The CUBE

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ABSTRACT

By rapidly oscillating the polarity of its magnetic field, an electromagnet is capable of inducing vibrations in other magnets. By precisely controlling the current through this electromagnet, the resultant vibrations are deterministic and can produce something that is sonically pleasing. In this project, we aimed to explore this phenomenon through the creation and design of a machine that can use electromagnetism to perform music. Our machine, titled "The CUBE", employs this concept by inducing vibrations in a magnetic cube coupled to an acoustic resonator. The final design is MIDI-controlled, and provides significant compositional freedom with a wide range of pitches, precise volume control, and modifiable timbre.

1. CONCEPT, MOTIVATION, PURPOSE

Music at its fundamental level consists of a collection of sound waves, which in turn are differences in pressure at a given point. At a certain frequency, our brain stops hearing the individual peaks and troughs of a wave and rather interprets it as one continuous sound. We wanted to explore one way of manipulating these waves by inducing rapid movements in a sonic object. For this project, that object was a box with which houses a seemingly innocuous cube. While the design of our machine changed over time, the basic idea of creating music via rapid actuation of a simple cube was our main goal. Based on this design we envisioned that the "CUBE" would produce a synth-like sound effect for a more modern composition. Figure 1 shows a rough model of what we initially envisioned.

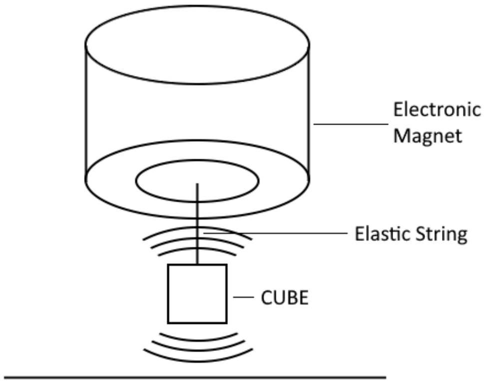

Figure 1 - A rough model of the system. Not shown is the circuitry required to run the electromagnet.

The concept of the CUBE was initially inspired by the design of an electromagnetic solenoid. When a standard back-driven solenoid is switched on and off by a MOSFET, and the MOSFET is rapidly and continuously toggled, the solenoid will begin to vibrate at a pitch. Depending on the solenoid, the sounds produced by this vibration can be quite audible and have a unique synth-like timbre. The CUBE represents our attempt to design a musical machine around this effect.

2. PRIOR ART

In 2020, Menghini et al. conducted a study of creating music through use of the transient electromagnetic method, a tool used for geological mapping, which collects responses in the form of electromagnetic waves the Earth produces.[8]

Figure 2 - The coil used by Menghini et al. to receive the electromagnetic response from the Earth. [8]

While the technical aspects of the study do not entirely relate to our idea, the musical aspects do. For example, they held performances for the study, showing they understood how to integrate the data they received into music. They recorded the rate of change of the Earth's electromagnetic responses using the coil shown in the figure above and converted their data into specific pitches logarithmically as shown in Figure 3.

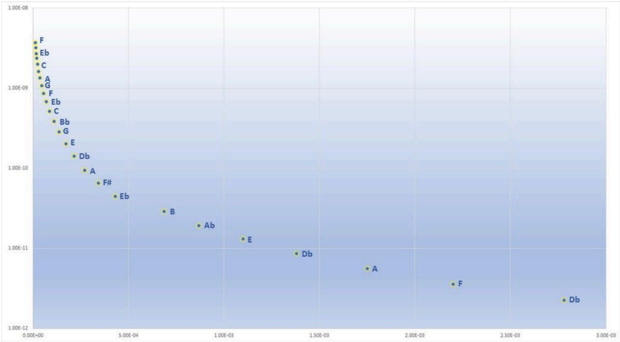

Figure 3: A graph from Menghini et al. showing how the data they collected was mapped to different pitches [8]

To make it more appealing to listeners, they used fixed, more traditional pitches rather than microtones. Discretizing the notes allowed them to integrate acoustic instruments into their performances without having to apply an abnormal tuning or producing jarring and unfamiliar sounds to western listeners.

For our project, we do not necessarily require the use of acoustic instruments, meaning that we theoretically have more freedom with our pitches and, more importantly, what we compose with them.

Another more relevant example to the CUBE is the Magnetic Resonator Piano (MRP). [7] The purpose of this instrument is to expand the capabilities of the piano with dynamics, pitch, and timbre. This is done by mounting electromagnets above the piano strings to vibrate them when inducing a current into the magnets. This works because the strings are made of steel, which is a ferromagnetic material.

