SUTD 2019 10.005 Physics II 1D Project - AM Radio

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I. INTRODUCTION

Amplitude Modulation (AM) is the first method developed in the early 1900s to transmit audio through radio signals and it is still currently used worldwide. An AM radio varies the strength or amplitude of the carrier oscillations to broadcast information via radio. AM transmissions, however, are more vulnerable to interference than FM (Frequency Modulation) or digital signals. Thus, most people have moved on from AM radio due to its lower audio fidelity.

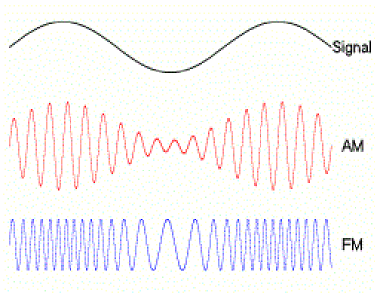

FIG. 1: Comparison between AM and FM radio signals.[1]

In this project, we would attempt to design and build a simple L/C circuit which would act as an AM radio receiver with a zero-dollar budget to receive the transmitted AM signals and play the designated audio, which is Singapore's National Anthem.

II. VARIABLE CAPACITOR

Working Principle

Our rotary variable capacitor utilised a group of semi-circular acrylic discs, which are glued with aluminium foil on their surface, attached on a rotary axis and positioned in between stationary acrylic discs, arranging the capacitors as parallel. Air is used as the dielectric material. By changing the effective area of overlap A between the stationary and the rotating semi-circles while keeping the distance d between the discs as constant, we could vary the value of effective capacitance C between the set of rotating discs (rotors) and the set of stationary discs (stators), since $C \propto \frac{A}{d}$. Notice in Figure 2 that the rotors are in contact with the central shaft, but the stators are not.

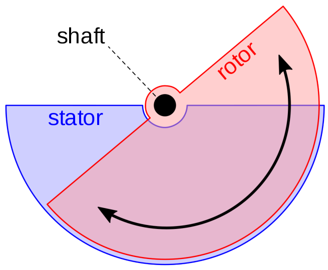

FIG. 2: Working principle of our rotary variable capacitor.[2]

Design Considerations & Features

We found inspiration from the industry-standard variable capacitors that utilised the same rotary design. Before choosing such a design, we built a coaxial cylindrical variable capacitor as a backup. We also experimented with cups and rectangular plates before settling on the disc design. We considered a butterfly variable capacitor design but decided to go against it since it could only cover a maximum angle of 90° (instead of 180° for the semi-circular rotary design).

A comb-shaped wire wrapped with aluminium foil was pressed by a PLA bracket to connect the stators together. On the other hand, the rotors were connected together by the central shaft. Rubber fasteners were attached to ensure contact between the central shaft and the aluminium foil of the rotors.

Since the arrangement was quite tight, each disc's surface was strategically taped in order to prevent each disc from conducting to its neighbor discs. Only the outer rim surfaces of the stators and the inner rim surfaces of the rotors were exposed in order to allow them to stay in contact with the comb-shaped wire and the central shaft, respectively.

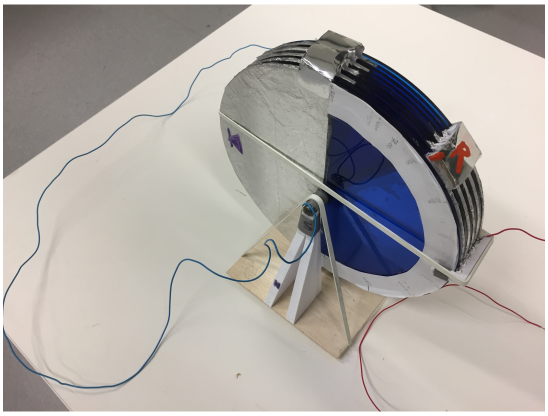

FIG. 3: Our rotary variable capacitor design.

