The Electromagnetically Sustained Rhodes Piano

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ABSTRACT

The Electromagnetically Sustained Rhodes Piano is an augmentation of the original instrument with additional control over the amplitude envelope of individual notes. This includes slow attacks and infinite sustain while preserving the familiar spectral qualities of this classic electromechanical piano. These additional parameters are controlled with aftertouch on the existing keyboard, extending standard piano technique. Two sustain methods were investigated, driving the actuator first with a pure sine wave, and second with the output signal of the sensor. A special isolation method effectively decouples the sensors from the actuators and tames unruly feedback in the high-gain signal path.

Keywords

Rhodes, keyboard, electromagnetic, sustain, augmented instrument, feedback, aftertouch

1. INTRODUCTION

The motivation behind this project comes from compositional experiments in the recording studio editing Rhodes piano samples in Pro Tools to create swelling and sustaining effects impossible to play on the original instrument. We desire these new affordances in a live performance setting controlled through the existing keyboard interface, extending standard piano technique all while leaving the original functionality of the instrument intact.

We present a novel system that offers limited control over the amplitude envelope of a Fender Rhodes electric piano, including infinite sustain, controlled by aftertouch on the existing keyboard interface. A primary design goal was to preserve the timbral qualities of the original electromechanical instrument, which rely on both the tone source (the vibrating tine) and the sensor (the magnetic pickup). With the addition of some circuitry and electromagnetic actuators to the existing electronics, we have extended the affordances of the instrument without compromising its original functionality.

2. EXISTING INSTRUMENTS
2.1 The EBow

The EBow is a device designed for sustaining vibrations in ferromagnetic guitar strings through positive feedback [2]

and is controlled simply by moving the device toward or away from the strings. The EBow uses one sensing coil to generate a signal that drives a second coil which in turn exerts a time-varying magnetic force on the string supporting its oscillation. Permanent magnetic cores in each coil temporarily magnetize the ferromagnetic string greatly increasing efficiency of the actuator and allowing for both attractive and repulsive forces between the actuator and string. Without this magnetization, the actuator would exert only an attractive force on the string, effectively rectifying the actuator signal and adding undesirable high frequency distortion.

We found that direct magnetic coupling between the sensor and actuator coils leads to uncontrollable feedback in our system. There appears to be no compensation for this effect in the referenced EBow patent so we assume the EBow did not suffer from the same complications given the position and orientation of the coils and the amount of gain in the feedback circuit. Besides the compensation for this direct magnetic coupling, our electronics system is most similar to that of the EBow.

2.2 The Electromagnetically-Prepared Piano

The Electromagnetically-Prepared Piano [1] is an acoustic piano with electromagnetic actuators placed above certain strings. Each actuator is driven with an arbitrary audio signal (the creators suggest pure sine waves, orchestral samples, noise, etc.) through a standard audio amplifier and the strings filter the signal before acoustic amplification via the soundboard. Control is achieved through software such as Cycling 74's Max/MSP [8] and the original key/hammer action is left unaltered.

This differs from our system in that we drive the actuators with a signal generated by the vibrating mechanism thus completing a feedback loop. Furthermore, we control the system through pressure sensors retrofitted to the existing keyboard interface.

2.3 The Magnetic Resonator Piano

Andrew McPherson's Magnetic Resonator Piano [4] inspired our project and this is apparent in the similarity of our design goals. He also uses mechanical-electrical feedback to drive the piano strings but his actuator signals are generated through a much more complex system. A single piezo-electric sensor placed on the soundboard is the source for all of the actuators. This signal is distributed to a series of individually tuned bandpass filters that then drive phase-locked loops with adjustable delay to compensate for the propagation time through the soundboard. He achieves control through continuous sensing of each key with a modified Moog Piano Bar [5] and a complex mapping scheme of this control data to amplitude and spectral parameters for each note.