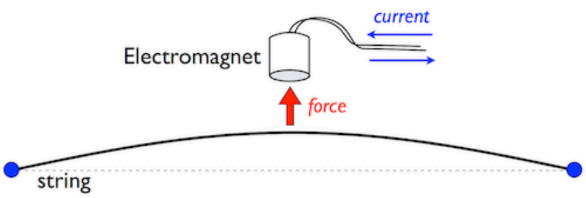

Figure 4: A diagram showing the basics of how an electromagnet can actuate the string on the Magnetic Resonator Piano. [7]

With this setup, the strings of a piano can vibrate without being struck by a hammer. As a result, a lot of unique sounds can be introduced. For example, the possibility of exploring between traditional pitches by "bending notes away from where the strings are tuned".

Since the CUBE also uses electromagnets for actuation, there are a lot of relevant parts towards our project. Firstly, the aforementioned pitch bending which we can adapt to our instrument to play pitches outside of what we normally hear in more traditional performances. However, with special features comes limitations. For example, the volume of the magnetic resonator piano tends to decrease at the higher frequencies, which is also the case for the CUBE. Yet, the magnetic resonator piano is somewhat limited by using a real piano, a problem that the CUBE does not have.

Mechanically, the idea of the CUBE is also similar to that of a loudspeaker. [9,10] In loudspeakers, sound is created by turning electrical impulses into pressurized air. The general design of a loudspeaker consists of a magnet that vibrates a coil, which in turn vibrates an insulated suspended elastic membrane, resulting in changes in air pressure and therefore sound. The typical box design of a speaker is used to prevent pressure waves in both directions from colliding and canceling out, which would result in destructive interference, worsening the sound quality. Speakers can be tuned to or made to produce specific frequency ranges, which results in different types of speakers, such as tweeters for treble and woofers for bass. [2,6]

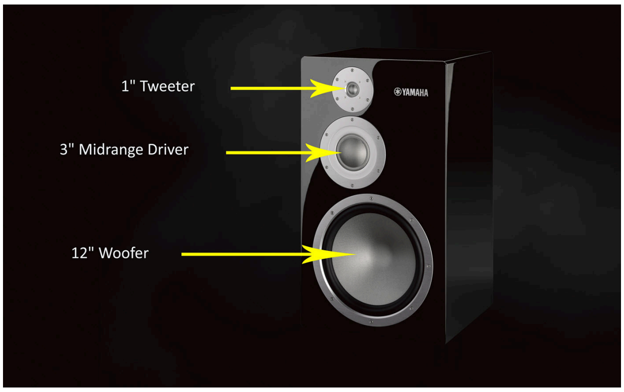

Figure 5: A labeled rendering of a Yamaha NS-5000 speaker showing the size differences between different speaker drivers. [4]

On speaker systems such as the Yamaha NS-5000 speaker shown in Figure 5, the different sized and shaped membranes result in the ability to resonate with multiple ranges in frequency, with larger membranes able to produce lower pitches at higher volumes, and smaller membranes being able to more accurately produce higher frequencies.[4] A speaker, however, lacks the mystery and intrigue that our CUBE is capable of producing in a performance.

A closer example to our machine's initial design are the instruments used in David Tudor's Rainforest [3,5]. This piece contains a variety of sounds produced by using artistically shaped and arranged resonators vibrated by electromagnetic transducers. The objects are all suspended and are amplified by directional microphones. Rainforest uses similar ideas to loudspeaker mechanics, with electromagnets causing sonic bodies to produce pressure waves, and it was intended to be both a visual and musical experience. Rainforest was also able to involve the addition of new objects to be used as resonators as time went on. While Rainforest, as its name suggested, aimed to have a more natural feel that allowed listeners to walk around inside the performance room and take in all the sounds as if they were inside a real rainforest, the Cube aims to capture a more mysterious, yet simple feeling.

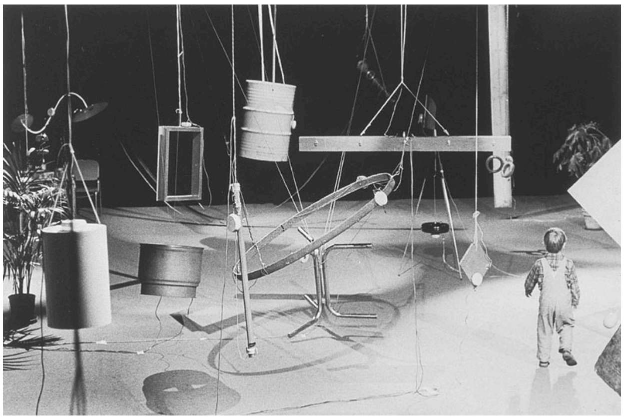

Figure 6: A photograph of David Tudor's Rainforest from L'espace Pierre Cardin, Paris, France, 1976. [3,5]

