PHYSICS EXTENDED ESSAY

An Investigation into the Effect of Physical Properties of Materials on the Conduction of Sound

Word Count: 3910

Table of Contents

Research Question

How do the physical properties like density, thermal conductivity, and electrical conductivity of different materials influence the conduction of sound?

Introduction

As a prospective architect, I acknowledge the significance of architecture in one's daily lives. Having been fascinated by the different architectural structures and how they differ from each other in terms of sound conductivity, I decided to conduct an experiment related to the usage of materials in architectural structures.

The acoustic performance of a material is one of the main reasons it is or not selected to be used for a certain environment. For instance, in opera houses and concert halls, reflective materials are preferred in order to enhance acoustics. In contrast, absorptive materials are used to minimize echoes and reduce reverberation as used in recording studios to control sound reflections.

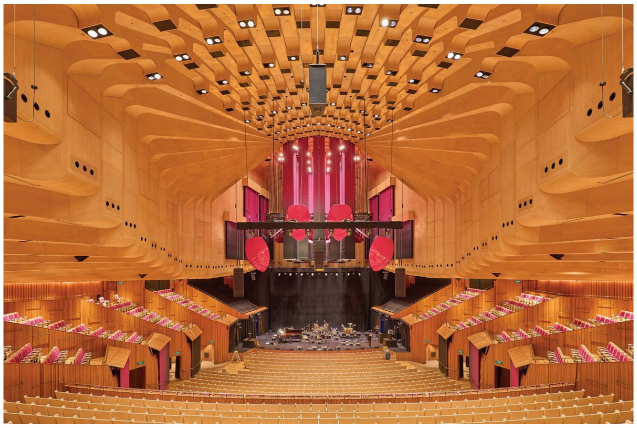

Figure 1: Interior of Sydney Opera House [1]

Each substance, each material has its unique size, mass, and arrangement of atoms and molecules, and other characteristics. That is why each material differs in qualities like density, thermal and electric conductivity. Through this experiment, I will be investigating the relationship between the unique properties of different materials and their sound conductivity.

Background Information

For the interior of each different architectural structure, a different material is selected and used according to the function and purpose of the structure. The management of sound is amongst one of the main reasons for this alongside aesthetic or financial purposes.

Sound

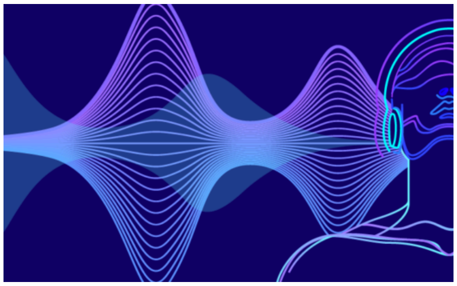

Figure 2: Sound [4]

Sound is created through vibrations. It travels as waves through a medium. There are three aspects that any sound can be affiliated with: there must be a source for a sound, energy transferred from the source is in the form of longitudinal sound waves in air or other material, and sound is detected. [2]

Loudness of Sound

Loudness of sound refers to how loud or soft a sound seems to a distant listener and is determined by the intensity or amound of energy present in sound waves and is expressed in decibels. [3] Loudness is related to intensity of the sound which can be defined as the energy transported by a wave per unit time across a unit area perpendicular to the energy flow. Presumably because of the wide range of intensity of sounds that the average human ear can detect, what is perceived as loudness is not directly proportional to the intensity. Producing a sound that sounds about twice as loud requires a sound wave that has about 10 times the intensity. [2]

Sound waves are measured according to their amplitude. Wave amplitude is determined by the energy that caused them. Waves with larger amplitudes have more energy and are more intense, so they are louder. [3]

Sound Level

The sound level refers to various logarithmic measurements of audible vibrations. Due to the relationship between the subjective sensation of loudness and the measurable quantity intensity, sound intensity levels are usually specified on the logarithmic scale with a unit of "decibel" (dB). The relationship between the sound level and its intensity is given with the equation,

$$\beta = 10 \times log\frac{I}{I_0}$$ [2]

where; β = sound level (dB)

I = intensity (W/m^2)

I_0 = intensity of a chosen reference level (W/m^2)

Longitudinal Waves

Sound is a longitudinal wave. In a longitudinal wave, the vibration of the particles of the medium is along the direction of the wave's motion. As shown in Figure 3, a series of compressions and expansions travel along the spring. Compressions and expansions correspond to the crests and troughs of a transverse wave.

