Implementation of planar magnetic drivers for precise sound reproduction

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Contents

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Abstract

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Declaration of originality

I hereby confirm that this dissertation is my own original work unless referenced clearly to the contrary, and that no portion of the work referred to in the dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Intellectual property statement

Acknowledgements

No need to include, but can if want to.

1 Introduction

1.1 Background and motivation

Headphones have become an omnipresent device in our lives, with increased accessibility and usage growing year after year. Each year, more companies introduce new headphones with higher sound quality. Yet, despite this rapid production and innovation, 99There are various driver technologies, each with unique characteristics and benefits, yet one drastically dominates public use. This raises the question: Why is this the case? What makes this technology so prevalent, and are there more novel alternatives that could provide better solutions to the issues we've grown accustomed to—simply because we've only been exposed to one dominant technology? This report will provide a brief overview of the different implementations of driver technologies within headphones, alongside historical context and relative adoption today. We will then take a closer look at a technology seldom mentioned (planar magnetics), and how they differ from more traditional solutions, and if their advantages can overcome the inherent limitations of their alternatives, all in attempt to provide a better sound quality.

1.2 Literature Review

The core driver technologies have remained largely unchanged since the 1920s, with most advancements focusing on material improvements, stronger magnets and acoustic tuning through shaping earcups. The fundamentals of all the driver technologies is the same: have a force move a material, which in turn vibrates air and thereby creating sound. To understand the evolution, you need to understand the historic timeline of these technologies.

The most common implementation, which you would have been in contact with at some point, are dynamic drivers. Dynamic drivers were invented in 1920 and commercialized in the 1940s. Their continued prevalence is due to their simplicity and cost-effectiveness. A dynamic driver consists of a coil attached to a diaphragm, usually cone-shaped, suspended within a magnetic field. When electric current flows through the coil, it creates a magnetic field that interacts with the static field of the magnet, causing the diaphragm to move and produce sound.

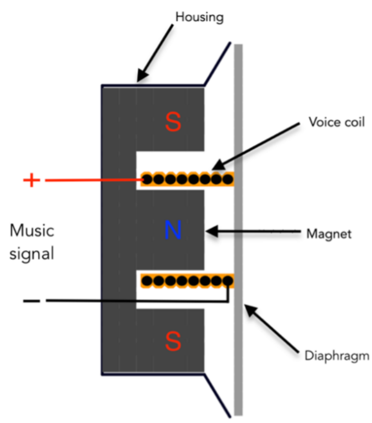

Fig. 1. Dynamic Drivers

This configuration of driver provides a larger diaphragm for movement, meaning that it can displace large amounts of air, increasing perceived loudness. The limitation of this implementation is visible in figure 1, the coil is located at the centre of the diaphragm surface, and since this is the inducer of force applied, the diaphragm is not feeling an equal and uniform force across its surface, which can lead to distortion and uneven movement, affecting the accuracy of sound reproduction. This non-uniform distribution of force can cause certain areas of the diaphragm to move more or less than others, leading to issues like frequency response anomalies or sound coloration, which is more prominent than in alternatives which would apply equal force along the whole diaphragm surface.

Each implementation has it trade-offs, the dynamic drivers are good due to their large cone which displaces a lot of air and produces loudness, however a large cone has a larger mass, which increases its inertia and the difficulty to stop the diaphragm moving after it begins its movement, making it a less accurate representation of the original sound signal and potentially leading to resonance peaks. There are several conflicting goals to consider when designing drivers, and a successful implementation will involve a certain number of trade-offs, which trade-offs you choose are dependent on intended application of use.

In attempt to mitigate the limitations of the dynamic drivers produced during the 1920s, a new type of driver technology called Electrostatic drivers was invented in 1959. The primary goal was to avoid the distortion created by the mechanical limitations of dynamic drivers, by creating an even and uniform force across the diaphragms surface.

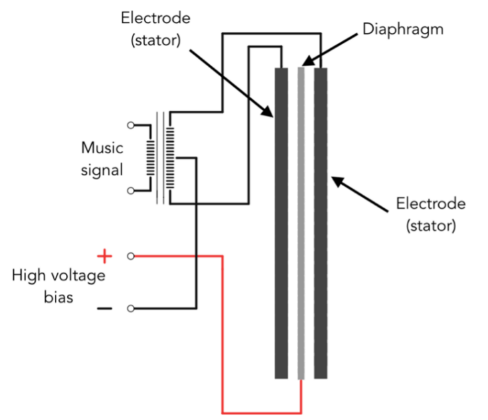

Fig. 2. Electrostatic Drivers

In this configuration of driver, there are no magnets to drive the diaphragm, nor is the diaphragm a cone-like shape. Instead, the diaphragm is made of a very thin, flexible film-like material. This diaphragm is electrically charged and suspended between two electrically charged metal plates. The polarity of charge on the metal plates corresponds to the alternating ”music signal” from the amplifier, meaning that the plates will have opposite charges at any given moment.

The diaphragm moves due to electrostatic forces, similar to how a balloon sticks to a wall after being rubbed on your head. When rubbed, the balloon becomes negatively charged, and when brought near a neutral wall, its electrons are repelled and protons are attracted, causing the balloon to stick. In this case, the diaphragm is like the balloon, and the metal plates are like the wall. The diaphragm is positively charged and is attracted to the negatively charged plate and repelled from the positively charged one. As the audio signal alternates the charge on the plates, the diaphragm is alternately attracted to one plate and repelled by the other, causing it to move back and forth, which generates sound.

This design eliminates a key limitation of dynamic drivers: mass and inertia. The lightweight diaphragm allows for more precise control over its movement, resulting in improved transient response. This leads to an extremely detailed representation of the input signal, high clarity and little distortion. As reiterated there are always drawbacks, in this case, the electrostatic drivers act as large capacitors, the impedance of capacitors is not constant across all frequencies, this is called a reactive load. Meaning at some frequencies the amplifier sees the load as a short circuit, having a direct connection to it, which is problematic since from the amplifier’s perspective, it’s as if there’s hardly any resistance, and it could push a lot of current through the speaker, stressing the amplifier. To solve this we would need a buffer between the amplifier and load, matching the impedance of the amplifier to the impedance of the drivers. This is the role of a transform, it ensures that the amplifier ”sees” the correct load and helps convert the low-voltage signal from the amplifier into the high-voltage signal needed for the electrostatic panel. The challenge, however, is that designing a transformer capable of handling high power across the full frequency range is complex and costly. As demonstrated, there are many complications when trying to strike a balance between the high-fidelity audio offered by electrostatic drivers and the accessibility of dynamic drivers. Planar magnetic drivers were invented in the 1970s in an attempt to combine some of the best features of both technologies. Their mechanical characteristics are similar to electrostatic drivers, using a thin diaphragm, but this time suspended between an array of magnets. This design provides high sound quality, and the rapid advancements in magnet technology during the 2000s gave them a similar accessibility to dynamic drivers.