3. REQUIREMENTS

For the CUBE to function to our specifications, it needs to be able to produce audible music. A goal of around 60 dB, synonymous to the volume of a normal conversation, was predicted to be a feasible benchmark for our design. The CUBE must also be played autonomously using software, and must visibly use an electromagnet to control a suspended object's movements to make sound. Based on our designs, it seems we should be able to produce a wide range of pitches, around 3-4 octaves, through increasing and decreasing the frequency of the suspended object's vibrations. An autonomous system may limit possibilities of expression during a performance since a machine will have a set of instructions whereas humans can be more expressive and execute their own musical interpretations on the fly. For versatility, we want the machine to change pitches quickly. One of the strengths of our system should be the perfect and repeatable execution of musical phrases at an arbitrarily fast tempo. Our group set a goal of around 31 ms. This is equivalent to the duration of a 64th note in 4/4 time at 120 bpm. Lastly, we require control of its dynamic range so it can either perform as a lead voice or an accompaniment within an ensemble of instruments. For a performance with the CUBE, we would like to have several devices to create a full polyphonic experience.

4. PRELIMINARY DESIGN

The CUBE's preliminary design produced sound by oscillating a permanent magnet encased in a cube-like housing via the attraction and repulsion force generated by an electromagnet. The cube-mass was suspended by a spring and attached to the fixed electromagnet. The electromagnet was fed a signal that controls the system's behavior, and the induced vibrations from the alternating polarity of the magnetic field produced pressure (sound) waves. The pitch and volume of the CUBE were controlled by modulating the frequency and strength of the input signal responsible for relaying power to the electromagnet. The CUBE could theoretically be run as a standalone system, producing variable pitched sounds at different volumes, or used as a percussive instrument akin to a piston; repeatedly and consistently striking a surface at the tempo set by a driving signal.

The specifics of the preliminary design were created around the goal of fulfilling our musical requirements. For example, perhaps the most pressing requirement is the necessary ability to produce sound at an audible volume, and the design reflects this challenge in a few ways. First, it incorporates a strong 500N electromagnet, since the amplitude of the cube's vibrations (and thus, the volume of the sound) is directly proportional to the magnitude of the force applied. Additionally, the cube itself is a strong permanent magnet, and contributes to the resultant pressure wave. To accomplish the rapid changes in the magnetic field, the circuit would implement an H-bridge, which allows current to flow in either direction through the electromagnet, and can be controlled via a software-created input signal.

The nature of this design also allows quick and simple pitch changes, since the pitch depends only on the frequency at which the electromagnet changes polarity. With a fast enough control loop, microtonal precision is feasible; and with it, a wide range of producible pitches. However, higher pitches produced by this system necessarily have a lower volume. This is because, at higher frequencies, the cube has less time to move and displace air, since its period of oscillation is shorter. Additionally, the elastic string works as a damper, which has more effect as the frequency of oscillation increases. As a result, the exact range of pitches that can be produced by this system depends on the volume that it is able to achieve, where the highest possible note is the note that can be played at the minimum required volume. This was a constraint we had to keep in mind throughout the entire design process.

The design also requires the system is able to control the volume of the sound produced, otherwise all higher notes would be significantly quieter than lower notes. If we have control of volume, we can normalize the dynamic range across all of the pitches we want to produce. Volume control comes by the wave of a digital potentiometer in our circuitry. It can be controlled via software and works to adjust the current fed to the electromagnet (and thus the force it applies) depending on the frequency of the note being played.

Percussive sounds are also quite easily producible as the magnet can be given a constant positive signal, which would push the cube into the surface opposite the magnet. The exact surface can be changed to adjust the timbre produced. Furthermore, the variation between these percussive movements and vibrations should produce a visually appealing performance.

Each circuit element is digitally controlled by an Arduino Uno, which allows for all of these actions to be performed without human intervention.

As a proof of concept, we devised a preliminary simulation of the system to assess its viability. By modeling the system as a damped-driven oscillator, and adjusting input parameters to realistic values, we were able to create oscillations in the system with amplitudes around 0.17cm at a rate of 440hz (A4). By measuring the amplitude of the oscillations, we can estimate the intensity of the sound waves produced and provide evidence that the driving frequency produces audible results.