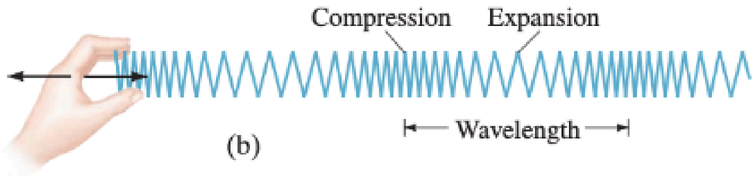

Figure 3: Longitudinal Wave [2]

Each section of the medium in which a longitudinal wave passes oscillates over a very small distance, whereas the wave itself can travel large distances. The wavelength is the distance between successive compressions (or successive expansions), and frequency is the number of compressions that pass by a given point per second. [2]

Physical Properties of Materials

It refers to the characteristics that can be observed without changing the material itself, such as color, density, and melting point. In this investigation, the relationship between only three physical properties of materials and their ability to conduct sound will be questioned. [5]

Density of a material is the mass per unit volume. Its unit in SI system is kg/m^3. Density is given by $\rho = \frac{m}{V}$ where ρ is density (kg/m^3), m is mass (kg), and V is volume (m^3). [5]

Thermal conductivity represents how easily heat can be conducted by a material. It is defined as the amount of heat transmitted by unit thickness of material normal to the unit area surface in unit time when the temperature gradient across the material piece is unity in steady state condition. Its unit in SI system is W/mK. [5]

Electrical conductivity represents how easily the electricity can be conducted by a material. Its unit is S/m. [5]

Prior Experimentation Information

Aim

The aim of this experiment is to determine the relationship between the sound conductivity of different materials with different density, thermal conductivity, and electric conductivity. Accordingly, an inference will be made regarding what properties of the materials will allow it to be a good conductor.

Hypothesis

If a material is more dense, sound will travel faster. So, as density increases, the ability to conduct sound will increase. Since both thermal conductivity and sound conductivity depend on atomic structure, and materials with strong atomic bonds tend to conduct heat better, as thermal conductivity increases, the ability to conduct sound will increase. Because both electric conductivity and sound conductivity depend on the mechanisms involving free electrons and phonons, as electrical conductivity increases, sound conductivity will increase.

Variables

Dependent Variable

The dependent variable is the distribution of the sound waves and thus; how intense the sound ends up being. According to the density, thermal conductivity, and electrical conductivity, the absorbance and reflectivity of the materials will change. The sound intensity will be less in models made by materials that absorb sound waves better compared to those that reflect sound waves. The sound level will be measured using an online sound level meter.

Independent Variable

The independent variable is the material that the model will be made of. Each model will be made using a different material which are determined to be cardboard, glass, foam, cork, and fabric. The texture, characteristics of its surface and hardness are some of the determining factors while the sound hits the material. These materials will absorb and reflect sound in varying ways.

Controlled Variable

Variable	Why is it controlled?	How is it controlled?
Sound source	If the sound source differs in any aspect, the actual sound efficiency of any material cannot be accurately measured.	The sound source will remain the same sound, created by the same source, of the same volume and intensity.
Distance of the sound source from the material	If the sound source is closer or further away from some materials, it would impact the absorption.	The sound source will be 30 cm away from the materials so as to avoid
Distance of points from	If the intensity is measured	The intensity will be

which the intensity is measured in relation to the source	closer to some of the materials, because sound waves will travel to different directions as well, intensity would be higher compared to one measured from further away regardless of the materials’ properties.	measured from 30 cm away from the materials so as not to receive the sound too early or too late if absorbed.
Size and shape of the materials	If a material is smaller than the rest, it can enable the sound to be absorbed easier.	Each material will be a square shape, 10 cm to 10 cm to facilitate obtaining the resources.
Thickness of the materials	If a material is too thick, it could even prevent the sound from being absorbed.	Each of the materials will be 15 mm thick so as to ensure that each one of them can absorb sound to a certain level even though not the same amount, and to ensure that the materials can easily be found or layered if necessary.

Environment	Environmental circumstances such as unintended noise pollution, wind-like intrusions etc. can impact the results of the experiment.	The experiment will be conducted under the same environmental conditions, in the same place and relatively the same time for each of the materials.

Table 1: Controlled Variables

Materials

Material	**Specification**	**Uncertainty**
Cardboard	Thickness 15 mm.	±1mm
Glass	Thickness 15 mm.	±1mm
Foam	This is one of the materials as an independent variable. Thickness 15 mm.	±1mm
Cork	Thickness 15 mm.	±1mm
Fabric	Silk. Thickness 15 mm.	±1mm
Plexiglass (Plastic)	Thickness 15 mm.	±1mm
Wood	Cypress. Thickness 15 mm.	±1mm

Metal	Iron. Thickness 15 mm.	±1mm
Foam for isolation	1 m x 0.5 m x 0.5 m dimensions with 15 mm thickness for each piece. This will be used to create an isolated system for the experiment's exterior.	±1mm
Sound Source	The same sound, with the same intensity will be played for each material, different frequency for trials of the same material using a phone (Youtube Video). The sound is monotone and does not differ in frequency during.	Is open to human error. Because an electronic device will be used, if the intensity varies ever so slightly, an error in the trials may occur.
Decibel meter	Application on phone.	± 1 dB
Ruler	Standard, up to 50 cm.	± 0.05 cm

Table 2: Materials

Safety and Ethical Concerns

There are no safety or ethical concerns with this experiment.