3. THE FENDER RHODES

The Fender Rhodes piano [6] is an electromechanical instrument that uses a steel cantilever beam (the *tine*, seen in Figure 1) as its primary tone source. In each piano there is one tine per note with fundamental vibrating frequencies ranging from 27 Hz to 4.2 kHz on the 88-key model, and 41 Hz to 2.6 kHz on the 73-key model. Each tine is sensed by a dedicated passive magnetic pickup: vibration in the tine disturbs the magnetic field through a coil of wire thus generating an electrical signal. The average[1] of the signals from each sensor is present at the output jack of the instrument for amplification. Similar to an acoustic piano, the tine is struck by a hammer and damped by a felt pad. The *tuning spring* is a stiff wire wrapped around the free end of the tine that adds mass and allows for adjustment of the fundamental frequency.
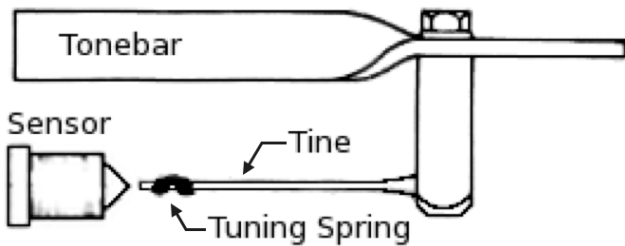
3.1 The Tine and Tonebar

Figure 1: Tone generator assembly [6].

Each tine is paired with a *tonebar* and together they behave as an asymmetrical tuning fork. Although their fundamental frequencies are different, the tonebar stores energy from the initial hammer strike and helps to sustain vibrations in the tine [6].

Unlike a piano string, which is fixed at both ends and vibrates with overtones at near integer multiples of the fundamental, the tine is free at one end and has a decidedly inharmonic overtone series with the first overtone at a non-integer multiple several times higher than the fundamental (depending on the physical parameters of the tine) [7]. These inharmonic overtones give the Rhodes piano a somewhat bell-like timbre.

The tine itself is cylindrical (except near the base) with a diameter of 1.5 mm and lengths ranging from 18 mm to 157 mm. The free end of the tine swings up and down reaching a displacement of up to 50 mm for the longest tine, while shortest tine reaches a displacement of less than 1 mm.

3.2 The Pickup

The sensor (pickup) and vibrating tine behave nonlinearly, adding harmonic distortion to the sensor signal. The spectrum changes with their orientation: as the equilibrium point of the tine approaches the sensor axis, the fundamental and all odd harmonics are reduced, leaving the second harmonic as the strongest frequency in the series. Vertical adjustment of the tine (in the direction of oscillation) is known as *voicing* and the effect is consistent with the findings in [3] where a modeled guitar string oscillates perpendicularly to the axis of its pickup (motion similar to that of our vibrating tine with respect to the sensor). Figure 2 compares the spectra of two different tine alignments - one on the sensor axis (as seen in Figure 1) and the other 5 mm above the axis.

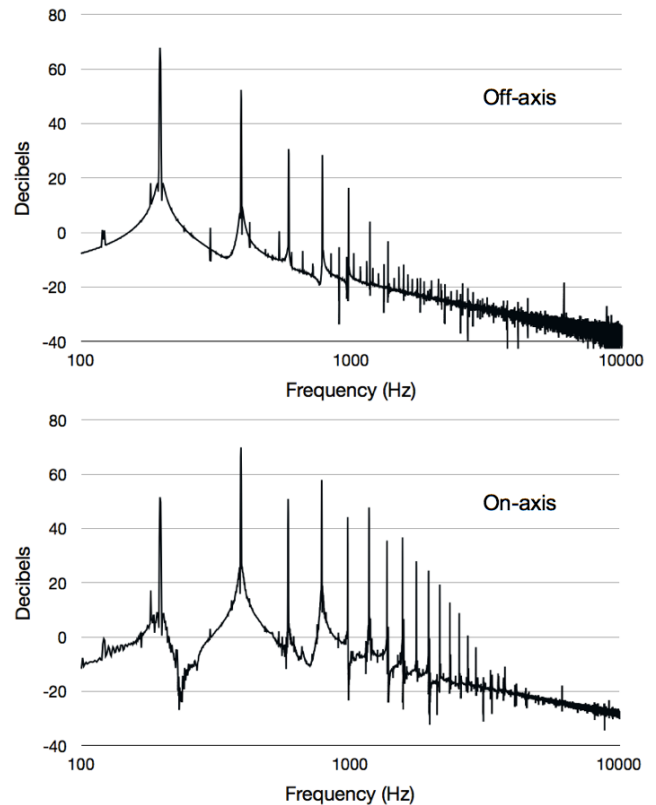[1]Given all passive electrical components.