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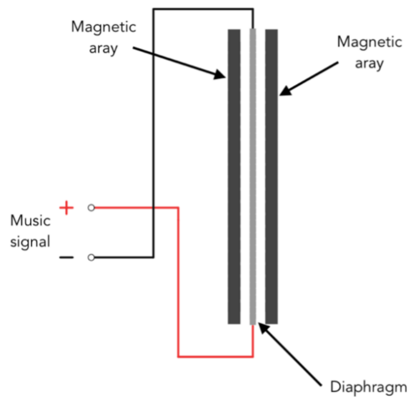

Fig. 3. Planar Magnetic Drivers

Similar to electrostatic drivers, there is a thin diaphragm, but instead of a fixed charge, it has a serpentine-wound coil that carries an alternating audio signal as a current. The diaphragm is suspended between two magnet arrays, configured so their fields superpose. The traces on the diaphragm align with the magnetic field, so when current flows through them, an induced field interacts with the magnets, creating a uniform force across the surface. This implementation eliminates the heavy diaphragm and the non-uniform force seen in dynamic drivers, resulting in detailed sound. Since the mass being moved is very light and the force applied is uniform, distortion is reduced.

It also resolves the issues faced by electrostatic drivers, as the load is purely resistive and remains constant across all frequencies, making it easier for the amplifier to drive. However, the primary drawback is that planar magnetic headphones tend to be heavier and bulkier, which can affect comfort during long listening sessions.

1.3 Aims and Objectives

The aim of this report is to explore a novel technology utilizing a Halbach array to enhance the audio quality of planar magnetic headphones without sacrificing weight. By leveraging a higher field strength and reducing the number of magnets required, this innovative configuration seeks to address the primary limitation of traditional planar magnetic designs—weight—while maintaining exceptional sound performance. The report will investigate whether this new configuration can overcome the challenges faced by other driver technologies, such as the complexity of electrostatic drivers and the non-uniform force distribution seen in dynamic drivers. Ultimately, this exploration aims to determine if this approach can improve both the sound quality and comfort of planar magnetic headphones, making them a competitive, high-performance alternative to other headphone technologies.

To achieve the aforementioned aim, clear objectives have been defined to limit and focus the scope:

- Firstly, finding a magnet configuration which provides a strong, alternating field at its surface
  - Use simulations to visualise the created field and determine the force it will cause on the diaphragm
- Secondly, determine the relative magnetic field distribution on a set of parallel current carrying traces
  - Use simulations to visualise the created field
- Thirdly, choose a material for the diaphragm of the drivers
- Next, design a serpentine PCB design, aligning the tracks, but more specifically their areas of largest magnetic density, with the magnetic field loops created by the magnet configuration.
  - Ensuring the direction of the current carrying traces matches with the alternating magnetic field of the magnets
- Design and 3D print driver enclosure, which fits the magnet arrays found, and suspends the created PCB between them.
- Test the drivers with a test signal, to ensure they function as expected
- Design an earcup enclosure to house the drivers, with design characteristics for intended output sound.
- Produce and analyse frequency response plots of the headphones, to determine if their performance.

1.4 Report Structure

The report is structured to systematically explore the design and implementation of high-quality planar magnetic headphones. It begins with a Literature Review, analysing existing research on planar magnetic technology and its applications. Following this, the Methodology section outlines the theoretical development and design choices, leading to the Implementation. Testing is conducted to assess performance, with findings presented in the Results and Discussion section. The project also includes an analysis of test data to explain why the system performed how it did. Finally, the Conclusion and Future Work section summarizes key insights and suggests potential improvements for further research.

1.5 Conclusion

2 Methodology

2.1 Theoretical Development

Sound is caused by the displacement of air molecules due to vibrations. These molecules don't travel with the sound wave; instead, they move back and forth in place parallel to the direction of the waves propagation. As they do this, they either compress together, compression, or spread apart, rarefaction. This cycle of compression and rarefaction moves through the air as a pressure wave, carrying energy from the source to your ears, where it is interpreted as sound. The difference between the highest and lowest pressure points in a wave is called its amplitude—the greater the amplitude, the louder the perceived sound.

Therefore, to create sound, air molecules must be displaced through vibrations. In headphones, this is achieved using a diaphragm—a light, thin, and flexible material that vibrates in response to a force. The diaphragm's motion determines the sound perceived by the ear and is directly influenced by the force acting upon it. Therefore, the accuracy of the perceived sound depends on how precisely an input sound signal is converted into force, which then drives the diaphragm's motion.

For the diaphragm to create compressions and rarefactions, it must receive a push-pull force. In planar magnetic headphones, this force comes from the interaction of magnetic fields. A static magnetic field is generated by suspending the diaphragm between two arrays of magnets, however, a static magnetic field alone isn't enough—the diaphragm needs a changing force to vibrate and produce sound. The alternating magnetic field is produced by the traces on the diaphragm, which carry an alternating current. When the AC current flows through these traces, it generates a magnetic field that interacts with the static field from the permanent magnets. This interaction produces a force on the diaphragm, causing it to move back and forth. The strength of this force on any given trace is determine by Fleming's Left-Hand Rule:

$$F = I \cdot B \cdot L \quad (1)$$

Where F is the force felt by the trace, I is the current through the traces, L is the effective length of the current-carrying conductor, and B is the magnetic flux density of the static magnetic field. The total force on the diaphragm in planar magnetic headphones is the sum of the forces on all the individual traces. Since each trace is carrying current and interacting with the static magnetic field from the permanent magnets, we can derive the total force as follows:

$$F_{total} = N \cdot I \cdot B \cdot L \tag{2}$$

Where variables have their aforementioned meaning, F_{total} is the total force felt by the diaphragm and N is the number of traces subjected to the force.

