Further Developments in the Electromagnetically Sustained Rhodes Piano

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ABSTRACT

The Electromagnetically Sustained Rhodes Piano is an original Rhodes Piano modified to provide control over the amplitude envelope of individual notes through aftertouch pressure. Although there are many opportunities to shape the amplitude envelope before loudspeaker amplification, they are all governed by the ever-decaying physical vibrations of the tone generating mechanism. A single-note proof of concept for electromagnetic control over this vibrating mechanism was presented at NIME 2011.

In the past year, virtually every aspect of the system has been improved. We use a different vibration sensor that is immune to electromagnetic interference, thus eliminating troublesome feedback. For control, we both reduce cost and gain continuous position sensing throughout the entire range of key motion in addition to aftertouch pressure. Finally, the entire system now fits within the space constraints presented by the original piano, allowing it to be installed on adjacent notes.

Keywords

Rhodes, piano, mechanical synthesizer, electromagnetic, sustain, feedback

1. INTRODUCTION

The Rhodes Piano sound has been a staple of mainstream music since its introduction and has recently found a place in contemporary electronic music. Contemporary electronic artists, however, desire modern control affordances standard on synthesizers. The amplitude envelope of a Rhodes Piano, for instance, can be shaped with compression and variable gain, but these tools are limited when the signal source of each note inevitably decays to silence.

We present recent developments on a novel system that controls the signal source itself, making swelling attacks and infinite sustain possible through aftertouch while preserving the original functionality and characteristic timbre of the Rhodes Piano. Cost and ease of installation are also considered with hobbyists in mind and, because Rhodes enthusiasts may be reluctant to make permanent alterations to their vintage instruments, these modifications are non-destructive by design and may be undone.

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2. BACKGROUND

Figure 1: Limited space inside the Rhodes Piano.

The Rhodes Piano [1] [2] is an electromechanical instrument containing asymmetrical tuning forks, the *tone generators*, that are struck from below by a simplified key/hammer action. The *tine* and *tonebar* are the small and large prongs of the tone generator, respectively, and although these two halves are very different in size and shape (as shown in Figure 1), each is tuned to the same natural vibrating frequency. The tone generator vibrates with inharmonic overtones that are most prominent during the attack of each note and give the instrument a somewhat bell-like timbre.

Vibrations in the tine are sensed by an electromagnetic pickup that generates an analog voltage signal (the *audio output*) for loudspeaker amplification. After the initial attack transient, the tine settles into steady state oscillations with predominantly sinusoidal motion [3]. The signal produced by the pickup, however, has strong harmonic overtones that depend on the adjustable position of the tine relative to the pickup. This adjustment is called *voicing* and is critical to the characteristic sound of the Rhodes Piano.

While there are many opportunities to shape the amplitude envelope between the pickup and eventual loudspeaker amplification, they are all governed by the ever-decaying physical vibrations in the tine. We presented a single-note proof of concept at NIME 2011 [4] where the audio output signal also served as the *excitation signal* that drove an electromagnet to reinforce tine vibrations.

Of course, the pickup also sensed the excitation signal emitted by the electromagnet, creating another feedback loop apart from the vibrating tine. This loop was controlled by placing a second pickup near the stationary end of the tine and taking the difference of the two pickup signals. The placement of the second pickup, however, made it impossible to install the system on adjacent notes in the original piano where space is very limited (Figure 1). Fur-