Figure 2: Variation in harmonic distortion due to sensor/tine alignment. Fundamental at 196 Hz.

4. ACTUATION

Driving the tine with electromagnetic actuators is straightforward given the large body of prior art, but in our case the magnetic pickups sense the driving magnetic field in addition to the tine thus directly coupling the actuation system with the sensing system. There are no obvious alternatives for either the sensor or the actuator: a piezo element in direct contact with the tine would change its resonant properties, and optical sensors are prohibitively expensive and would not add the same harmonic distortion described in Section 3.2. With these constraints we investigated two methods, driving the actuator first with a pure sine wave, and then with the signal generated by the sensor thus creating a feedback loop.

4.1 Synthesized Sine Wave

Driving the actuator with a pure sine wave at the tine's fundamental frequency initiated and sustained oscillations, but this strong driving signal completely dominated the signal generated by the tine as the pickup is sensitive to both. The actuator-sensor signal path introduces a scaling factor and phase shift that varies with frequency. This can be compensated for at a single frequency with a relatively simple circuit allowing us to subtract the pure sine wave and isolate the tine signal. Unlike filtering, this will not affect the signal when the actuator is inactive.

4.2 Feedback

We assume that actuation with a pure sine wave at the tine's fundamental frequency will not excite any of the non-harmonic overtones described in Section 3, whereas the mechanical hammer introduces energy over a wide range of frequencies exciting many of these overtones in addition to the fundamental. Once the tine has been struck, these overtones
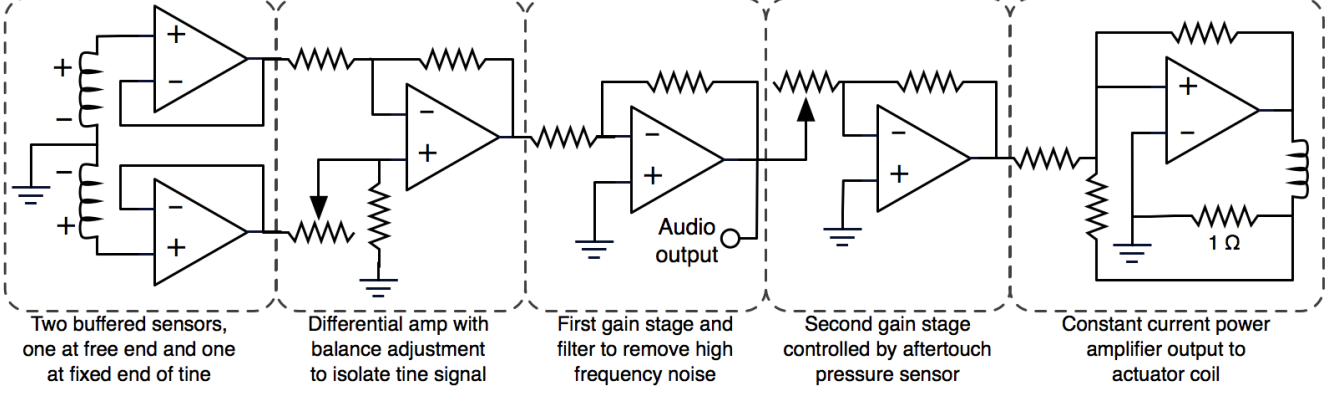
Figure 3: Sustainer circuit with feedback.

| Two buffered sensors, one at free end and one at fixed end of tine | Differential amp with balance adjustment to isolate tine signal | First gain stage and filter to remove high frequency noise | Second gain stage controlled by aftertouch pressure sensor | Constant current power amplifier output to actuator coil |

Table 1: Variable key.