Understanding how the diaphragm responds to this force is essential in predicting the frequency response and resonance behaviour of the system. Since the external force on the diaphragm is known, we can begin to derive an equation of the motion for the diaphragm as a consequence of this force. The calculations can be simplified due to the absence of free vibrations in the normal operation of planar magnetic drivers, in this case the system can be modelled as a second-order mass-spring-damper system:

$$F_{\text{total}}(t) = M\ddot{x} + c\dot{x} + Kx \tag{3}$$

Where F_{total} maintains the previous meaning, $M\ddot{x}$ is the inertial force, $c\dot{x}$ is the damping force, representing air resistance and material damping, and finally Kx is the restoring force, which represents the restoring tension in the diaphragm. This can be further analyzed to find the effects of the force on the system within the frequency domain, by simplifying the differential equation of motion using the Laplace transform:

$$\mathcal{L}\{F_{\text{total}}(t)\} = \mathcal{L}\{M\ddot{x} + c\dot{x} + Kx\} \tag{4}$$

$$F_{\text{total}}(s) = M(s^2X(s)) + C(sX(s)) + KX(s) \tag{5}$$

$$F_{\text{total}}(s) = X(s)(Ms^2 + Cs + K) \tag{6}$$

We can rearrange to get a transfer function for the frequency response of the system:

$$H(s) = \frac{X_s}{F_{\text{total}}(s)} = \frac{1}{Ms^2 + Cs + K} \tag{7}$$

$$H(s) = \frac{1}{Ms^2 + \frac{C}{M}s + \frac{K}{M}} \tag{8}$$

This we can rearrange to get into a more familiar form and derive our gain, damping ratio, and natural frequency of the system:

$$H(s) = \frac{1}{Ms^2 + 2\zeta\omega_n s + \omega_n^2} \tag{9}$$

Where ζ is the damping ratio and ω_n is the natural frequency of the system.

The transfer function in Equation (9) describes the frequency response of the diaphragm system, showing how it reacts to external forces across different frequencies. It highlights the influence of mass M, damping C, and stiffness K on the system's behavior.

Firstly, the natural frequency (ω_n):

$$\omega_n = \sqrt{\frac{K}{M}} \tag{10}$$

Determining and knowing the relationship of the natural frequency of the system is paramount to avoiding resonance peaks in the frequency response. Ideally, the system's natural frequency would lie outside the audible frequency range to prevent resonances, which occur when the excitation frequencies approach the natural frequency of the material.

Secondly, the damping ratio (ζ):

$$\zeta = \frac{C}{2\sqrt{MK}} \tag{11}$$

The damping ratio determines how quickly oscillations dissipate after the diaphragm is subjected to an external force, thereby controlling the system's transient response.

Finally, the gain of the system:

$$\text{Gain} = \frac{1}{M} \tag{12}$$

The gain relationship clearly indicates that the mass of the diaphragm is inversely proportional to the responsiveness of the system, meaning a lighter diaphragm more efficiently converts the inputted force into motion.

Fundamentally, the functioning of the drivers can be explained using a combination of equation (2), representing the external force felt by the diaphragm and equation (9), showcasing it's response in the frequency domain due to the force applied. Equation (2) also provides a relationship between the flux density of magnetic field and the force, demonstrating how changes in variables can increase the force applied, similarly equation (9) produces insights, demonstrated in equations (10), (11) and (12) of how changes can be made to variables to affect the systems behaviour. These two fundamental equations will be used to inform the design choices.

2.2 Design

2.2.1 PCB Design

The PCB should be designed to maximise the overlap between the magnetic field produced by its tracks and the field loops generated by the magnets. To achieve this, the respective field distributions must be analysed to identify regions of maximum flux density, which will inform the optimal positioning of PCB tracks.

Beyond maximizing field overlap, there are two additional key factors to optimize:

1. Minimising PCB mass – A lighter PCB improves control over the diaphragm and increases the system's gain.
2. Maximising impedance – A higher impedance reduces the current required to achieve the same power output, making the headphones easier to drive.

The impedance of the PCB not only affects the efficiency of the system, and how much current is required by the source to drive the load but also has an effect on the damping factor of the headphones. Damping factor is the ratio of the headphones input impedance (load) to the output impedance of the amplifier (source), and it measures how well the amplifier can control the diaphragm of the headphones:

$$DF = \frac{Z_{\text{load}}}{Z_{\text{source}}} \tag{13}$$

Where DF is the damping factor and Z_{load} is the impedance of the diaphragm and Z_{source} is the impedance of the amplifier. Planar magnetic drivers have a purely resistive load; therefore, their impedance curve is virtually flat, which means a constant current can be drawn to produce the same sound. However, damping factor still matters because even though planar drivers do not exhibit large impedance fluctuations like dynamic drivers, a low damping factor, due to a smaller output impedance load, can still reduce the amplifier's ability to exert control over the diaphragm. This can result in a looser transient response, how quickly the diaphragm responds to sudden changes to the input signal, as the amplifier may struggle to properly damp unwanted motion of the diaphragm after the signal stops.

To increase the impedance of load, the width of the current carrying traces on the diaphragm need to be reduced, and the length of the total trace should be increased. The minimum width and separation of the traces on the PCB is determined by the manufacturers capabilities, in this case University of Manchester PCB facilities. UOM facilities have a restriction of 0.3mm trace width and separation. Utilising the minimum width ensures we maximise the resistance according to:

$$R = \rho \cdot \frac{l}{w \cdot t} \tag{14}$$

Where R is the resistance, ρ is the resistivity, l is the length, w is the width, and t is the thickness of the trace. By reducing the trace width, we increase trace resistance whilst also allowing more traces to fit on the PCB, therefore increasing resistance again.

Tracks are a parallel set of traces on a PCB, the relative shape of a track's magnetic field distribution will be dependent on their thickness and separation, which we have defined as 0.3mm. Knowing this, we can begin to derive the field distribution of the tracks by first finding the magnetic flux density B of an individual current carrying trace, which can be defined using Ampere's law:

$$B = \frac{\mu_0 I}{2\pi r} \tag{15}$$

Where B is magnetic flux density, μ_0 is the permeability of free space, I is the current through the trace, and r is the radius of the trace. Since we are primarily interested in the relative field distribution, the magnitude of the current, I, and the number of traces in a track can be disregarded for this analysis. To find the flux density at any given point due to multiple traces, we apply the principle of superposition. This means the total magnetic field at any given point is the vector sum of the individual magnetic fields at said point. This can be visualised using a script to plot the field distribution in Python for an arbitrary amount of traces per track.