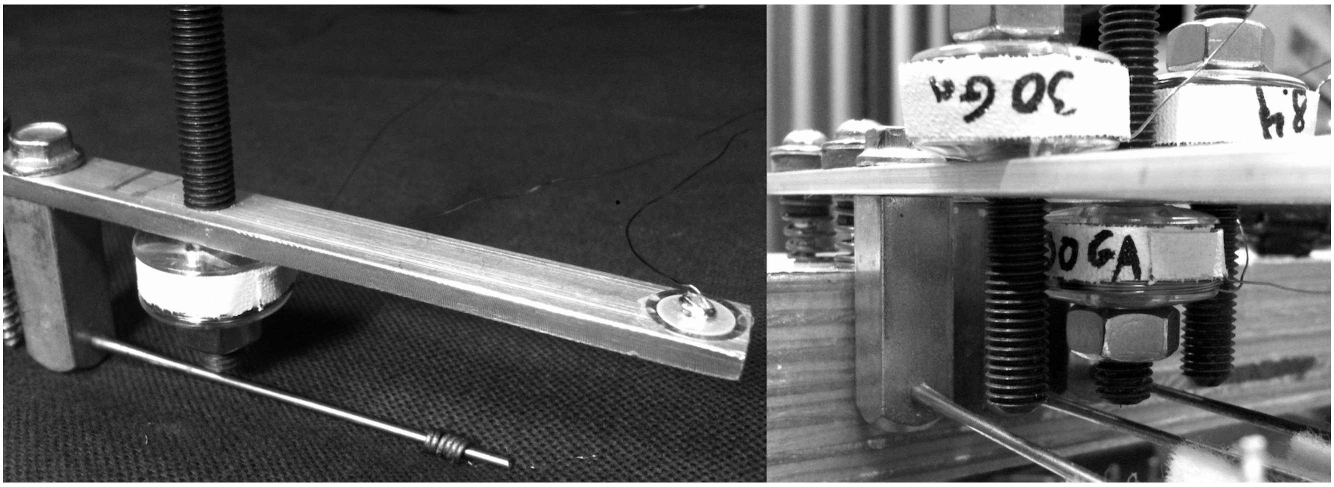

Figure 2: Left: Custom tonebar with attached electromagnet and piezo sensor (see Section 5). Right: Electromagnet coils mounted above and below tonebars.

thermore, it was unclear how this differential cancellation method would work in the presence of multiple electromagnets each producing a different signal at various distances from the pickups.

Key insights over the past year have altered our course with improvements made in every aspect of the system: We now use a piezo-electric vibration sensor that is immune to interference, thus eliminating the troublesome electromagnetic feedback. For control, we both reduce cost and gain continuous position sensing throughout the entire range of key motion in addition to aftertouch pressure. Best of all, the entire system has been made to fit within the space constraints presented by the original piano allowing it to be installed on adjacent notes.

Figure 3 shows an overview of the system for a single note. See Section 5 for details on the excitation circuit, Section 6 for the audio output circuit, and [3] for vibrational mechanics of the tone generator system.

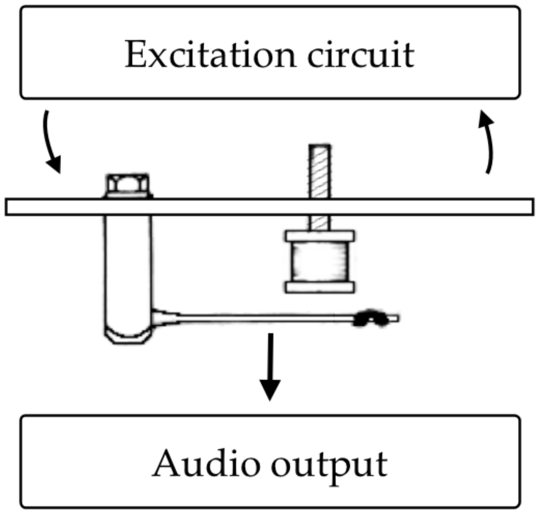

Figure 3: System overview.

3. PRIOR ART

3.1 Electromagnetically Actuated Instruments

The Electromagnetically-Prepared Piano [5] and the Magnetic Resonator Piano [6] are both acoustic grand pianos that electromagnetically drive oscillations in the strings. A computer controls multiple excitation signals (orchestral or voice samples, noise, etc.) for the Electromagnetically-Prepared Piano where each electromagnet is driven by a dedicated channel on an audio interface. The Magnetic Resonator Piano, on the other hand, uses a piezo element to sense vibrations in the soundboard and generate a single excitation signal that is then conditioned and distributed to all of the electromagnets. A continuous position sensor on each key provides both amplitude and spectral control over individual notes. Both of these instruments take advantage of the ample space in an acoustic piano where mounting hardware may lay across the piano frame suspending a row of electromagnets above the strings. As shown in Figure 1, this is impossible inside a Rhodes Piano.