Experimental Setup

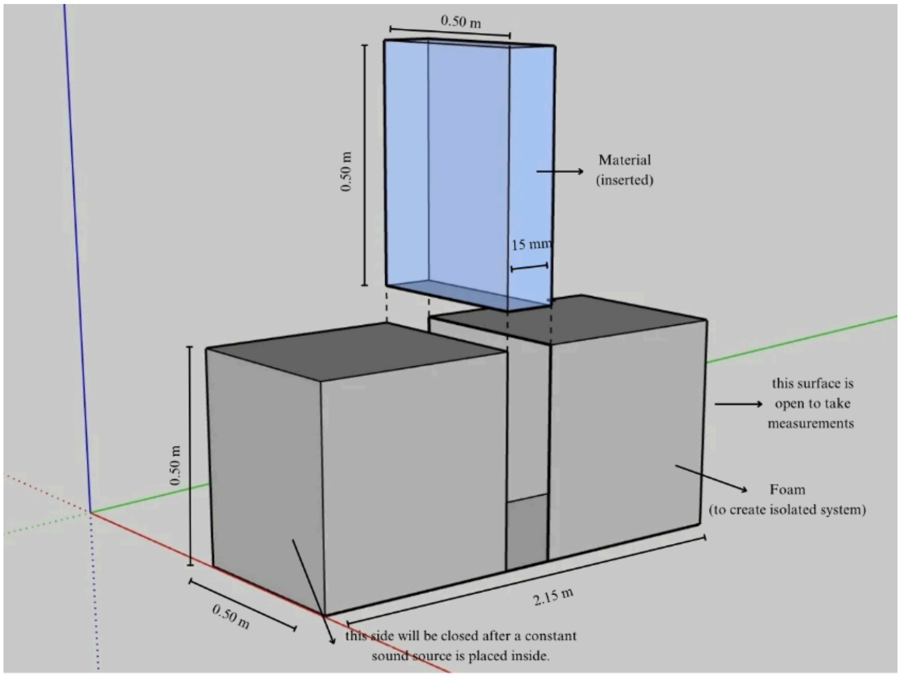

Figure 4: Labeled Experimental Setup Drawn on SketchUp (not drawn to scale)

Methodology

Preparing the Experimental Setup

1. The 1m x 0.5 m x 0.5 m foam is used to create an isolated system (as seen in Figure). The thickness of one piece of the foam is 15 mm and two pieces are used for each wall. A 15 mm gap is left empty in between the walls for the material being investigated.
2. The phone from which the sound will be played is placed inside the system, towards the edge of the side that will be sealed after it is placed. A line is drawn where the phone is placed so as to avoid human error due to placing the phone in the wrong place (nearer, further) for other trials.
3. A foam wall is placed to seal the side where the sound source is placed.

4. A separate electrical device to measure sound is placed on the opposite side of the setup.
5. First material is placed in the gap between the two foam walls.

Data Collection

1. The material being invested is placed in between the two foam walls.
2. The first sound is played. (200 Hz)
3. It is waited until the number on the decibel meter starts being a constant value. The value shown on the decibel meter is recorded.
4. The second and third sound is played one by one (400 Hz and 600 Hz) and the value shown on the decibel meter is recorded.
5. At each frequency, three trials are taken.
6. The material is changed and steps 2, 3, and 4 are repeated for the new material until all eight materials are used.

Data Processing

1. A different table and graph will be generated for each different frequency trials.
2. The trials made in different frequencies will be analyzed separately and the trends will be compared.

Data Analysis

Reference Values

The sound amplitude measured when no material is placed in between the detector and the sound source and the relative physical property (density, thermal conductivity, electrical conductivity) values of the materials are the reference values in this experiment.

Materials	Frequency of the sound source (Hz)		
	200	400	600
	Sound Amplitude Measured (dB) ±1 dB		
No material	26	40	42

Table 3: Reference Values for dB measured when no material is present

Materials	Density (kg/m^3)	Thermal Conductivity (W/mK)	Electrical Conductivity (S/m)
Foam	30	0.02	10^{-12}
Cork	240	0.04	10^{-14}
Glass	2500	0.80	10^{-14}
Plexiglass	1150	0.20	10^{-14}
Fabric	1320	0.77	10^{-12}
Wood	510	0.09	10^{-14}
Cardboard	689	0.07	10^{-14}
Metal	7800	73	10^{5}