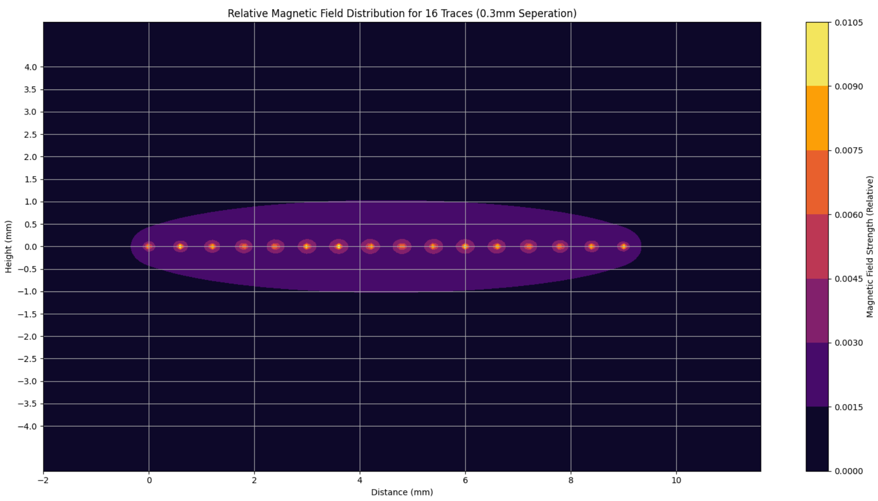

Fig. 4. Relative Magnetic Field Distribution For a Track

This figure demonstrates the relative field distribution for any implementation of tracks, showing here 16 point traces each carrying a current, producing a magnetic field around them, the field distribution is symmetrical around the centre of the traces, which is is expected due to the symmetrical arrangement of the traces themselves. The centre exhibits the greatest summation of vector magnetic fields, which logically results being in the region of the greatest number of traces. This figure, suggests that each track should be centred directly beneath each magnetic field loop produced by the magnets, to achieve maximum field overlap and therefore maximum interaction, without wasted efficiency.

While the optimal track positioning for maximum efficiency is established, the track configuration for diaphragm movement must be defined. The diaphragm is suspended in an alternating magnetic field, with adjacent magnetic field loops created by the magnets acting in opposite directions. To complement this setup, the current direction in the tracks must alternate as well. The tracks follow a serpentine layout, alternating current direction with each fold, ensuring that all traces in a track carry current in the same direction. Adjacent tracks, however, carry current in opposite directions. This arrangement ensures that the magnetic fields generated by the tracks complement the alternating field loops from the magnets, resulting in a uniform force on the diaphragm. Using the predefined trace width and separation, alongside the magnet length of 50mm, the serpentine configuration can be visualized in Python:

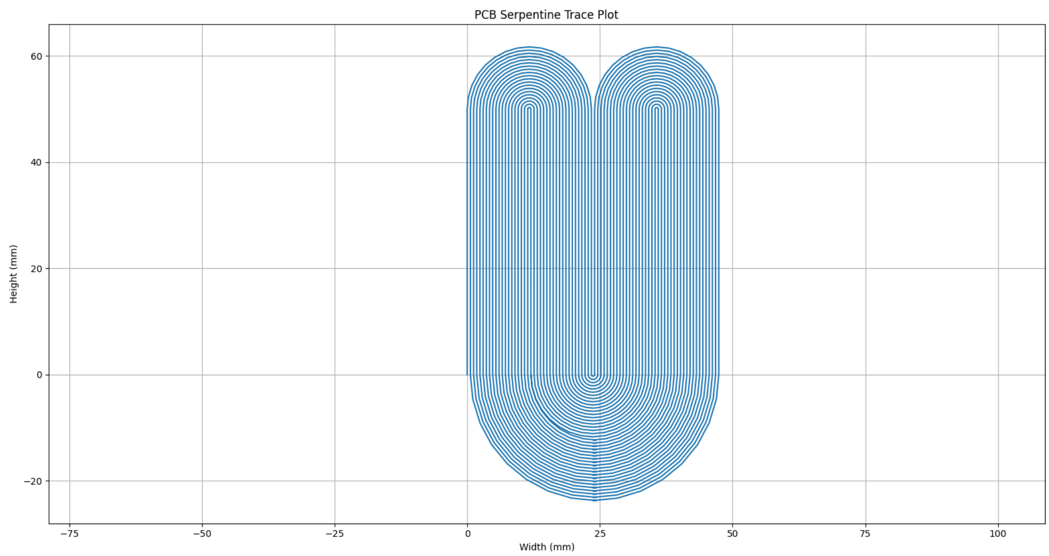

Fig. 5. Serpentine trace plot

Figure 2 shows the theoretical design of the PCB, with an arbitrary number of traces per track. The exact number of traces per track will be determined once we calculate the magnetic field loop width created by the magnets. Since the audible frequency range is up to 20 kHz, our design does not need to account for high-frequency signals. Therefore, traces can be routed close to each other without concern for crosstalk or interference causing noise in the sound signal, as frequencies above 20 kHz are inaudible. However, it's always good practice to take precautions. Since bends are required, the best approach is to ensure they are rounded, preventing trace width variation along the bend, which could cause impedance changes and result in signal reflections.

The subsequent phase involves selecting a suitable substrate material for the PCB. Given the application's requirement for flexibility, minimal inertia a polyimide-based flexible circuit is the optimal choice since they provide flexibility alongside a low mass. Additionally, polyimide based PCBs offer a strong textile strength, meaning they are resistant to warping, providing flexural endurance, which is essential in creating consistent sound reproduction, since it mitigates the chances of resonance peaks at altering locations. In combination the flexibility and low mass of PCBs made from this material ensure the diaphragm's dynamic response is highly sensitive to the input signal, thereby maximising the system's gain, as described by the relationship shown in equation (12). Furthermore, employing a low-mass substrate directly influences the damping factor, demonstrated in equation (11), a higher damping factor allows oscillations to dissipate quickly after the input signal changes, effectively meaning the amplifier has more control over the movement of the diaphragm. This enhanced control is crucial for accurately reproducing transient signals and maintaining stability. The flexible PCB printing capabilities of the University provided us with Kapton as the PCB material, ensuring both high flexibility and low mass while retaining the mechanical strength needed for consistent performance.