The EBow [7] is a handheld device for electromagnetically actuating ferromagnetic guitar strings, containing a pickup, electromagnet, active electronics, and a battery inside a small plastic housing. The pickup generates a voltage signal in response to string vibrations which then drives the electromagnet, producing a magnetic field and supporting the motion of the string. An EBow held near exposed Rhodes Piano tines originally demonstrated electronically initiated and sustained tine vibrations and its small form factor encouraged us to pursue a similarly compact design that would fit within the limited space inside the piano.

3.2 Experiments with Elastic Waves in Solids

Rossing et al. find natural modes of a metal bar [8] or a tuning fork [9] by inducing vibrations with an electromagnet driven by a synthesized sine wave. Similarly, Kraftmakher suggests a classroom demonstration of electromagnetically induced oscillations in a tuning fork [10]. He first drives the electromagnet with a synthesized sine wave at frequencies in the range off the natural vibrating frequency of the tuning fork. Stronger physical vibrations are produced as the synthesized sine approaches the natural frequency of the tuning fork, and amplitude beating is observed as the synthesized sine deviates from the natural frequency. Kraftmakher also creates a mechanical-electrical feedback loop driving the electromagnet with an amplified microphone signal from the vibrating tuning fork. With the exception of the sensing method, this system is most similar to our current design despite having such unrelated motivations.

4. ELECTROMAGNET AND TONEBAR

Electromagnets remain the only feasible way of electronically initiating and sustaining oscillations in ferromagnetic strings or tuning forks. Because of the tonebars, however, we cannot simply suspend an electromagnet above each tine as in the Electromagnetically-Prepared Piano and the Magnetic Resonator Piano. Instead, we mount the electromagnets securely to custom tonebars (Figure 2) designed to compensate for the additional mass and maintain the correct natural vibrating frequency. This solution preserves the critical separation between the tip of the electromagnet core and the tine during installation and voicing adjustments. The high magnetic permeability of the steel core carries the magnetic field down to the tine with minimal attenuation when the electromagnet coil is mounted above the tonebar.

Figure 1 shows original tonebars that are twisted at the base, whereas we drill through the wide side of the tonebar to mount the electromagnet and therefore require it to remain flat. This modification has no appreciable effect on the resonant properties of the tone generator, as described in Section 7.3.

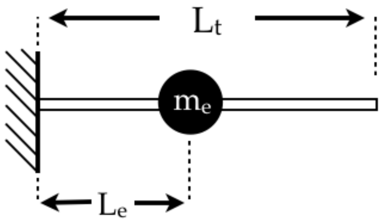

Figure 5: Simple model of tonebar with attached electromagnet.

We calculate the length of the custom tonebar beginning with a simple model of an ideal cantilever beam (with mass) of length L_t [11] [12]. The attached electromagnet is modeled as a point mass m_e at distance L_e from the base, shown in Figure 5. This model leads us to Equation 1 giving the tonebar length L_t in terms of the desired frequency f_0 and the width w, height h, density ρ, and Young's modulus E of the tonebar. See Appendix A and [3] for full details.

$$L_t^4 = \frac{\frac{3EK}{(2\pi f_0)^2} - m_e L_e}{0.346 wh\rho} \tag{1}$$

$$\text{where} \qquad K = \frac{h}{\sqrt{12}} \tag{2}$$

5. EXCITATION SIGNAL

The Magnetic Resonator Piano senses soundboard vibrations with a piezo-electric sensor and distributes this signal to each electromagnet. Unlike in an acoustic piano, each Rhodes tone generator is acoustically decoupled from the body. For this reason we mount a piezo-electric sensor directly to the end of the tonebar (shown in Figure 2), which produces a nearly perfect sine wave as the tone generator vibrates. These piezo elements are small, light, and immune to electromagnetic interference. At about \$1 US each, they are by far the cheapest source for the excitation signal we encountered.

5.1 Physics and Phase Relationship Theory

An ideal, undamped harmonic oscillator has constant amplitude because the restoring force F is a function of only spring constant k and displacement x:

$$F = -kx \tag{3}$$

The vibrating tine is a damped harmonic oscillator that experiences the same restoring force $-kx$ and also a damping force $-cv$ (damping constant c multiplied by velocity v):

$$F_{net} = -kx - cv \tag{4}$$

To sustain oscillations at a constant amplitude, a magnetic force must be exerted on the tine equal and opposite to the damping force, so that the net force is equal to that experienced by an ideal, undamped oscillator:

$$F_{net} = -kx - cv + F_{mag} = -kx \tag{5}$$

$$F_{mag} = cv \tag{6}$$

Equation 6 shows that the magnetic force must be proportional to and in phase with the velocity of the tine, which is predominantly sinusoidal during steady state oscillations. This velocity function may be approximated by adding a 90° phase shift to the accelerometer signal (which is also sinusoidal) provided by the piezo sensor. The only delay between the piezo sensor and the electromagnet is in the electronic circuit. Here, the delay is easily measured and may be adjusted to synchronize the excitation signal and the resulting magnetic force with the velocity of the tine.