Table 4: Reference values of physical properties of materials

Raw Data

Materials	**Frequency of the sound source (Hz)**								
	200			400			600		
	Sound Amplitude Measured (dB) ±1 dB								
	Trial **1**	Trial **2**	Trial **3**	Trial **1**	Trial **2**	Trial **3**	Trial **1**	Trial **2**	Trial **3**
No material	26	26	26	40	40	40	42	42	42
Foam	22	22	22	28	28	28	29	29	29
Cork	23	23	23	27	27	27	32	32	32
Glass	25	25	25	37	37	37	39	39	39
Plexiglass	24	24	24	32	32	32	37	37	37
Fabric	25	25	25	38	38	38	38	38	38
Wood	24	24	24	31	31	31	33	33	33
Cardboard	24	24	24	30	30	30	35	35	35
Metal	26	26	26	36	36	36	41	41	41

Table 5: Raw Data

Processed Data

Because all trials for separate frequencies gave the same results at each trial, the mean value of all trials is equal to the value itself. Therefore, the processed data graph is as given below and standard deviation cannot be calculated. The same value was recorded due to the measurement tool not being sensitive enough.

Sample calculation for percentage uncertainty:

$Percentage\ Uncertainty\ = \left(\frac{Absolute\ Uncertainty}{Measured\ Value}\right) \times\ 100$, where absolute uncertainty is the uncertainty of the measurement tool used.

So, sample calculation for percentage uncertainty of sound amplitude measured with no material while the frequency of the sound source is 200 Hz:

$Percentage\ Uncertainty\ = \left(\frac{1}{26}\right) \times\ 100\ \approx\ 3.85\%$ rounded to 3 significant figures.

Materials	**Density (kg/m3)**	**Thermal Conductivity (W/mK)**	**Electrical Conductivity (S/m)**	**Frequency of the sound source (Hz)**					
				200		400		600	
				Sound Amplitude Measured (dB) ± 1 dB					
					% unc.		% unc.		% unc.
No material	0	0	0	26	3.85%	40	2.5%	42	2.38%

Foam	30	0.02	10^{-12}	22	4.55%	28	3.57%	29	3.45%
Cork	240	0.04	10^{-14}	23	4.35%	27	3.70%	32	3.13%
Glass	2500	0.80	10^{-14}	25	4%	37	2.70%	39	2.56%
Plexiglass	1150	0.20	10^{-14}	24	4.17%	32	3.13%	37	2.70%
Fabric	1320	0.77	10^{-12}	25	4%	38	2.63%	38	2.63%
Wood	510	0.09	10^{-14}	24	4.17%	31	3.23%	33	3.03%
Cardboard	689	0.07	10^{-14}	24	4.17%	30	3.33%	35	2.86%
Metal	7800	73	10^{5}	26	3.85%	36	2.78%	41	2.44%

Table 6: Processed Data of Mean Value dB measured

Graphs

Three separate graphs representing the relationship between the three physical properties (density, thermal conductivity, electrical conductivity) of each material will be drawn and different frequencies of the sound source will also have separate graphs.

Because the electrical conductivity (the dependent variable) values of the materials are relatively the same, except for metal, a reliable graph showcasing the relationship between sound amplitude and electrical conductivity cannot be drawn and therefore, a concrete statement cannot be made on their relationship.

When the frequency of the sound source is 200 Hz;

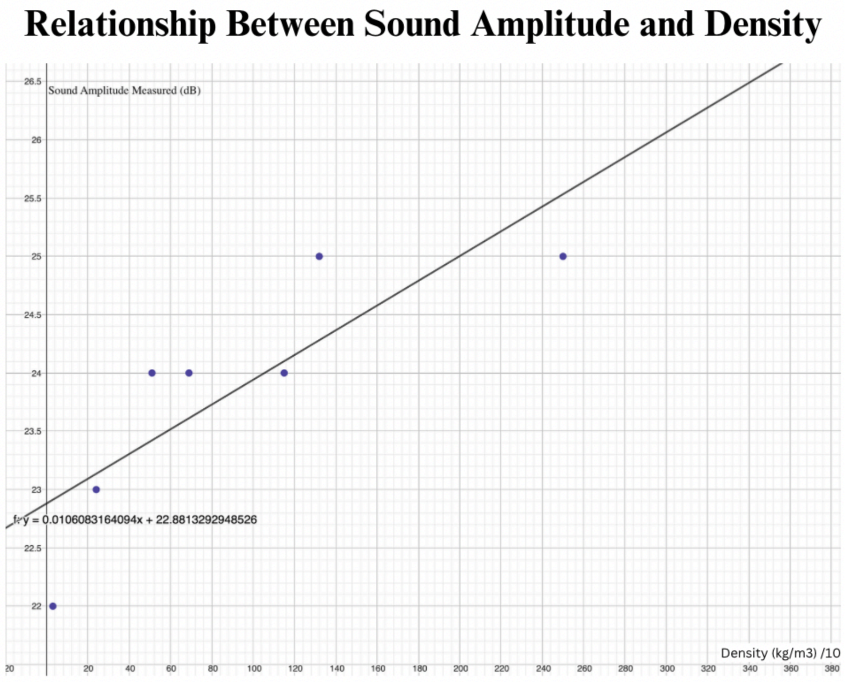

Figure 5: Graph of relationship between sound amplitude and density (200 Hz)