2.2.2 Magnet Design

The sound quality of the drivers is highly dependent on the magnet configuration, since the magnet configuration directly corresponds to the force felt by the diaphragm. To ensure less distortion a larger force is required, as a larger force maintains tighter control over the diaphragms movement, allowing it to effectively stop and start the diaphragms movement in more closely in response to the input signal. Using equation (2), it is evident that the force can be increased by increasing the magnetic flux density B, this is ideal since less current is needed for a given diaphragm movement. The diaphragm has a fixed resistance, therefore the power required to drive our system is proportional to the square of the current, meaning less power is required to drive the system according to equation (13):

$$P \propto i^2 R \tag{16}$$

A Halbach array is an ideal magnet configuration for this use case because it maximises the magnetic flux density on the side toward the diaphragm, whilst minimising it on the other side, this is due to its alternating magnet orientations which effectively traps the field on one side whilst creating alternating magnetic field loops.

This is useful as the magnetic flux density that would normally be wasted in air is redirected towards the diaphragm increasing efficiency, mean whilst it reduces electromagnetic interference with surrounding technologies.

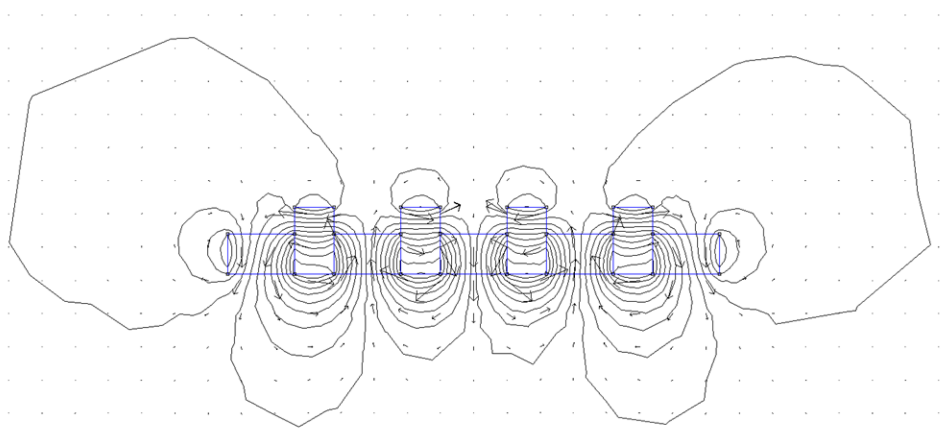

Fig. 6. Magnetic field distribution of 0mm gap Halbach array

Figure 1 shows the magnetic field distribution of a Halbach array, with a strong localised field on the bottom, represented by the higher density of magnetic field lines. The vector arrows indicate the direction of the magnetic field at each point, showing the alternating behaviour of the magnetic field loops. In practice, this configuration will be two arrays opposite each other, aligned to superpose their magnetic fields:

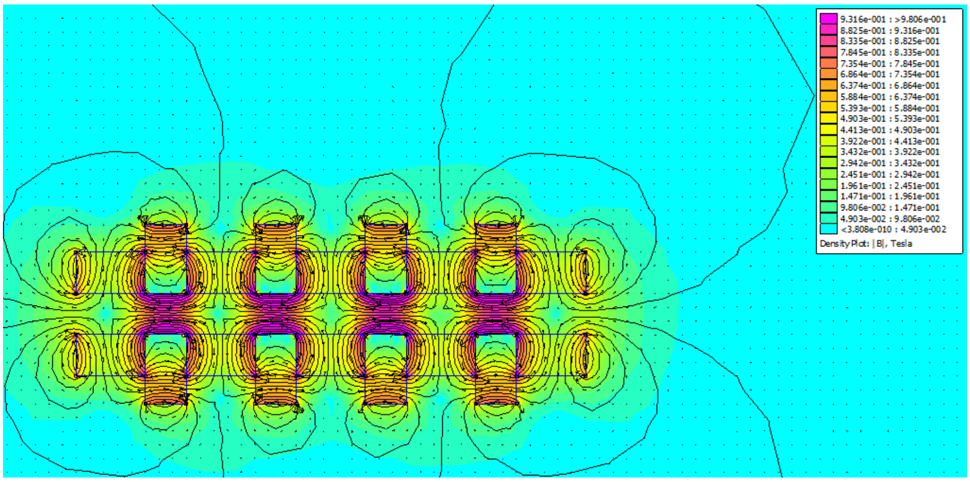

Fig. 7. Flux density plot of 2 row, 0mm gap Halbach array

Figure 2 displays the magnetic flux density as a colour density plot, where the darker colours represent a higher magnetic flux density B. From this plot it is evident that there will be four distinct loops with high flux density close to their surface, with a peak flux density of 0.93 T. To truly interpret the effect these fields will have on the movement of the diaphragm, the tangential flux density plot at the middle of the air gap should be derived, the tangential flux density plot will show the shape of the flux density which the field of our traces will interact with.

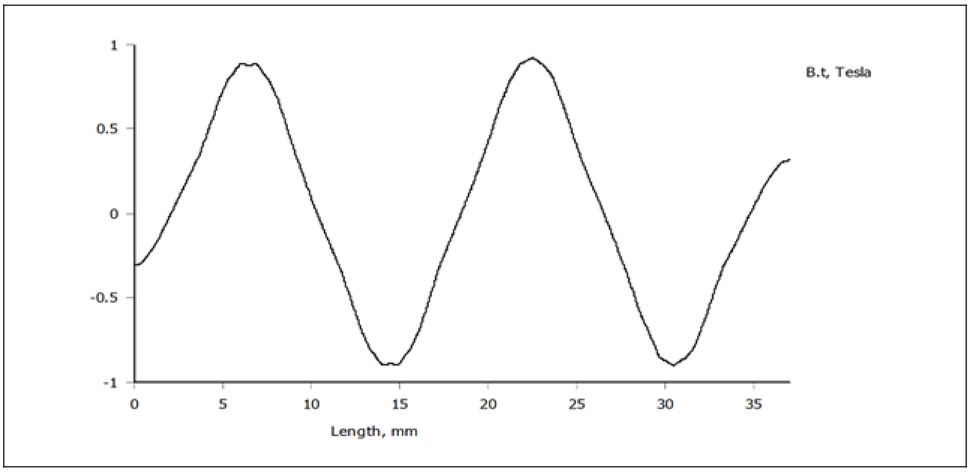

Fig. 8. Tangential flux density plot of 0mm gap, 2 row Halbach array

Figure 3 allows us to easily visualise the alternating magnetic field in each loop, alternating between $\pm 0.9\ B\hat{t}$.