5.2 Magnetized Core for Efficient Excitation

Both the EBow and Electromagnetically-Prepared Piano use a magnetized core. Through trial and error we chose an N42 grade magnet 0.25" in diameter and 0.5" long - this magnet, when mounted to the top of the core, maximizes tine deflection given a constant amplitude excitation signal.

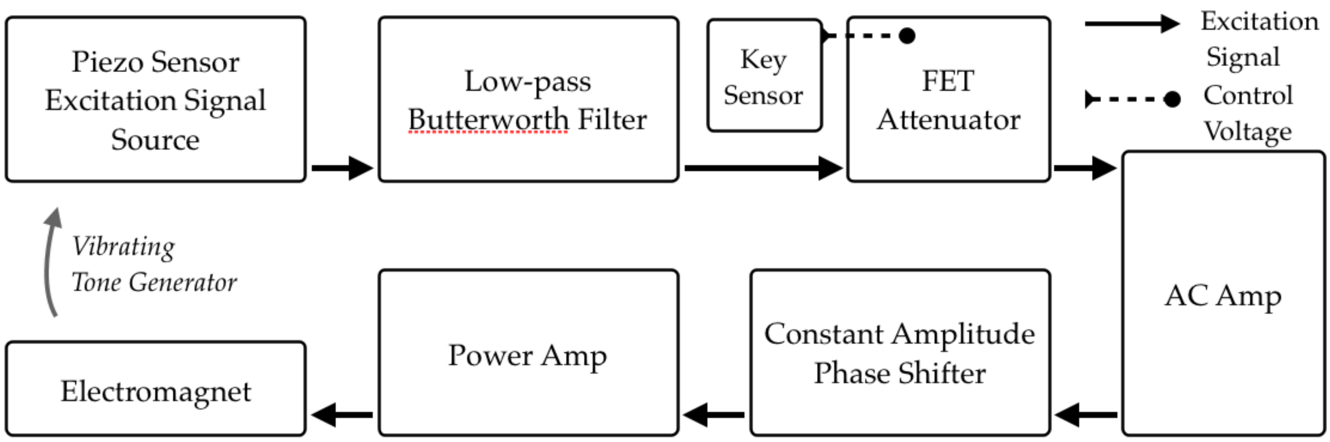

Figure 4: Excitation signal path block diagram.

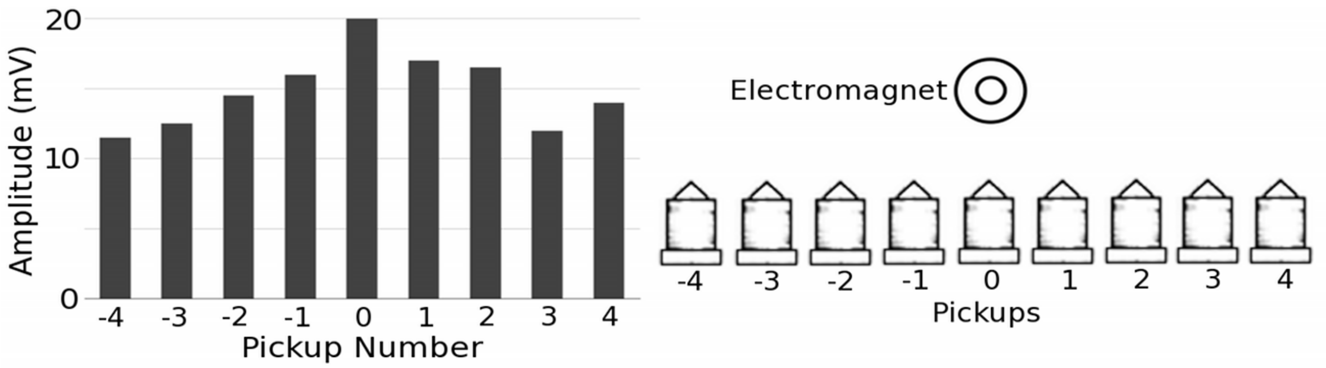

Figure 6: Bar graph of signal amplitude sensed by pickups as shown to the right.