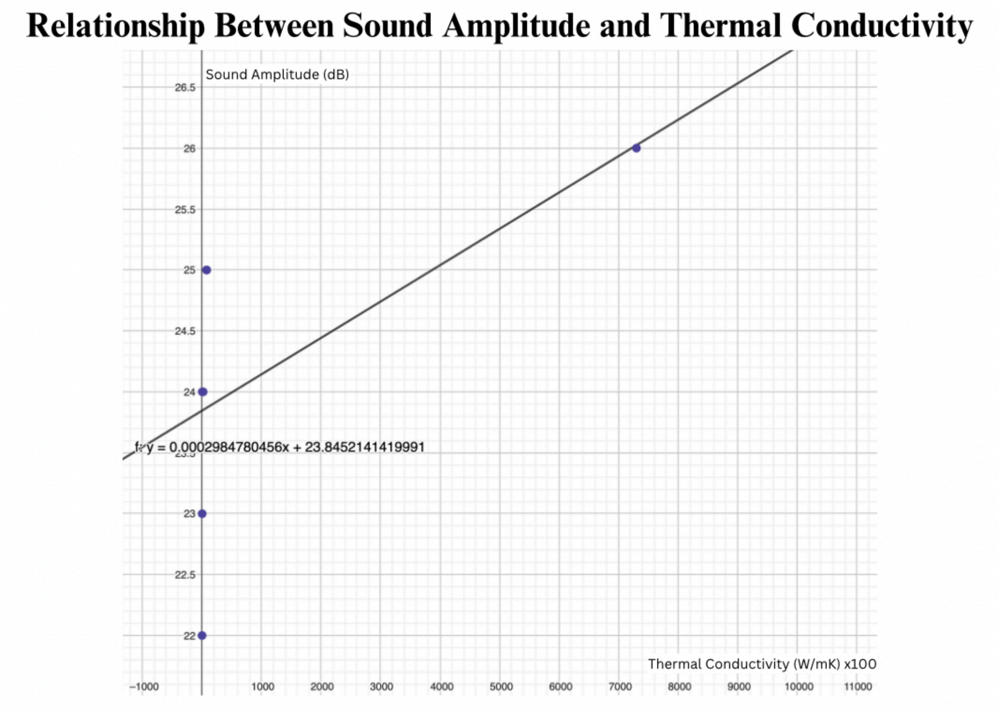

Figure 6: Graph of relationship between sound amplitude and thermal conductivity (200 Hz)

When the frequency of the sound source is 400 Hz;

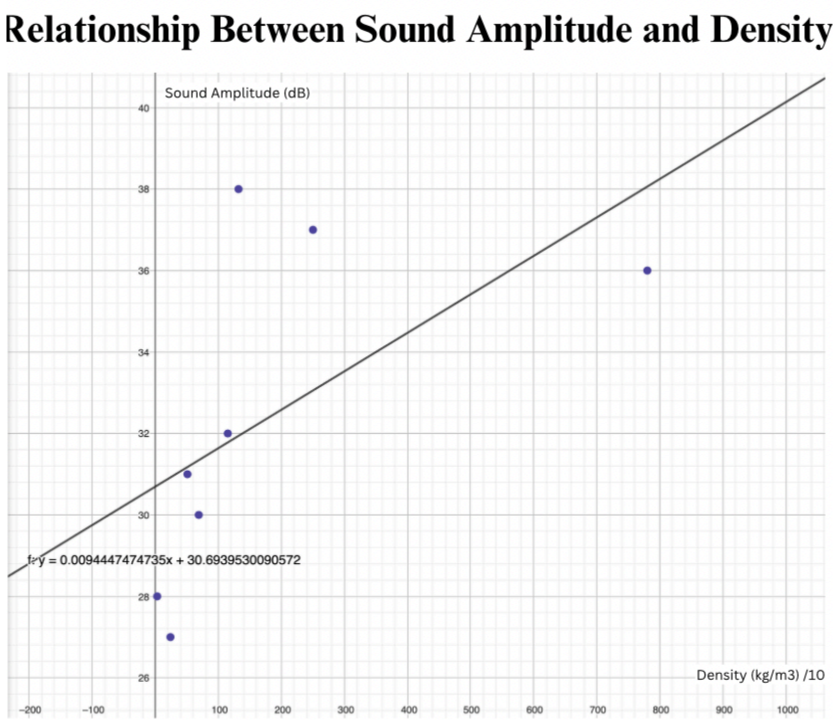

Figure 7: Graph of relationship between sound amplitude and density (400 Hz)

