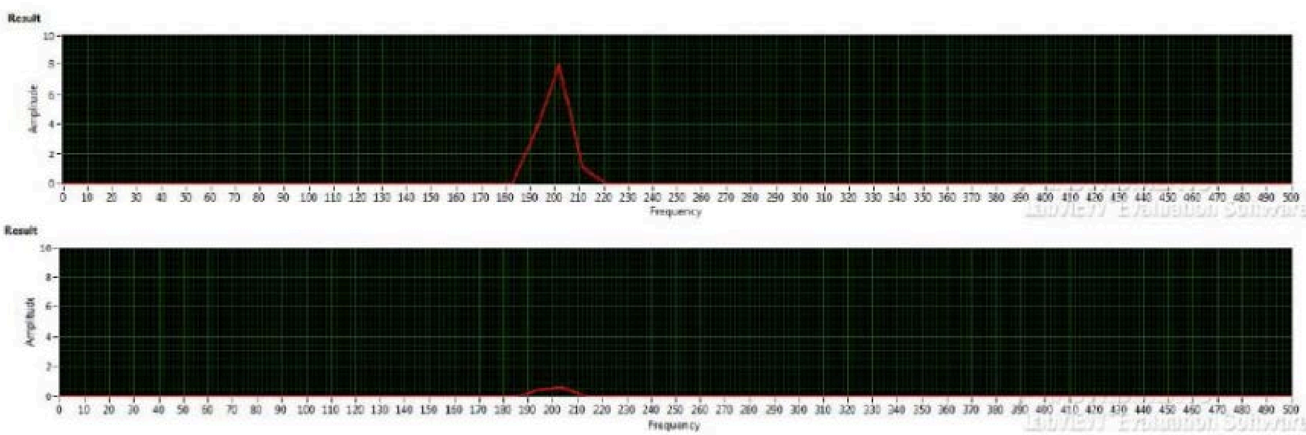

Figure 6 Frequency domain before and after cancellation by ANC system

For the result stating rectangle is also the best at noise cancellation among five shapes, Figure 6 shows an experiment using the rectangular enclosure to create a noise cancellation microphone. In this experiment, the anti-noise generator (the microphone) is started to cancel the sounds coming from the original microphones. This can be seen as a way to demonstrate the usefulness of the rectangle – the values of the frequency significantly go down. (SHUKOR, et al., 2017)

Since the investigation is designed to get primary data to obtain a conclusion, there might be errors contained in the process of the investigation. When cutting the materials to designed shapes, the Design and Technology Department made use of the laser-cut machine. This machine is great in terms of getting perfect indexes for designed shapes. However, it faces shortcomings such as the laser can be too hot to damage some parts of the materials. This shortcoming plays the greatest effect on the 0.005m and 0.01m thickness because the thickness is the lowest. As sound waves may be interfered by minor changes, the sound pressure level obtained may then be interfered by those damages from the laser-cut machine.

4.3. Fast Fourier Transform Analysis

Along with the analysis of root mean square of the sound pressure level, the Fast Fourier Transform is vital to prove the values obtained. In the graph of FFT, the amplitudes of the FFT demonstrates the ability of noise cancellation. The greater the amplitudes, the worse the noise cancellation the Styrofoam becomes. I took the sample graph of Circle with 2.5cm thickness:

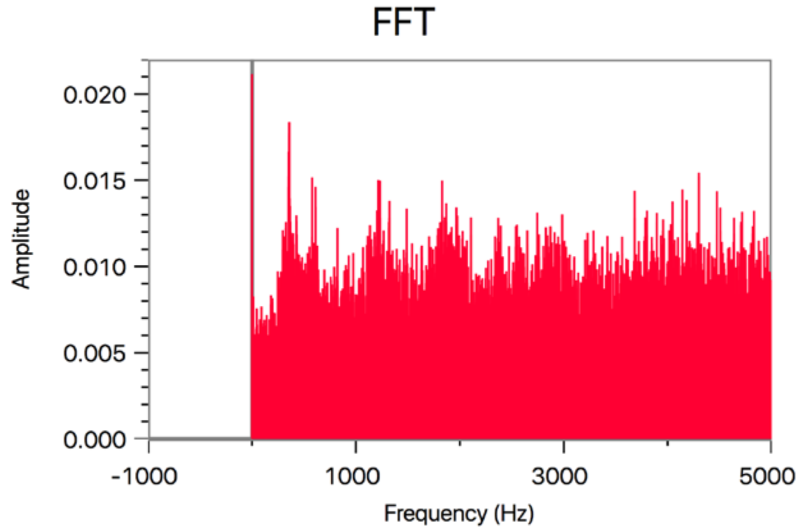

Figure 7 Sample FFT graph of Circle with 0.025m

Figure 6 shows that frequency goes towards 5000Hz and Amplitude reaches more than 0.020 PU at its peak. Even the amplitudes of the graph give me a sense of the general effects of noise cancellation of individual shape and thickness, visually, it is still complicated to value each thickness and shape with such graph. Therefore, I took the mean of FFT to further analyze the effects of noise cancellation.