5.3 Excitation Circuit

Figure 4 is a block diagram of the excitation signal path, beginning at the piezo sensor. The low-pass Butterworth filter stabilizes the feedback loop by removing unwanted high frequency components, while leaving the excitation signal well within the passband. An optical key position sensor provides control voltage for the field effect transistor (FET) attenuator described in Section 5.4. The AC amplifier provides gain and blocks the DC bias introduced by the FET attenuator. The constant amplitude phase shifter adjusts the overall delay of the circuit and allows the phase relationship between piezo sensor voltage and the force exerted on the tine to be set to the desired 90° as described in Section 5.1.

5.4 Aftertouch Control

FETs have resistive properties for small signals where the resistance is variable by a control voltage [13]. Our system relies on two cascaded FET variable resistors connected to ground to control the amplitude of the excitation signal driving the electromagnet.

The QRD1114 Reflective Object Sensor is a small component that varies its output voltage as an internal phototransistor senses light reflecting off a nearby surface [14]. This part and a dual op-amp for signal conditioning provide the control voltage for the FET variable resistors.

Depending on how much aftertouch pressure is applied to the key, the original Rhodes Piano action flexes a few millimeters at the bottom of its range of motion causing a small change in output voltage from the phototransistor placed below. The Magnetic Resonator Piano also relies on a similar electronic component in the Moog Piano Bar to sense small changes in key position as a result of aftertouch pressure [6].

This optical sensor has the added benefit of sensing the key position throughout its entire range of motion. Possible applications for this additional control signal are discussed in Section 8.3.

6. AUDIO OUTPUT

Rhodes tines are very short compared to piano or guitar strings, forcing close proximity between electromagnet and pickup; this causes the excitation signal to appear as a strong component in the audio output. This interference, however, is sensed by all of the pickups, while only one pickup senses each vibrating tine.

Figure 6 graphs the excitation signal amplitude as a function of pickup number. Deviation from the expected amplitude drop-off (for pickups 3 and 4) may be explained by variation in number of turns of wire on a particular pickup and variation in component value in the circuit.

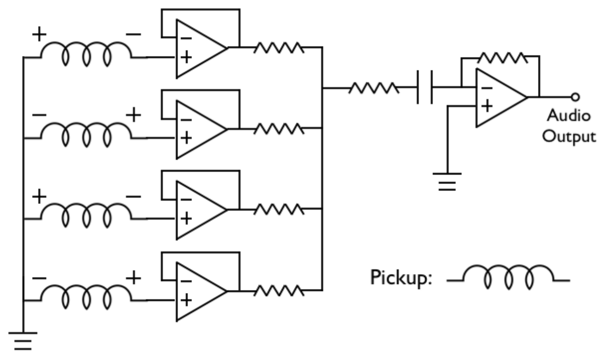

Figure 7: Partial diagram of alternating polarity pickup array circuit.

We reduce the presence of this excitation signal interference in the audio output by reversing the polarity on every other pickup before summing the output signals of all of the pickups. Figure 7 shows a partial circuit diagram.

7. RESULTS AND EVALUATION

We achieve the desired infinite sustain and tremolo controllable through aftertouch.[1] Furthermore, through electronic excitation and manual damping, we are able to reproduce the amplitude envelope of a reversed percussive note.

7.1 Phase Theory Verification

As described in Section 5.1, we approximate a sinusoidal excitation signal in phase with the tine velocity by shifting the piezo (accelerometer) signal by 90°. The only delay in the mechanical-electrical signal path is introduced in the circuit and can easily be measured with an oscilloscope. Indeed, adjusting the phase shifter to achieve a 90° phase difference between input and output signals results in the highest amplitude oscillations during active sustain.

7.2 Excitation Signal Interference

We tested the cancellation method by holding the tine motionless and then driving the electromagnet with a synthesized sine wave. Wired with the same polarity, each pickup in the array would add the excitation signal to the audio output. Our alternating pickup array, however, produces a signal approximately equal to that of only the single pickup nearest to the electromagnet - destructive interference removes a significant portion of the unwanted excitation signal from the audio output.