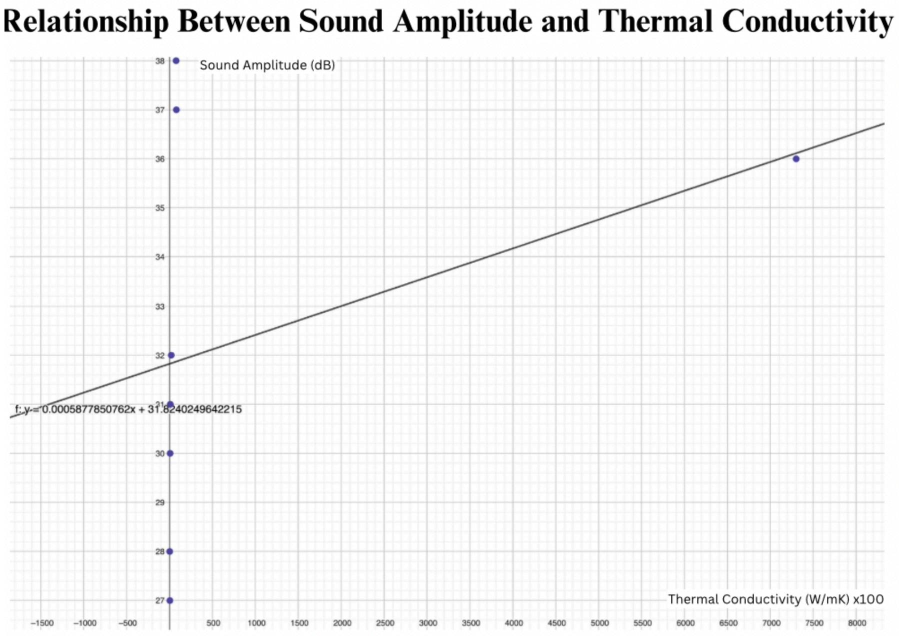

Figure 8: Graph of relationship between sound amplitude and thermal conductivity (400 Hz)

When the frequency of the sound source is 600 Hz;

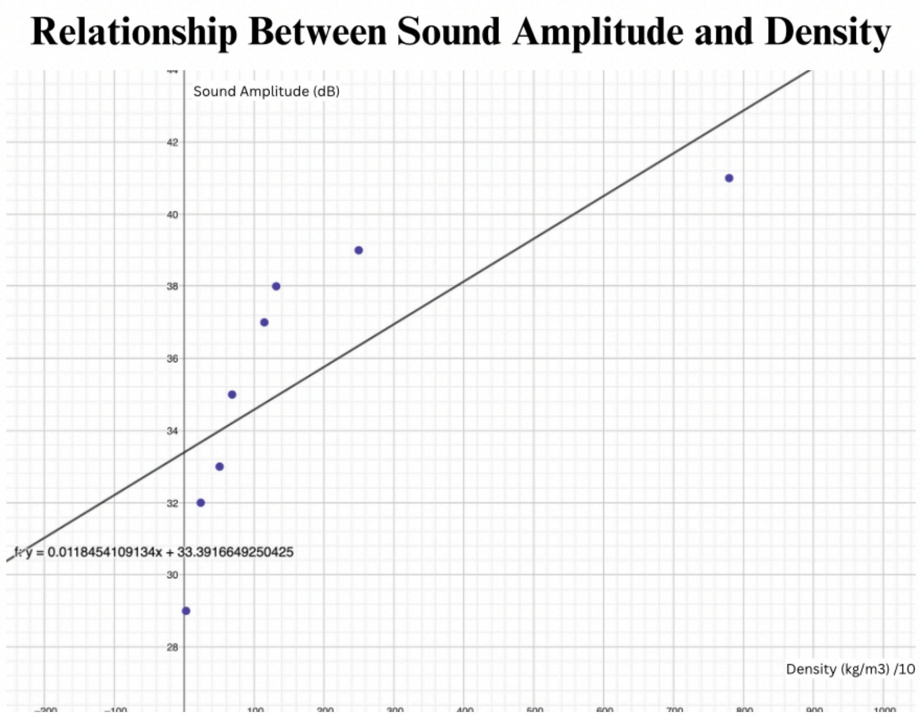

Figure 9: Graph of relationship between sound amplitude and density (600 Hz)