Table 6 All the values of FFT of shapes and thickness

	FFT of the sound pressure value				
	0.005m	0.01m	0.015m	0.02m	0.025m
Circle	0.00452666	0.00437115	0.00434284	0.00424486	0.00430842
Triangle	0.00441205	0.00434787	0.00439977	0.00434760	0.00446791
Rectangle	0.00428500	0.00459718	0.00432919	0.00443349	0.00422328
Square	0.00458087	0.00458092	0.00453060	0.00431211	0.00442134
Trapezium	0.00431968	0.00438142	0.00445610	0.00479152	0.00430921
Sum for thickness	0.02212426	0.02227854	0.02205850	0.02212958	0.02173015

Table 6 shows the mean FFT values of all the thicknesses and shapes. The mean value is taken from the offset pressure of FFT, which is indicated as the amplitudes in the graph of FFT. Therefore, the higher the values, the worse the effects of noise cancellation. To analyze the mean, I take the sum of shapes and thickness respectively. Firstly, Table 7 below shows the analysis in FFT values in shapes.

Table 7 Performance of shapes and comparison

Effectiveness Ranking	Square	Rectangle	Triangle	Trapezium	Circle
5th	2	1	1	1	
4th	2	1		1	1
3rd			3	2	
2nd	1			1	3
1st		3	1		1
From 5th to 1st (Shapes)	Square (20)	Trapezium (16)	Triangle (15)	Rectangle (12)	Circle (11)

The comparison methodology is the same as the methods to analyze sound pressure level, which can be evaluated as circle has the best performance, and square has the worst.

When comparing this value to the root mean square of the sound pressure level, it can be seen that both results obtain roughly the same conclusion. The results gained from analyzing the FFT is taking the integral of the FFT values, and that should be exactly same as the results gained from RMS. Also, since Fourier integral excludes 0-mode, the results gained from taking the FFT integral should be the same as the standard deviation. It also aligns with the RMS because the 0-mode is unchanged during different tests. Therefore, from the conclusion, it can be seen that the investigation had been carried out well. In FFT analysis, square has the worst effects of noise cancellation. Moreover, in the analysis of root mean square of sound pressure level, square also has the worst effects of noise cancellation. There is one difference between the results of FFT and sound pressure level: In FFT, rectangle has slightly worse effects of noise cancellation than circle. However, in RMS of sound pressure level, rectangle and circle has the same effects of noise cancellation by the sum of numbers. To understand the difference, we can see that since the analysis is concluded by assigning numbers to performances of shapes in every thickness, the difference of 1, from 11 to 12 does not create a big difference. Also, the errors such as the laser-cut machine contained in the investigation can become the cause of the difference between the performances of circle and rectangle in the analysis of FFT. In general, the shapes values taken for FFT supports the conclusion drawn from the RMS of sound pressure.

After analysis of shapes, the FFT values for thickness should also be considered to potentially prove the conclusion drawn from RMS of sound pressure. By taking the sum of all the shapes in every thickness, the results are as followed:

Table 8 Comparison of thickness according to FFT value

From Worst to Best	0.01m	0.02m	0.005m	0.015m	0.025m

Table 8 demonstrates the effects of noise cancellation in respect of the thickness. With the conclusion drawn from RMS of sound pressure, the results of FFT are exactly the same as the RMS of sound pressure. Therefore, the FFT value of thickness proves that the conclusion drawn from RMS value is precise.

Beyond the analysis of shapes and thicknesses, I also take the mean value of FFT for the measurement without any Styrofoam. The value is 0.00471573. This value exceeds the all the FFT values taken for the measurements with Styrofoam. This further supports that placing a Styrofoam can make the noise cancellation more effective.

4.4. Integral Analysis

The use of the integral analysis can allow me to determine within chosen range of frequency, which thickness and shape holds the greatest effects of noise cancellation. The conclusion drawn from this analysis can allow me to provide advices on future use of noise cancellation.

Firstly, since sound pressure level is taken in small numbers, the integral taken for the sound pressure level measured by the microphone will not be different even the thickness and the shapes are different. To develop a conclusion, I take 1-1000, 1001-2000, 2001-3000, 3001-4000 and 4001-5000 Hz as the range of frequency for FFT values. After setting the range, I take the integrals to see the result. 0 frequency means no motion, which does not imply anything in the analysis of Fast Fourier Transform. Therefore, I excluded the 0 frequency.