[1] Audio examples: www.mat.ucsb.edu/gshear/EMSRhodes

7.3 Q Comparison

Our design goals maintain that new affordances must not come at the expense of original functionality - the instrument should still sound like a Rhodes Piano when the active electronics are switched off. Specifically, we want the modified tone bars to behave as closely as possible to stock tone bars. We quantify this as *quality*, or Q:

$$Q = \pi f_0 \tau \quad (7)$$

where τ is the time it takes for vibrations to decay to $1/e$ (about 37%) at fundamental frequency f_0. A damped or improperly tuned tonebar will reduce Q and shorten the sustain time of a naturally decaying note.

Table 1 contains a few example Q values from the midrange of the piano and there is no appreciable variation between modified and stock tonebars.

Table 1: Q values for midrange notes, modified tone generators in bold.

Note	f_0 (Hz)	τ (sec)	Q
B3	246.9	1.419	1101
C4	**261.6**	**1.506**	**1238**
D$^\flat$4	**277.1**	**1.195**	**1040**
D4	**293.7**	**1.253**	**1156**
E$^\flat$4	311.1	1.555	1520

7.4 Timbre Comparison

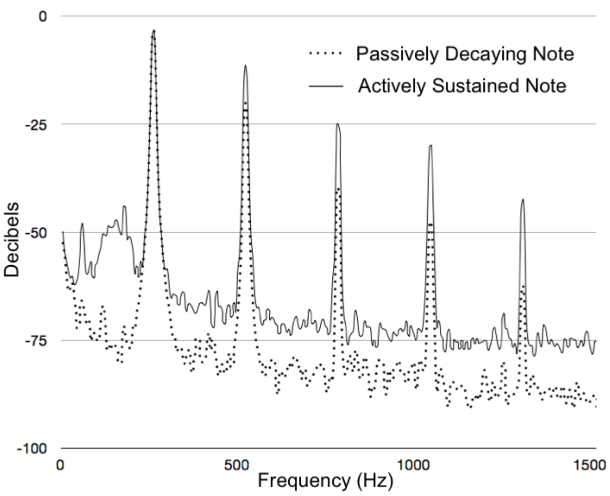

Figure 8: Normalized spectra comparing passively decaying and and actively sustained steady state oscillations.

The magnitude frequency spectrum of the actively sustained tine signal is similar to that of the passively vibrating tine signal during steady state oscillations (see Figure 8). The main difference is that the passively vibrating note has greater amplitude for the lower harmonics and lower amplitude for the higher harmonics as compared to the actively sustained note. We can attribute this to the general tendency for higher frequencies to decay faster: the spectrum of the decaying note shows that the high frequencies have already decayed relative to the fundamental, whereas the spectrum of the actively sustained note is closer to the spectrum earlier in the natural decay. This may also be related to interference of the excitation signal described in Section 6.

8. FUTURE WORK

8.1 Effective Frequency Range

The current system works well in the middle octave of the piano, but the extreme high and low ends will present new challenges. The highest frequency tines are only 18 mm and the attached tonebars are correspondingly short - we do not yet know if our method of mounting the electromagnet directly to the tonebar will be possible in this range. We are also unsure if the excitation signal will cancel as nicely given the tight proximity between electromagnet and pickup at this end of the piano.

At the low end, the long tines reach a much greater maximum deflection from equilibrium when vibrating at full amplitude, so much so that the original tonebars in this register are shaped to provide clearance. Furthermore, on the 88-key model, the lowest seven tone generators have no tonebars at all. We don't fully understand the vibration mechanics involved at this end of the piano - more research will be necessary before we determine what modifications are possible on these notes.

8.2 Adaptive Gain

Aftertouch pressure controls the attack time of notes initiated from silence via the level of gain in the feedback loop. The high gain necessary for this musical result, however, will clip the large signal generated by the piezo sensor when the tone generator is vibrating at full amplitude, and this clipping adds high frequency distortion in the audio output. A performer who is aware of this possibility may ease off on aftertouch pressure as amplitude increases, but adaptive gain limiting will prevent this undesirable effect all together.