Our variable capacitor is able to measure capacitance of about 200 to 2800 pF for a varying angle range of about 145°, with $\theta = 0°$ meaning that the rotors are completely not overlapping with the stators. We did not cover the whole 180° since, due to the positioning of the PLA bracket and the rubber fasteners, the variable capacitor was unable to reach the full 180° as it was too tight. Forcing the capacitor to reach 180° might cause some minor breakage.

$\theta/°$	C/pF
0	200
14	500
18	600
25	700
34	800
53	1250
70	1550
83	1800
100	2000
118	2200
145	2800

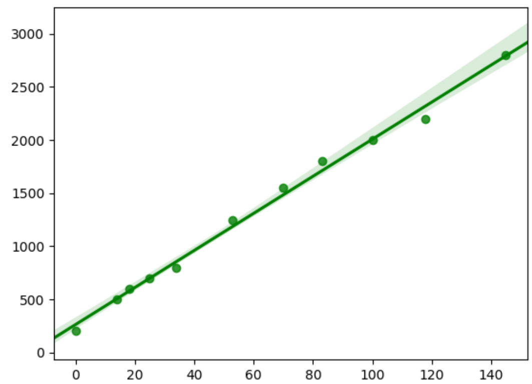

FIG. 4: Data and plot of C/pF against $\theta/°$.

By performing a linear regression on the collected data, we obtain a relationship of $C = 17.5\theta + 262.0$, with a value of $R^2 = 0.994315$. This data fairly convinces us that there is a linear relationship between the value of θ, the angle by which the rotors are rotated for from the orientation of the stators, and the value of C.

III. SPEAKER

Working Principle

When the audio jack, which was soldered to the copper coil, is connected to an audio source, it converts the digital signal to electrical current. This time-varying current will flow through the coil, generating a magnetic field around the coil. In the presence of external magnetic field generated by the neodymium magnets, by Lenz's Law, the coil would experience a force as the system would try to oppose the change (as a byproduct of the Law of Conservation of Energy). This time-varying force would be synchronized to the changes in the music signal as the magnetic field generated by the coil would be changing according to the strength and direction of the current. This vibration of the coil would then be transferred to the cone, which would magnify the amplitude of the vibrations, resulting in an audible sound.

Design Considerations & Features

Initially, we tried to modify the default speaker and follow the normal industry-grade speaker arrangement (Figure 5). We also tried to 3D-print an exponential cone described by a parametrically-defined exponential curve in SolidWorks. However, after some experimentation, we were able to produce a louder noise if we were to just simply attach the voice coil to a large paper cone. We did not inflate the paper cone until it becomes too big since it would then be unable to play higher frequencies. We flipped the speaker arrangement with the larger circular side as the base to maintain stability without any paper spider support. The table proved to be a good conductor of sound vibrations without muffling much of the acoustic texture.

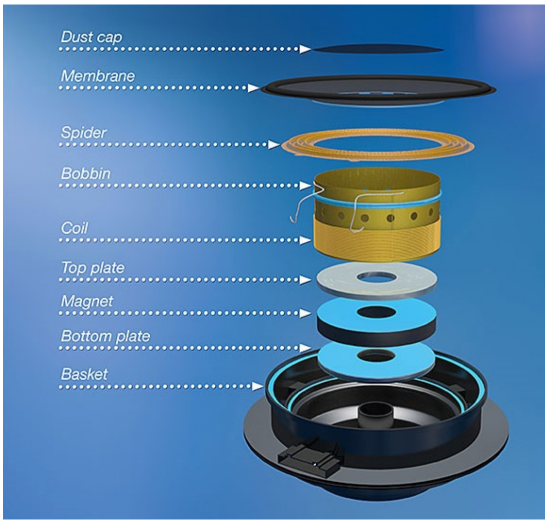

FIG. 5: Exploded view of industry-standard speaker assembly.[3]

We utilised a stack of smaller but stronger magnets (grade N52 of diameter 12 mm) instead of the default one (grade N35 of diameter 25 mm). This comes at the cost of them being more brittle, but since we had plenty of them to make a relatively small-sized speaker, it does not matter so much. The copper-wire coil was wrapped around a 3D-printed cylindrical shell placed as near as possible to the center of the magnets so as to capture most of the magnetic field lines and maximise the force generated without sacrificing much kinetic energy through mechanical friction. The coil had about 80 turns since if there were too little turns, the magnetic field generated by the coil would not be strong enough, while too many turns would lead to the setup being too heavy to vibrate efficiently.