Figure 7 shows the shape of circle with the thickness of 0.005m, and the frequency is taken from 1-1000 Hz. As shown in the figure, the integral taken in this range is 4.025, and the y-axis demonstrates the amplitudes and the x-axis demonstrates the frequency bin.

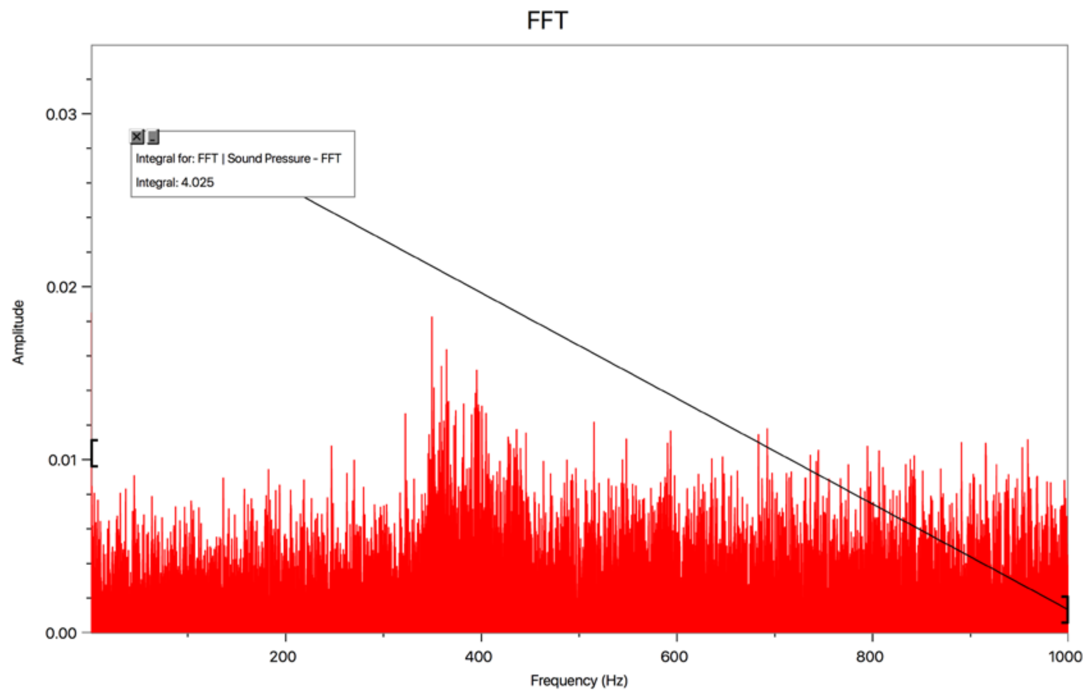

Figure 8 Integral of circle with 0.005m thickness (1-1000Hz)

Figure 8 shows the integral of the rectangle with 0.01m thickness, and its frequency ranges from 1001 to 2000Hz. As seen, the amplitudes started to reach on the same level, where the integral of it become wider as the soundwave started to become more intense.