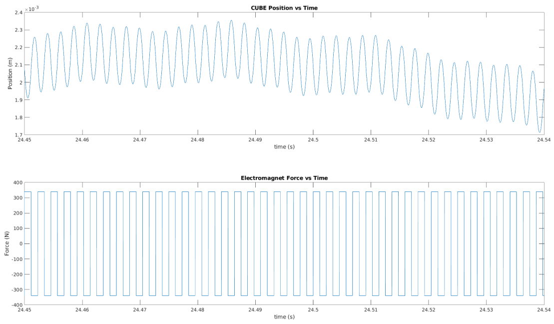

Figure 7: simulated position vs time graph (top) and electromagnetic force vs time graph (bottom). Matlab simulation shows the cube oscillating at ~440 hz.

This model was used to both gauge the plausibility of the concept ("a sanity check" of sorts), and was used to justify components for this module. One of our design goals was to use this model to find a combination of inputs in the solution space that provides an adequate balance of all three aspects; a reasonably-low cost, high output and easy to manufacture musical machine.

Other configurations were considered before deriving this iteration, with some components potentially being addable if the output does not meet our expectations. One facet that we considered pivoting away from is the acoustic nature of our design. In an alternate delineation, we could rely on a high-precision, high-speed position sensor to digitize the amplitude signal. Feeding the signal into a DAW allows us to produce digital sounds from a physical signal, and allows us to build a system that does not require our membrane to produce large pressure differentials. This idea, despite containing a larger software stack, would ease our physical design requirements at the cost of the unique intrigue of an acoustically oriented instrument.

Keeping the acoustic aspect of this project was also theorized in a different alternate design. This idea involved oscillating the cube against a hollow object to amplify the sound produced from the vibrating membrane. It has the advantage of easing our design constraints. We would no longer have to tailor our system design to maximize the stable amplitude of the system, but rather focus on developing other aspects like the control scheme or compositional platform for this device. Our final design ended up being quite similar to this one.

5. FINAL DESIGN

The final design of the CUBE involves a neodymium cube placed on top of a polystyrene box resonator, with an electromagnet and supporting circuitry affixed inside as shown in the figure below.

Figure 8: The setup of the CUBE modules used for its performance 15 December, 2023

The box resonator was incorporated in order to boost the volume of the sound produced. We decided that a cube-shaped resonator would best fit our theme, and while this meant the cube could not be suspended, we were still able to show its sonic potential during the initial portion of our demonstration by placing and removing cubes on our two modules. Additionally, during testing we determined that the goal of producing percussive sounds wasn't possible given time constraints and the strength of our electromagnet, so this design instead focuses primarily on producing pitched music.

Our final design benefits from having a strong permanent magnet as its focal point. This magnet reacts well to our electromagnet's oscillating magnetic field and causes ample vibration in the resonator, producing our device's sound. Additionally, the magnet's passive attraction to the electromagnet's steel casing serves to couple the magnet to the resonator and help to transfer vibrations. The circuit used to control these mechanisms can be shown in Figure 1.

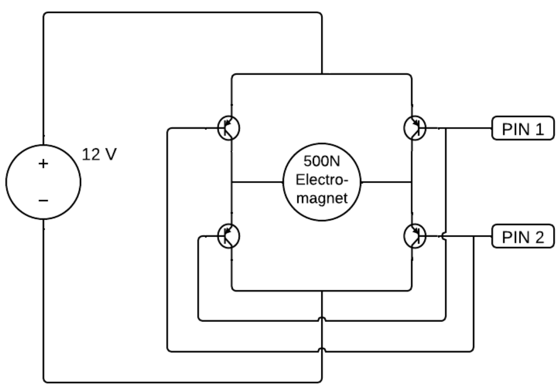

Figure 9: The diagram of the control circuit. A 12V power supply is used to power the magnet. This power is fed through the H-bridge, which controls the electromagnet's oscillations.

The electromagnet and its accompanying circuitry are housed in a custom-made 3D-printed frame. The electromagnet slides into place and is prevented from jumping up into the resonator.

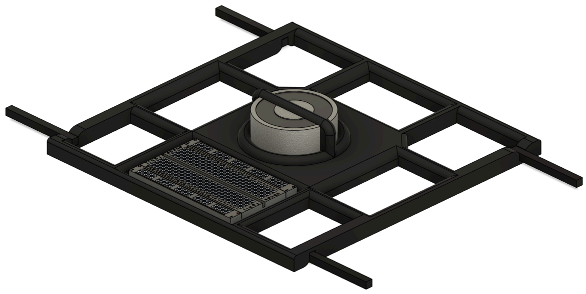

Figure 10: CAD model of housing with electromagnet, breadboard included.