This configuration produces the strongest magnetic field at its surface but due to the proximity of the magnets with no gap between them, though the width of their magnetic field loop is smaller than if they had a gap between, in this case the loop is 8mm wide. This is important when we begin to consider the fundamentals of our design: The movement of the diaphragm is caused by the interaction between the field created around its tracks (parallel traces) and the magnetic field loop created by the magnets, it was previously justified that the trace width and the gap between traces are both 0.3mm, therefore we can use the magnetic loop width to determine the number of traces which can fit into it:

$$\text{Magnetic field loop width} = 0.6n - 0.3 \tag{17}$$

$$8 = 0.6n - 0.3 \tag{18}$$

$$n = \frac{8.3}{0.6} = 13.83 \tag{19}$$

From equation (15) in this configuration only about 13 traces can fit within one magnetic field loop, to increase the amount of traces per track, the field loop width would need to be increased, which means a separation would have to be implemented between the magnets. The benefit of increasing the number of traces per track, is firstly due to an increase in load resistance as justified early but also since it will give a more even distribution of current and therefore force across the PCB. However, to introduce a gap and maintain it would require support for the magnets, this will be implemented using a 3D printed enclosure, the minimum accuracy of the 3D printing at the University of Manchester is 2mm, so to ensure the maximum amount of traces per track whilst also maintaining the field strength produced by the magnets the minimum width constraint will be used, this can be visualised:

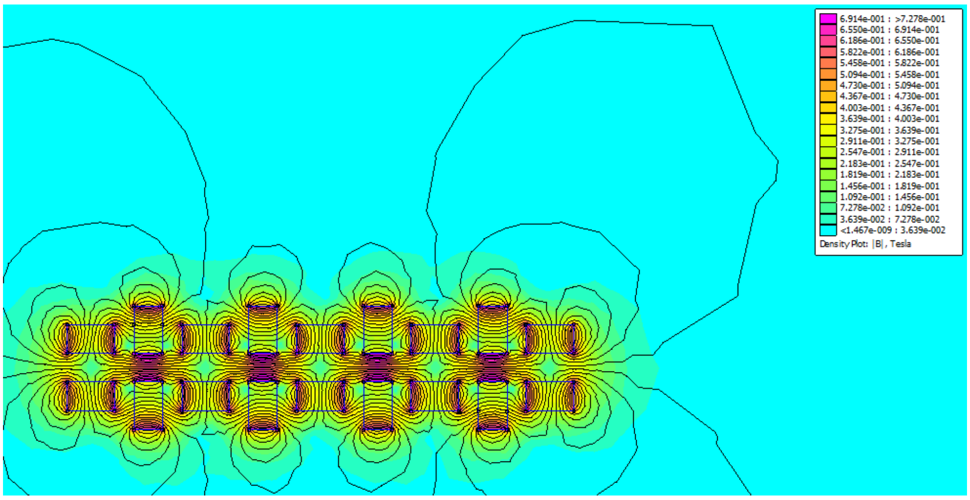

Fig. 9. Flux density plot of 2 row, 2mm gap Halbach array

This figure shows a slightly different configuration, implementing a gap between the magnets with the aim to increase the width of the individual field loops, this setup produces a loop with a 12mm width, using equation (15), this means we are now able to fit a maximum of 20 traces in a track, which is 7 more than previously, an additional 7 traces per track with four tracks in total for each loop, this means an additional 28 lengths of 50mm traces, which will increase the resistance of our circuit. In this figure we can also see more clearly than in the last one, that the area of highest magnetic flux density is concentrated at the centre of the loop, this is relevant since referring back to figure 1, the relative magnetic field distribution for a track, it is evident that the magnetic field is also concentrated at the centre of the tracks and peaks in the same location as seen in the field loops produced by the magnets. This alignment ensures maximum force on the PCB. The tangential field can be visualised for this configuration:

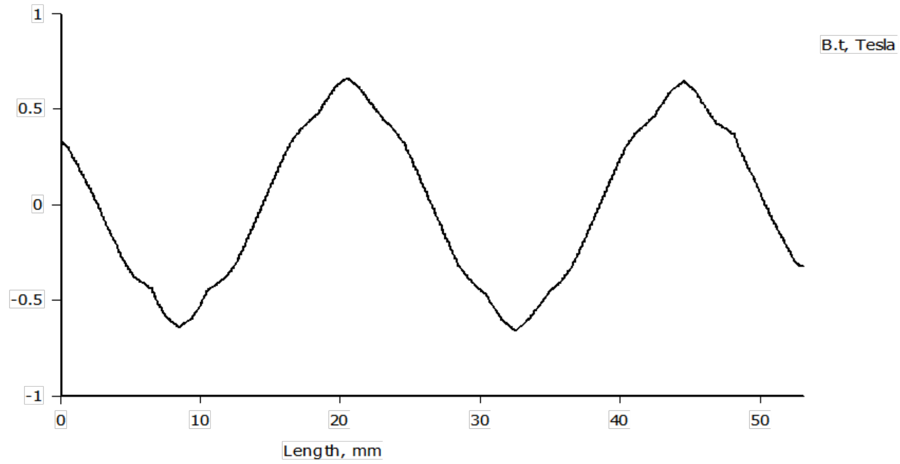

Fig. 10. Tangential flux density plot of 2mm gap, 2 row Halbach array

Figure 6 shows a configuration similar to the 0mm gap implementation, but with wider magnetic field loops. The peak flux density is slightly lower, alternating between alternating between $\pm 0.7\ B\hat{t}$. This decrease in flux density is acceptable since the primary goal is high-fidelity sound reproduction rather than maximizing loudness, which a higher flux density will do, since it leads to an increased force and sound pressure, where SPL directly correlates loudness.

To conclude, the 2mm gap configuration was chosen because it allows for a greater number of traces per track, leading to a more even current distribution. This results in a more uniform force across the diaphragm, reducing distortion and improving sound clarity. Additionally, the wider magnetic field loops align well with the traces, ensuring consistent diaphragm movement. The slight reduction in flux density is a worthwhile tradeoff for better accuracy and detail in sound reproduction.

2.3 Implementation

2.3.1 PCB Implementation

The diaphragm was designed to ensure track alignment with field loops produced by magnets. The initial step was to create guidelines on the mechanical layer (shown with purple lines in figure 7) to represent the width and height of tracks, where the height is the height of the chosen magnets (50mm) and where the width is determined by the width of the field loops defined during our magnet design chapter to be 12mm. With a clearly defined track shape on the PCB, and PCB directives implemented to follow the constraints set by the University PCB facilities: Minimum track width, separation of 3mm and whole size of 3mm, routing can start.