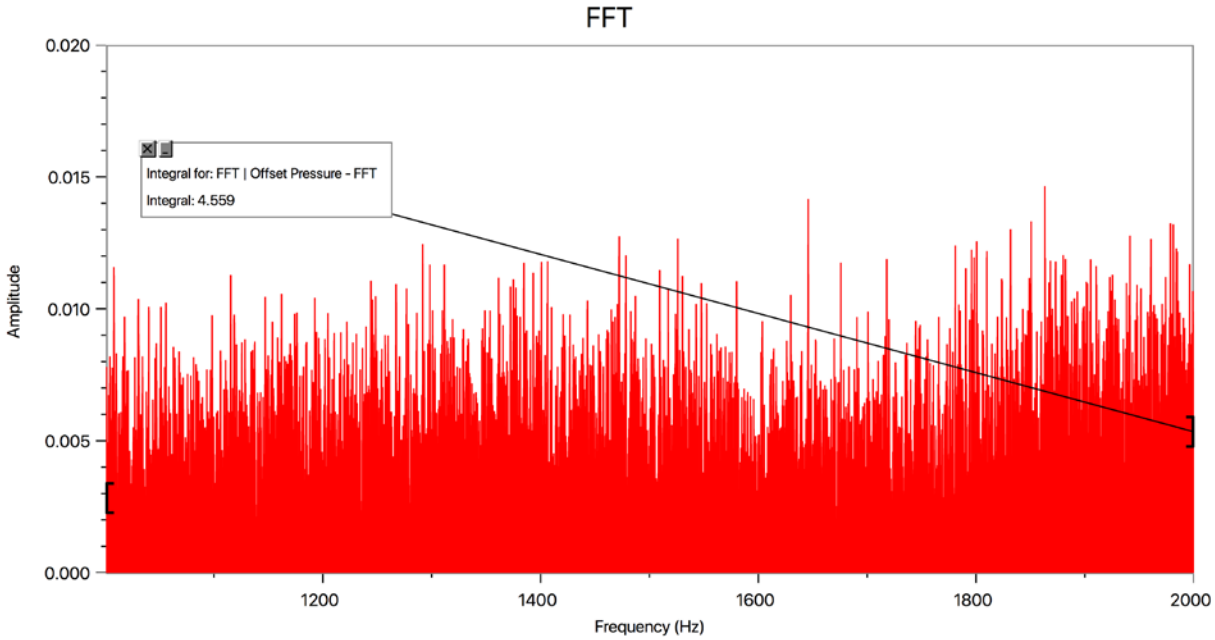

Figure 9 Integral of rectangle with 0.01m thickness (1001-2000Hz)

From these two figures, it can be seen that different shapes, thickness, and ranges will get different results throughout the investigation.

Taken the example of range 1-1000 Hz, Table 9 is shown below:

Table 9 Integral analysis of 0-1000 Hz

1-1000 frequency	0.005m	0.01m	0.015m	0.02m	0.025m	Average
Circle	4.025	3.799	3.880	3.780	3.945	3.888
Triangle	3.857	3.775	4.027	3.750	3.887	3.859
Rectangle	3.754	3.862	3.975	3.823	3.800	3.843
Trapezium	3.840	3.826	3.935	3.906	3.785	3.858
Square	3.928	3.996	3.883	3.930	3.732	3.894
Average	3.881	3.852	3.940	3.838	3.830	

According to the sum of the thickness, 0.025m has the greatest effects of noise cancellation, and 0.015m has the worst effects of noise cancellation. According to the average taken for the shapes, rectangle has the greatest effects of noise cancellation, and square has the worst effects of noise cancellation.

Conducting an integral analysis is purely a way to understand the results better. By separating the frequencies in different ranges, I can see how different ranges contribute to the noise cancellation. Sometimes, specific results from certain range will not be the same as the final result. This is because noise cancellation has different effects in different ranges.

Following the same strategy of analysis, Table 10 can conclude the integral analysis.

Table 10 Overall Integral analysis

	0-1000 Hz	1000-2000 Hz	2000-3000 Hz	3000-4000 Hz	4000-5000 Hz
Best (Shapes)	Rectangle	Circle	Rectangle	Circle	Circle
Worst (Shapes)	Square	Triangle	Trapezium	Trapezium	Triangle
Best (Thickness)	0.025m	0.025m	0.015m	0.025m	0.025m
Worst (Thickness)	0.015m	0.01m	0.02m	0.02m	0.01m

The results from each range of frequency highly corresponds to the conclusion drawn from RMS and FFT of sound pressure level. However, some ranges show different results from the general conclusion. This difference does not dispute the conclusion, but it suggests a potential improvement in future development of the investigation.

To support the conclusion drawn from the integral analysis, I take the integral for the investigations with no Styrofoam.

Table 11 Integral without the use of Styrofoam

Without Styrofoam	
0-1000 Hz	4.386
1000-2000 Hz	5.075
2000-3000 Hz	5.072
3000-4000 Hz	5.113
4000-5000 Hz	5.118

Table 11 shows the value of integral in each range of frequency for the measurement of without any Styrofoam. In every range of frequency, the integral obtained without any Styrofoam exceeds the average value for the measurements with Styrofoam. Therefore, it can be shown that placing the Styrofoam will help to improve the noise cancellation.

5. Limitations, suggestions, and future development

One of the limitations for the design of the investigation is the number of trials collected. For all, I only collected 25 samples which include 5 thickness and 5 shapes. The samples can be too small to generate a conclusion for noise cancellation. To resolve such issue, I could take more samples with more thicknesses and shapes.

Also, the testing environment is a normal room, which is not ideally suitable for measurement of noise cancellation. This is because the room has a lot of other materials that can reflect the sound waves. For example, the bed will reflect back to the microphone when the sound wave reaches it from the sound player. To resolve such issues, the investigation can be placed in a room with irregular surface. The irregular surface helps the diffusion to take place, where the sound will be broken into smaller parts to allow the microphone to receive less disturbance during the investigation. Therefore, placing the investigation in a room with irregular shapes of wall will help the better recording of the sound. In the future, the investigation should be held in special room with sound proof, the example can be music studio. The music studio is designed for signers to record their voices as much undisturbed as possible, and this design will be ideal for the investigation. Since the music studio makes use of vinyl as the materials for the wall, it can absorb sound that did not get recorded by the microphone and do not reflect back to the microphone to create interference. (Vinnie, 2021) This Styrofoam as much redundant sounds as possible.

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