FIG. 6: Our speaker design.

Multiple N52 magnets were used to amplify the strength of the electrical current produced. However, we noted that this effect has a tapering limit since it would only be most effective when the height of the stack of magnets is roughly equal to the diameter of a single magnet. This is reasonable since as the distance r from the center of the magnets increases, the magnetic field strength decreases by a factor of $\frac{1}{r^2}$.

We used plain paper for the cone as it proved to be one of the default and best cheap material for the cone. Other materials that would be as good would cost more (ranging from wood to metal to Kevlar or even diamond).[4]

IV. INDUCTOR

Working Principle

When the current flowing through an inductor changes, by Faraday's Law of Induction, the time-varying magnetic field generated by the inductor induces an electromotive force in itself by the equation $\mathcal{E} = -\frac{d\Phi_{\mathbb{B}}}{dt}$. By Lenz's Law, this induced voltage opposes the change in current that created it. In this AM radio receiver, we utilised the self-inductance property of the inductor.

By substituting in the values $f = 1 \times 10^6$ Hz and $C = 1 \times 10^{-9}$ F ($\theta \approx 42°$) into the equation $f = \frac{1}{2\pi\sqrt{LC}}$, we would obtain the value of our target inductance $L = \frac{1}{4000\pi^2} \approx 25.3\ \mu$H, which is relatively small. By substituting this value into the equation $L = \frac{\mu_0 N^2 A}{\ell}$, we would obtain $\frac{N^2 A}{\ell} = \frac{625}{\pi^3} \approx 20.2$ m. Considering a convenient value for the number of turns as $N = 25$ (since $25^2 = 625$) and since $A = \pi r^2$, we would get the relationship $\ell = \pi^4 r^2$, where r is the radius of the cylinder's cross-sectional circle. We could then choose a convenient value of $\ell = r = \frac{1}{\pi^4} \approx 0.010$ m, which is pretty reasonable.

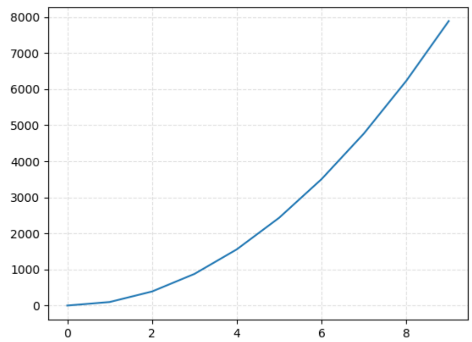

FIG. 7: Graph of ℓ/m against r/m.

From our experimental measurement, we measured the actual inductance value of $L \approx 24.5\ \mu$H, which is slightly smaller than the theoretical estimation. This is logical since in real life, there would be edge effects around the two ends of the inductor. Edge effects are especially relevant here since our inductor is quite small, leading to quite a significant diversion from the theoretical assumption of an ideal solenoid of infinite length. Edge effects would lower the actual value of inductance. Another possible cause would be the proximity effect, whereby the resulting current crowding in the wound coil of wire would increase the effective resistance and thus decreasing the value of inductance.

Design Considerations & Features

We wound some copper wire around a 3D-printed cylindrical shell of the specified size with some chamfer applied to prevent the coil from slipping off. We used the default cylindrical shape without any ferrite cores enclosed by the inductor. This is because the equation $L = \frac{\mu_0 N^2 A}{\ell}$ is applicable for an air core ideal inductor. This is also because our target inductance value is fairly low due to our chosen high capacitance value.