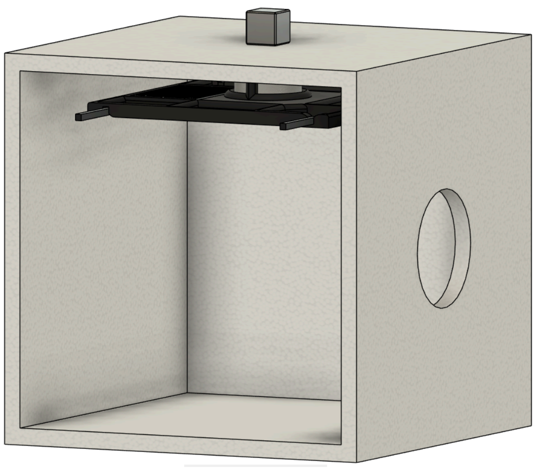

Figure 11: Full CAD assembly. One face of the resonator is removed to showcase internals of the resonator.

The necessary materials for construction are shown in the BOM chart (see Appendix).

The system is controlled using both a host computer and an Arduino microcontroller. MIDI instructions are sent from the host computer to the Arduino via serial communication, which the software can then interpret. These MIDI serial messages are composed of two bytes of information. The first byte stores the note's pitch, and the second byte stores the velocity.

To control the pitch of the note played, the Arduino sends a square wave signal to the H-bridge with the frequency of the desired note. These H-bridge signals continuously switch the direction that current flows through the electromagnet, which changes the polarity of the magnetic field. These oscillations then induce vibrations in the permanent magnet with a frequency equal to the frequency of the input signal, which then produces sound at the desired pitch.

6. EVALUATION

To evaluate the CUBE's effectiveness, we tested the range of notes it can play, the volume it can produce, as well as the timbre of the resulting sound. Our goal was for the CUBE to be able to play a full chromatic scale at a volume of at least 60 dB with a synth-like timbre. Within the range of notes it is able to play, the Cube was able to achieve microtonal precision. We also intended for the CUBE to provide some sort of visual appeal, whether through visible actuation or other means. In our final iteration, a focus was placed on the mysticism of the module, and the intriguing interaction between the box (which perfectly hides the inner workings) and an apparently unremarkable cube.

The final CUBE was successfully able to play a wide range of notes (around 3 octaves from C1-C4) at a reasonable volume, and switch between them quickly. In our demonstration of the device, we were able to produce a musical line that simulated multiple voices in one module; emulating styles such as chiptune and synth-pop.

However, the CUBE design struggled volume-wise. The resonator does amplify the volume to an audible level (around 50-60 dB), which mostly fulfilled our initial requirement, but for performances, a microphone was necessary to amplify the sound, and allow our machine to be played with other instruments (virtual or otherwise).

While the CUBE is quite successful with its musical capabilities, the design on its own does not produce a compelling visual experience. To remedy this, we introduced a brief oral presentation at the start of the performance. Specifically, we first describe its inner workings, then we manually place the magnet on top of the resonator to demonstrate that it produces sound. We then repeat this for multiple CUBEs to demonstrate harmony, which can then be seamlessly transitioned into music. We have found that this introduction helps to improve the visual performance significantly.

Overall, the CUBE's final design has proved to be a major success, providing significant compositional freedom, a desirable timbre, and sufficient pitch range. When combined with the introductory presentation, the CUBE creates a compelling performance both musically and visually.

7. REFERENCES

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Appendix

Bill of materials

Assembly	Part	Manufacturer	Part number	Spec	Quantity	Cost (USD)	Vendor
Actuator	Electromagnet	Uxcell	a16101700ux0261	12V, 500N holding force	1	$19.99	Amazon.com
Membrane Internals	Permanent magnet	MIKEDE	B095SD9SD6	Neodymium, 25x25x25mm	1	$11.98	Amazon.com
Membrane housing	3D printed housing	custom	N/A	PLA filament	1	$4.80 at $0.04 per gram	N/A
Resonator Housing	Polystyrene Sheets	Juvo Plus	B0896VSTWT	11" x 17" x 0.5"	1	$25.49	Amazon.com
Pitch Controller	H-bridge	Texas Instrument	L293D	36V, 1.2A tolerant	1	$5.50	Digikey.com
Microcontroller	Arduino Uno Rev3	Arduino	Uno Rev3	Operating voltage 5V, 16Mhz clock	1	$26.99	Arduino.cc
Wiring / Electronics mount	Breadboard	BusBoard Prototype Systems	B0040Z4QN8	165 x 55 x 9mm	1	$9.99	Arduino.cc