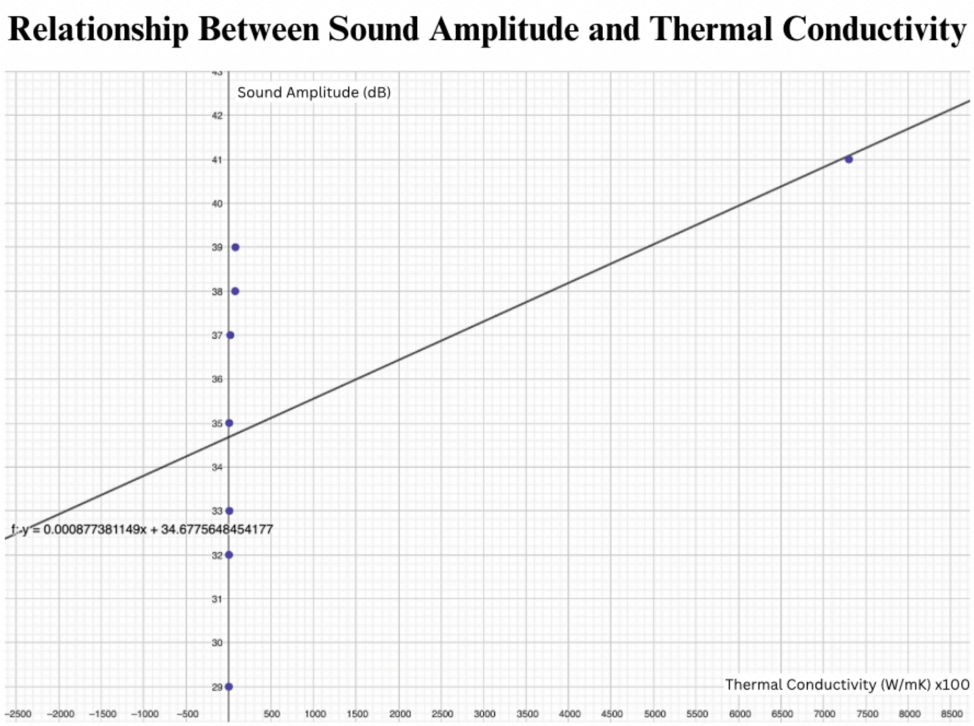

Figure 10: Graph of relationship between sound amplitude and thermal conductivity (600 Hz)

Error Propagation

According to the graphs, the y-intercept represents the value at which the density or the thermal conductivity is 0, meaning there is no material interference. The theoretical values are the y-intercept of the regression of the graphs given above. The experimental values are the measured sound amplitude when no material was present in the experiment seen in Table 3.

Sample calculation of error propagation when the frequency of the sound source was 200 Hz from the density graph:

$$\% \, Error = \frac{|experimental\ value - theoretical\ value|}{theoretical\ value} \times 100$$

$\% \, Error = \frac{|26 - 22.9|}{22.9} \times 100 \approx 13.6\%$ rounded to 3 significant figures.

The error propagation derived from density vs sound amplitude graphs is as follows:

Frequency of the sound source (Hz)					
200		400		600	
Sound Amplitude Measured (dB) ±1 dB					
Value	% Error	Value	% Error	Value	% Error
26	13.6%	40	30.3%	42	25.8%

Table 7: Error propagation derived from density vs sound amplitude graphs

The error propagation derived from thermal conductivity vs sound amplitude graphs is as follows:

Frequency of the sound source (Hz)

200		400		600	
Sound Amplitude Measured (dB) ± 1 dB					
Value	% Error	Value	% Error	Value	% Error
26	9.04%	40	25.7%	42	21.1%

Table 8: Error propagation derived from thermal conductivity vs sound amplitude graphs

Conclusion

The aim of this experiment was to find a correlation between the physical properties (density, thermal conductivity, electrical conductivity) of the materials chosen (foam, cork, glass, plexiglass, fabric, wood, cardboard, and metal) and their ability to conduct sound.

The graphs in Figure 5, 7, and 9 all show a positive linear correlation between density and sound amplitude measured.

In the graph in Figure 5, the equation of the best fit line, terms rounded to three significant figures, is;

$$y = 0.0106x + 22.9$$

The coefficient of x represents the rate of change of y with respect to x. For every $1 \times 10^{-1}\, kg/m^{3}$ increase in x, y increases by $0.0106\, dB$. Because the coefficient of x, the slope of the graph, is positive, it is indicated that the correlation between the two particles is a positive correlation.

The r-values of a graph shows the strength of the correlation. Because $r = 0.7786339872$ and $r^2 = 0.6062708861$, it suggests a moderate positive correlation as $0.7 \leq r < 0.87$.

Similarly in the graph in Figure 7, and 9, the equations of the best fit lines are relatively:

$$y = 0.00944x + 30.7 \text{ (Figure 7)}$$

$$y = 0.0118x + 33.4 \text{ (Figure 8)}$$

In the graph in Figure 7, for every $1 \times 10^{-1}\ kg/m^3$ increase in x, y increases by $0.00944\ dB$. In Figure 8, however, for every $1 \times 10^{-1}\ kg/m^3$ increase in x, y increases by $0.0118\ dB$. In both graphs, as the coefficient of x, the slope of the graph, is positive, it is indicated that the correlation between the particles is a positive correlation.