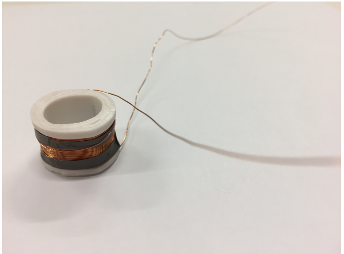

FIG. 8: Our inductor design.

V. AM RADIO

Performance Factors

1. Connections: This is the main performance factor of our circuit. Connection issues frequently arise from both the variable capacitor and the speaker components. Certain arrangements need to be done in order to achieve fairly consistent readings. Such arrangements include the specific positioning of the bracket and the stators as indicated by the various colored arrows such that a similar contact pressure is applied throughout the setup by gravity and air.

2. Material: For the variable capacitor, we used aluminium foil glued and taped quite tightly to the flat surface of acrylic discs that had been laser-cut. Due to the loose nature of aluminium foil, this is still not enough to ensure tight contact and full electrical connection. As such, we ran into multiple inconsistent reading issues during both calibration and demonstration.

Results & Analysis

We were able to produce the sound of Singapore's National Anthem with a decent volume by moving nearer to the transmitter. This is because the energy intensity spreads over a larger area as we go further away from the transmitter (by the inverse-square law) and thus, in order to capture enough energy to produce a hearable sound, the distance should be near enough.

Due to connection problems, the variable capacitor frequently produced rapidly oscillating and changing values of capacitance, even when the discs are not being intentionally moved. This happens especially just after re-adjustment of the discs. As such, if the variable capacitor were to suddenly change without warning, we would not be able to observe any sound since the current inside the L/C circuit would oscillate at an ever-changing frequency, causing the whole receiver setup to be incompatible with the steady 1 MHz AM radio transmitter frequency. If the L/C circuit was oscillating at a different frequency, it would not be able to achieve resonance with the transmitted AM radio signal.

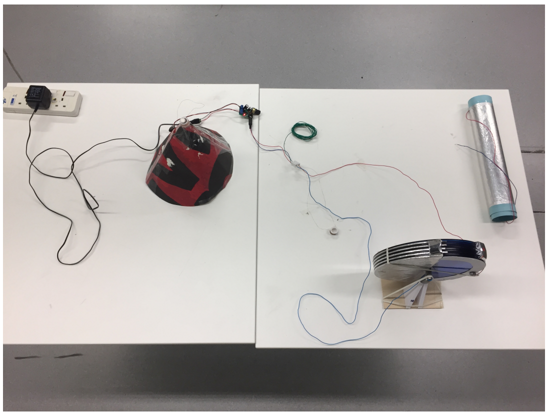

FIG. 9: Our whole AM radio receiver setup.

If the audio amplifier were to be used for a long period, it would gradually heat up. This would cause more noise to be added to the audio, decreasing the audio quality as time goes by. Thus, the amplifier would need to be disconnected and cooled every once in a while to prevent overheating and potential breakage.

Multiple amplifiers could have been used, although this has an upper limit since as the current increases, the current could more easily exceed the amplifier's ratings, leading to faster overheating and destruction of the amplifiers.

VI. CONCLUSION AND FUTURE WORK

We succeeded in building a roughly functional AM radio receiver. The variable capacitor was calibrated fairly well during testing, but faced a few connection problems during class demonstration. The speaker design is simple and yet effective, while the inductor provides the correct inductance value for the whole circuit to work.

Future improvements might include fixing the connection problem in the variable capacitor by either soldering the wire to the central rod or by entirely changing the setup from using aluminium foil to aluminium sheets instead. The speaker could be improved by increasing the cone's size and attaching a diaphragm/membrane layer made of polypropylene on top of the paper cone to further augment the air vibrations. The diaphragm's shape could follow a linear force-deflection curve with enough damping in order to fully absorb the vibrations from the cone interface, thereby increasing the sound volume.

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