Velocity of tine	v
Electromotive force	$\mathcal{E}$
Voltage across sensor, output amp	V_s, V_o
Current through actuator	I_a
Complex impedance of output stage	Z_{Out}
Circuit gain	G
Phase shift	ϕ
Magnetic field produced by sensor, actuator	B_s, B_a
Magnetic flux through sensor coil	Φ_B
Magnetic moment of tine	m
Force on tine	F
Distance from actuator of point on axis	x
Number of turns of wire in sensor, actuator	N_s, N_a
Cross-sectional area of actuator	A

should be present in the output signal and will self-sustain in the feedback loop.

4.2.1 Theory and Basic Equations For Control

We assume the vibrating tine is a damped harmonic oscillator that experiences a damping force proportional to its velocity v. To compensate for this and sustain oscillations indefinitely, the actuator must exert a force on the tine proportional to $-v$. The following equations (with variables defined in Table 1) show how the feedback system achieves this goal.

$$\frac{d}{dt}\Phi_B \propto v \cdot \nabla B_s \tag{1}$$

$$V_s = \mathcal{E} = -N_s \frac{d}{dt}\Phi_B \tag{2}$$

$$V_o = GV_s \tag{3}$$

$$I_a = \frac{V_o}{|Z_{Out}|e^{j\phi}} \tag{4}$$

$$B \propto \frac{N_a I_a A^2}{2(x^2 + A^2)^{\frac{3}{2}}} \tag{5}$$

$$F = \nabla(m \cdot B_a) \tag{6}$$

Equation (1) represents the relationship of magnetic flux rate of change to velocity of the tine traveling through the non-uniform magnetic field imposed by the sensor core. Equation (2) is the special case of Faraday's law for the EMF produced in a coil of wire. This also equals the voltage presented at the op-amp input assuming infinite input impedance.

Equation (3) shows the voltage gain through the circuit. Equation (4) shows the phase relationship ϕ between actuator current and voltage. Equation (5) shows the magnetic field produced by a current through a coil of wire, simplified for the different magnetic permeabilities of the core and the air gap between the actuator and the tine. Equation (6) shows the force on the tine due to the magnetic field produced by the actuator.

The phase shift ϕ introduced at the output stage reduces actuator efficiency, and with a shift of more than $90°$ the actuator begins to damp the tine. A constant current amplifier (seen in Figure 3) is used to minimize this phase shift and Figure 4 shows the phase response curve. The theoretical calculations ignore the amplifier's output impedance and this may account for some of the discrepancy with the experimental data.
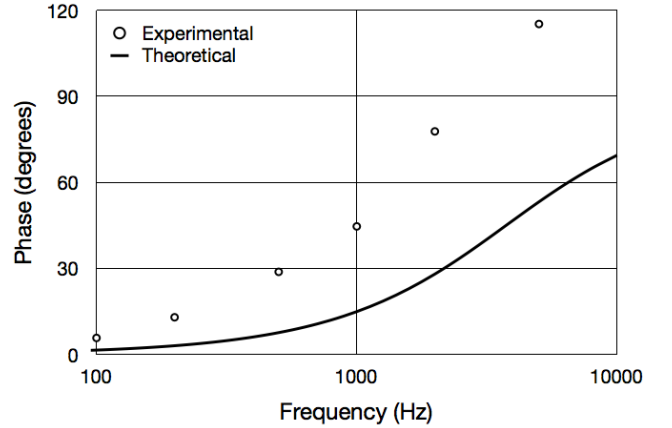

Figure 4: Phase response of constant current output amplifier.

4.2.2 Implementation

Again, direct magnetic coupling complicated early experiments as the high electrical signal gain far exceeded the attenuation of the magnetic field due to physical separation between actuator and sensor. Subtracting the actuator signal out of the sensor signal was necessary to control feedback; a second sensor with similar phase response placed near the fixed end of the tine (Figure 5) was used to provide the subtraction signal. In this configuration, the movement of the tine is detected by only one sensor, but the driving magnetic field is present at both sensors. Taking the difference of the two signals substantially removes

the actuator component and isolates the tine component. Please note that the distortion described in Section 3.2 is an effect of the physical vibration of the tine with respect to the stationary sensor; therefore, since the actuator is also stationary, no such distortion is imposed on the magnetic signal emitted by the actuator and received by the sensor.