Traces were firstly routed spanning from top to bottom of their mechanical guideline container, 20 traces were routed within each, in alignment with what was previously calculated during the magnet design in our theoretical development. After this arcs were used to connect the tracks to each other to create a serpentine structure, which was justified in 3.2.1 PCB design.

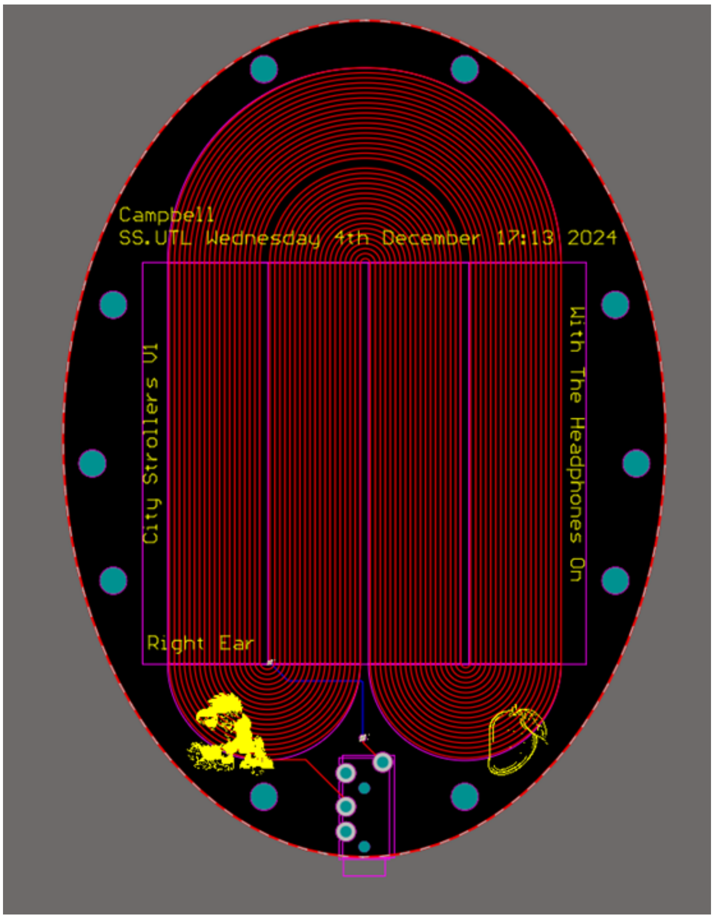

Fig. 11. PCB design using altium

Figure 7 displays the design of the PCB with all traces routed, with this information the total resistance of the diaphragm can be calculated, to do this a python script was created which utilises equation (14), the resistivity equation.

The estimated resistance for the PCB is 22.98 ohms. An important feature of this PCB design are the mounting holes, these holes have a 1.6mm radius, and will be used with 3mm screws. The symmetric distribution of the holes around the PCB and their closely matched size are design features used to ensure the diaphragm is evenly stretched and maintains a uniform tension across the entire magnetic field. Uniform tension ensures balanced sound production, without areas of excessive or insufficient movement, which could lead to distortion. An issue encountered during the PCB fabrication was due to the via sizes and the limitations of the university's facilities. After a PCB's design has been etched and holes have been drilled, connectivity between the layers must be established. This is achieved using plated through-holes, or vias, which are created through a process called electroplating.

Electroplating involves passing an electric current through a solution known as an electrolyte, which contains copper ions. These ions are attracted to and deposit onto the exposed surfaces of the drilled holes, forming a conductive copper layer that connects different layers of the PCB. This process is relatively straightforward for rigid boards, as they remain stable in the copper-based solution. However, flexible PCBs tend to sway in the solution, which can disrupt the plating process.

In large-scale manufacturing, specialized clamps are used to hold flexible PCBs in place, ensuring proper copper deposition inside the vias. However, due to limitations in the university's facilities, the PCB could not be adequately clamped, preventing the copper from plating inside the vias and resulting in open circuits. To resolve this, a thin piece of conductor had to be manually fed through each via and soldered on both sides to restore connectivity.

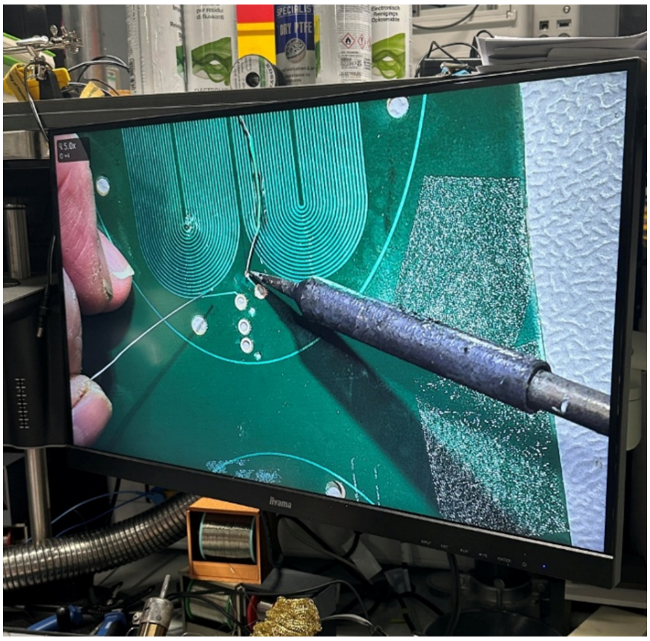

Fig. 12. Creating connectivity between layers on flexible PCB

2.3.2 Magnet Implementation

In magnetic applications, there are two main categories of magnets: electromagnets, which require an electric current to generate an electric field, like the copper traces in our diaphragm, and permanent magnets, which maintain their magnetism without external power. There are several types of permanent magnets each with their own characteristics, ranging from Neodymium, Alnico, Ceramic and Samarium Cobalt, the requirements for this project have been clarified, but to reiterate a strong magnetisation and a light form factor are needed.