Because $r = 0.57774643$ and $r^2 = 0.3337909374$ in the graph in Figure 7, it suggests a weak positive correlation as $0.5 \leq r < 0.7$. And because $r = 0.7558669456$ and $r^2 = 0.5713348395$ In the graph in Figure 9, it suggests a moderate positive correlation.

These graphs indicate that density and ability to conduct sound are directly proportional to each other meaning that as density of a material increases, its ability to conduct sound also increases proving the hypothesis stating that if a material is more dense, sound will travel faster. So, as density increases, the ability to conduct sound will increase.

If we were to analyze the graphs of thermal conductivity vs sound amplitude, it can be seen that in all three graphs, there is a positive linear correlation.

In the graph in Figure 6, the equation of the best fit line, terms rounded to three significant figures, is;

$$y = 0.000298x + 23.8$$

According to this, for every $1 \times 10^2\ W/mK$ increase in x, y increases by $0.000298\ dB$. Because the coefficient of x, the slope of the graph, is positive, it is indicated that the correlation between the two particles is a positive linear correlation.

Because $r = 0.6156926265$ and $r^2 = 0.3790774103$, it suggests a weak positive correlation as $0.5 \leq r < 0.7$.

Similarly in the graph in Figure 8, and 10, the equations of the best fit lines are relatively:

$y = 0.000588x + 31.8$ (Figure 8)

$y = 0.000877x + 34.7$ (Figure 10)

In the graph in Figure 8, for every $1 \times 10^2\ W/mK$ increase in x, y increases by $0.000588\ dB$. In Figure 8, however, for every $1 \times 10^2\ W/mK$ increase in x, y increases by $0.000877\ dB$. In both graphs, as the coefficient of x, the slope of the graph, is positive, it is indicated that the correlation between the particles is a positive linear correlation.

Because $r = 0.3621824763$ and $r^2 = 0.1311761462$ in the graph in Figure 8, it suggests a very weak positive correlation as $0 < r < 0.5$. And because $r = 0.5639563366$ and in the graph in Figure 10, it suggests a weak positive correlation as $0.5 \leq r < 0.7$.

These graphs indicate that thermal conductivity and ability to conduct sound are directly proportional to each other meaning that as the ability to conduct heat of a material increases, its ability to conduct sound also increases proving the hypothesis stating that since both thermal conductivity and sound conductivity depend on atomic structure, and materials with strong atomic bonds tend to conduct heat better, as thermal conductivity increases, the ability to conduct sound will increase.

Analyzing the relationship between electrical conductivity of a material and its ability to conduct sound, the data didn't allow for strong conclusions as the materials used, except metal, had electrical conductivity values very close to each other (10^{-12} to 10^{-14} S/m), making it difficult to observe a clear trend. While the highest dB measured was always with metal, because a trend cannot be confirmed due to the other electrical conductivity values. It can be predicted that considering metals conduct electricity well due to their high density of free electrons, this might also play a role in sound conduction. Other factors such as density may be more significant in determining sound conduction.

This investigation can be extended to help with the architecture, medical and industrial industries as the results can be used to test materials for noise insulation in different architectural structures and because how sound is transmitted across different materials is investigated.

Evaluation

Strengths

The experimental design is one of the strengths in this experiment. Important factors like sound source intensity, distance, material size, and thickness were kept constant. The setup was designed specifically, using foam walls to create an enclosed system, to reduce external noise contamination. Investigating multiple material properties, instead of just one, allowed for a broader understanding of which factors influence sound conduction the most. Varying the frequency of the sound source checks whether the relationship between material properties and sound conduction is consistent or frequency-dependent.

Limitations and Improvements

Limitation	Impact	Suggested Improvement
Materials used in the experiment have different levels of porosity.	Affects how materials absorb and transmit sound. Less porous materials reflect or transmit sound more efficiently compared to more porous materials.	Materials with similar porosity can be selected.
Small range of electrical conductivity	No clear trend could be determined except for metal.	Materials with a wider range of electrical conductivities

		can be selected.
Decibel meter uncertainty (± 1 dB)	Small sound variations cannot be detected	A more precise tool can be used or the number of trials can be increased.
Environmental noise cannot be reduced completely	Uncontrolled sound reflections can influence measurements	The experiment can be performed in a soundproof or anechoic room.
Surface texture of materials are different	It's another factor. Rougher surfaces scatter sound waves while smooth surfaces allow sound to reflect more uniformly	Materials with similar surface roughness can be selected.

Table 9: Limitations and Improvements

Extensions

This investigation can be extended to investigate other physical properties of materials that can affect sound conduction such as porosity and surface texture. While this investigation focuses on solid materials, it can be furthered to explore sound transmission through liquids or gases.

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