8.3 Active Damping and Percussive Attack

Reversing the electromagnet polarity in our excitation circuit *shortens* sustain of the vibrating tine. This encouraging result suggests a system where the tine is damped electromagnetically when the key returns to its upper position, thus simulating the effect of traditional felt dampers. As described in Section 5.4, our current phototransistor-based sensing system produces the continuous control signal through the range of key motion necessary for this feature.

We look forward to experimenting with more powerful electromagnets and various excitation pulses [15] in hopes of reproducing a percussive attack similar in sound to that of the original instrument. Full electromagnetic actuation and damping will allow us to remove the entire key/hammer action and instead control the instrument externally via MIDI or OSC.

8.4 Play, Practice, and Perform

Perhaps it goes without saying, but this work was motivated in part by our own musical aspirations and we are most excited about getting to *play* an electromagnetically sustained Rhodes Piano, instead of having to engineer one. It would be fun to learn the original compositions that inspired the project - compositions that could only be realized in the studio and with audio editing software.

9. ACKNOWLEDGMENTS

We thank Curtis Roads for his help in structuring the presentation of this work, Ben Mazin for vetting the physics theory, and Karl Yerkes and Daniel Bazo for brainstorming about vibrational mechanics in the lab.

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APPENDIX

A. SIMPLE TONEBAR MODEL

We model the tonebar as an ideal cantilever beam (with mass) of length L_t and the electromagnet as a point mass m_e attached at distance L_e from the base, shown in Figure 9.

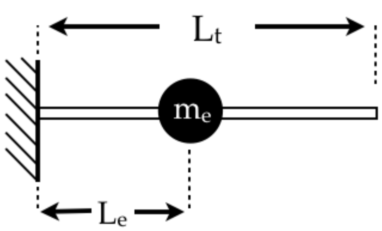

Figure 9: Simple model of tonebar with attached electromagnet.

Breaking this apart we have the original cantilever beam and a separate point mass at the end of a massless beam of length L_e, shown in Figure 10.

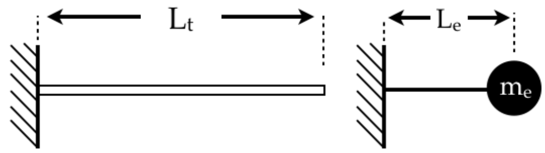

Figure 10: Separate tonebar and electromagnet models.

The cantilever beam vibrates at the same frequency as if it were a point mass $m_{t'}$ (the *effective mass*) at the end of a massless beam of the same length L_t. Similarly, the mass m_e vibrates as if it were a smaller mass $m_{e'}$ at the end of a longer beam, also of length L_t. These point masses are shown in Figure 11 and are related to known quantities in Equations 8 and 9.

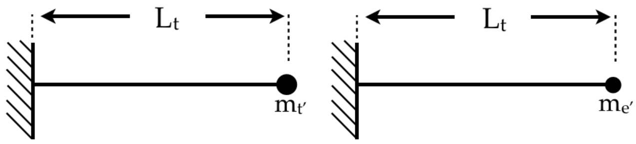

Figure 11: Effective masses at length L_t of tonebar and electromagnet.

$$m_{t'} = 0.346 L_t w h \rho \tag{8}$$

where L_t, w, h, and ρ are the length, width, height, and density of the original tonebar.

$$m_{e'} = m_e \left(\frac{L_e}{L_t}\right)^3 \tag{9}$$

Figure 12 shows these two masses added together and Equation 10 relates fundamental vibrating frequency f_0 to known quantities - E is Youngs modulus of the tonebar material.

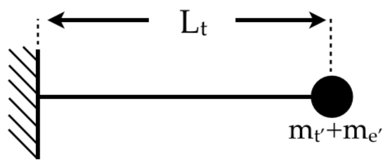

Figure 12: Aggregate effective mass on massless beam of length L_t.

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{3EK}{(m_{t'} + m_{e'})L_t^3}} \tag{10}$$

$$\text{where} \quad K = \frac{h}{\sqrt{12}} \tag{11}$$

Solving for L_t and substituting in Equations 8 and 9 leads us finally to Equation 12.

$$L_t^4 = \frac{\frac{3EK}{(2\pi f_0)^2} - m_e L_e}{0.346 w h \rho} \tag{12}$$