Magnetic material	Density (g/cm^3)	Max Energy product BH_{max} (MGOe)	Coercive Force Hc (Oersteds)	Maximum Operating Temperature (°C)	Curie Temperature (°C)
Neodymium 35	7.4	33-36	≥ 10900	80	312
Ceramic 8	4.9	3.5	≥ 3200	204	450
SmCo 30	8.4	28-30	≥ 9900	350	820
Alnico 8 (sintered)	7	4	≥ 1500	450	860

Table 1. Magnetic material properties

The most relevant property of this table is the maximum energy product BH_{MAX}, which is a measure of the magnetic energy a material can store per unit volume. Neodymium has the highest BH_{MAX}, meaning it produces the strongest magnetic field per unit size, which is ideal for this compact use case within headphones. Secondly, neodymium has the largest coercivity, which measures the ability of the material to withstand an opposing magnetic field before becoming demagnetized, an important property since the permanent magnets will be subjected to the magnetic field produced around each of the traces. A high coercivity ensures the magnets do not become demagnetized and maintain performance throughout use. Finally, the other characteristics such as maximum operating and Curie temperature are sufficient for the use case, since the headphones will not reach such high temperatures.

Therefore, the permanent magnets used in this implementation are N35-grade neodymium magnets, each measuring 50mm x 5mm x 3mm. These magnets were selected for the two key reasons: Firstly, they are significantly stronger than other magnets, with an adhesion force up to ten times greater than Ceramic magnetic materials for example, providing a large magnetic flux density B. Secondly, neodymium magnets have a larger magnetizing energy than any other magnet of the same size, making them ideal for applications requiring a strong magnetic field in a small form-factor.

However, there are details which need to be considered when operating with neodymium magnets. Whilst being strong magnetically, they are also extremely brittle, meaning they must be handled with care, not allowing them to jump due to attraction with other magnets, since this can lead to chipping or breaking of the magnets. The strong attraction alongside their fragility requires careful consideration when configuring them in the desired arrangement, and precautions taken to ensure they maintain that arrangement. The difficulty will be in the initial arrangement of the magnets, however, since the Halbach array is an inherently stable structure, once the magnets are aligned as intended they will be less likely to jump and move. To create a Halbach array, the poles of the magnets are arranged in a periodic pattern, such that the direction of the magnetic field rotates around the array, this can be seen in the figure below:

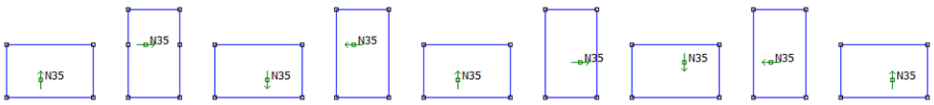

Fig. 13. Halbach array orientation

Figure 15 displays the final magnet configuration, 9 magnets were used, which creates 4 circulating flux paths, similarly to those shown in figure 3.

To maintain alignment throughout use, a 3D printed enclosure will be made with alternating slots of 3mm depth with 5mm width, and 5mm depth with 3mm width, which will tightly hold the magnets in their intended orientation, 2mm apart. The size of the enclosure will be made to fit the PCB design.

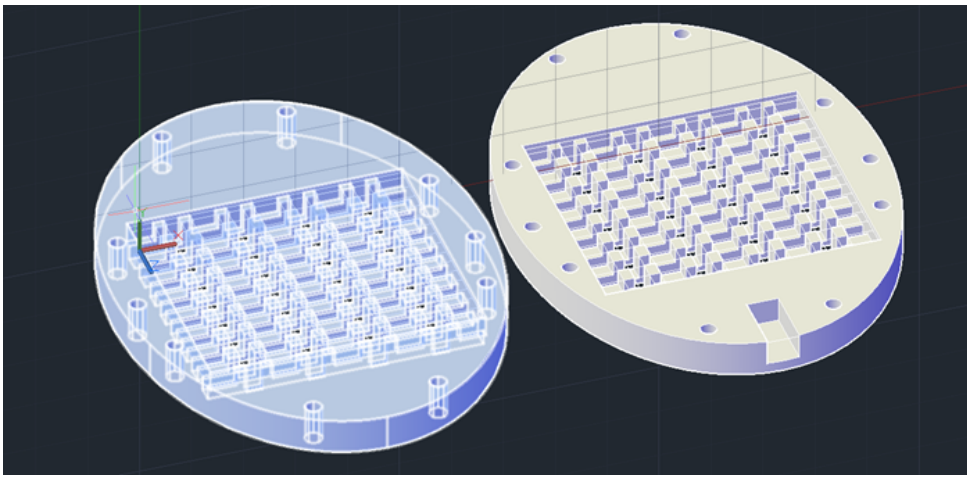

Fig. 14. 3D Printed Driver Enclosure

Figure 16 displays the driver enclosures with the alternating spaces for the magnets and also the surface mounted audio jack. The shape of the enclosures matches that of the PCB with corresponding holes for the screws. The enclosure will be 3D printed with PLA filament, since this method allows for accurate design whilst maintaining a light weight enclosure, a light weight enclosure is paramount since this will be a wearable device and must be comfortable for long durations of use. Each driver will contain 18 magnets in total. The weight of each magnet can be calculated from its known density of 7.4 g/cm^3:

$$\text{mass} = \rho \times \text{volume} = 7.4 \times 5 \times 0.5 \times 0.3 = 5.55 \text{ g} \tag{15}$$

According to equation (15), each magnet has a mass of approximately 5.55g, meaning the total weight of all magnets in one driver is approximately 100g. The weight of the drivers as a whole, including the screws, magnets, and the 3D printed enclosure, is 143g, therefore the headphones mass will be a minimum of 286g.

2.4 Testing

2.4.1 Results and Discussion

2.4.2 Analysis

2.5 Conclusion and Future Works

A Appendix: Source Code

Listing 1. Python Code for Resistance Calculation

```
import math

```

```
total = 0

def calculateResistance(length_meters):
resistivity = 1.77e-8  # Copper resistivity in ohm meters
width = 0.3e-3  # 0.3mm trace width
thickness = 35e-6/2  # 1/2oz micrometers
return resistivity * length_meters / (width * thickness)

def calculateStraightSection():
# 4 tracks of 20 traces each, each 5 cm (0.05m) long
return 4 * 20  * calculateResistance(50e-3)

def calculateMiniCurvedSection():
mini_curve_total = 0
radius = 12e-3  # 12 mm
for i in range(18):
mini_curve_total += (radius - (0.3e-3 * i)) * math.pi  # 0.3 mm steps

```
return calculateResistance(3 * mini_curve_total)

```

def calculateMainCurvedSection():
main_curve_total = 0
radius = 24e-3  # 24 mm
for i in range(18):
main_curve_total += (radius - (0.3e-3 * i)) * math.pi  # 0.3 mm steps

```
return calculateResistance(main_curve_total)

```


total = calculateStraightSection() + calculateMiniCurvedSection() +
    calculateMainCurvedSection()
print(total) # 22.980074035771178
```