Both sensors are original Rhodes piano pickups. The actuator is approximately 600 turns of 30 AWG copper wire wound around a plastic sewing machine bobbin mounted on a steel core. DC resistance is about 170Ω for the sensors and 11Ω for the actuator.
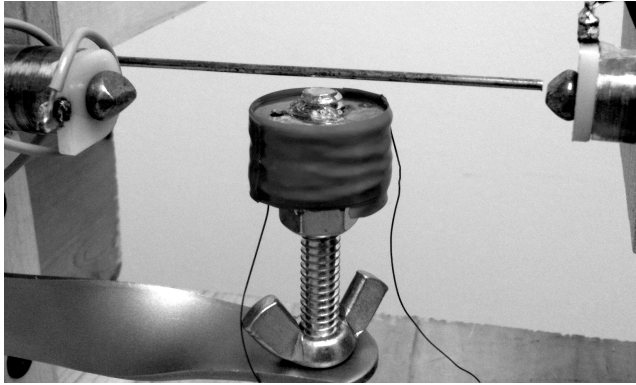

Figure 5: Actuator, two sensors, and tine.

5. PHYSICAL INTERFACE

Straightworward aftertouch control is achieved with a pressure sensor (variable resistor) placed on the keybed. This sensor has a resistance inversely related to applied pressure and is the input resistor on the second gain stage in the feedback circuit (Figure 3). This configuration maps aftertouch pressure to the rate of gain increase, within certain limits. Indeed, high pressure will quickly increase the signal through feedback to where the output amplifier clips severely and distorts. Decay time can be prolonged, but because our system (currently) lacks active damping the lower limit is governed by the natural decay of the tine.

6. RESULTS AND FUTURE WORK

Considering its simplicity, the control system is surprisingly effective. A wide range of arbitrary amplitude envelopes can be performed, including a slow attack achieved by exciting the tine with amplified noise in the system. Removing pressure against the keybed while still holding the damper away from the tine turns off the actuator and allows the note to decay naturally. See Figure 6 for a few examples of amplitude envelopes performed with this system. Subjective listening tests are also favorable - the perceived spectral quality of the electronically sustained note is the same as the naturally decaying note, though it is difficult to hear the difference between the two sustain methods. Driving the tine with a pure sine wave achieves reasonable sustain with a simple system, though we suspect the more complicated feedback method will be necessary if active damping is desired.

The actuator efficiency depends on the harmonic series of each note described in Section 3.2. We observe significant reduction in efficiency as the tine's equilibrium is adjusted towards the sensor axis and the second harmonic becomes the prominent frequency. Again, this voicing adjustment is important part of the instrument but we currently have no solution to the problem.
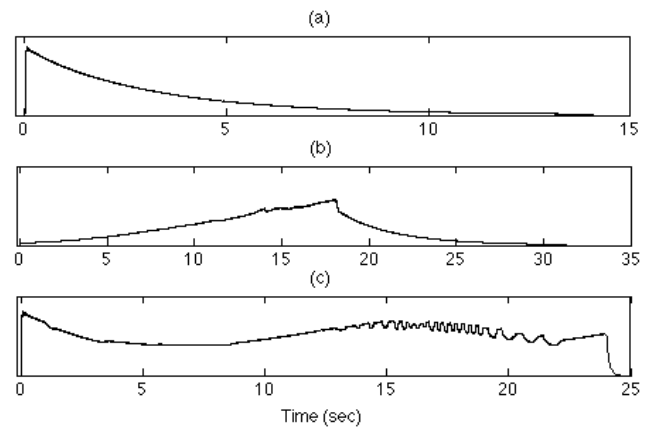

Figure 6: Amplitude envelopes of several notes produced by our instrument: (a) is a standard hammer attack with natural, unsustained decay; (b) also decays naturally, but reaches peak amplitude only by electromagnetic actuation; (c) is a standard hammer attack followed by tremolo and shortened decay by the felt damper.

Finally, the pressure sensor in the second gain stage (Figure 3) unsurprisingly adds a lot of noise to the signal path. Here a FET variable resistance would protect the signal while the pressure sensor provides a filtered control voltage.

7. ACKNOWLEDGEMENTS

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