Techniques and Circuits for Electromagnetic Instrument Actuation

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ABSTRACT

There is growing interest in the field of augmented musical instruments, which extend traditional acoustic instruments using new sensors and actuators. Several designs use electromagnetic actuation to induce vibrations in the acoustic mechanism, manipulating the traditional sound of the instrument without external speakers. This paper presents techniques and guidelines for the use of electromagnetic actuation in augmented instruments, including actuator design and selection, interfacing with the instrument, and circuits for driving the actuators. The material in this paper forms the basis of the magnetic resonator piano, an electromagnetically-augmented acoustic grand piano now in its second design iteration. In addition to discussing applications to the piano, this paper aims to provide a toolbox to accelerate the design of new hybrid acoustic-electronic instruments.

Keywords

augmented instruments, electromagnetic actuation, circuit design, hardware

1. INTRODUCTION

Several recent augmented instruments have been invented which use electromagnetic actuation to transform the sound of traditional acoustic instruments. The Electromagnetically-Prepared Piano [1, 3] and the Magnetic Resonator Piano [11, 12] each use electromagnets inside a grand piano to induce vibrations in the strings independently of the percussive hammer mechanism. The Electromagnetically-Sustained Rhodes Piano [16] applies a similar technique to the vibrating metal tines of a Fender Rhodes. The EMvibe [4] uses electromagnetic actuators to create infinite sustain and continuous timbre-shaping in vibraphone bars. The handheld Ebow [8] for electric guitar uses feedback between a pickup and an electromagnetic actuator to produce continuous vibrations in guitar strings; Berdahl [2] has extended these concepts to allow active damping of guitar strings. A good general overview of "actuated instruments" can be found in [13].

Each instrument is based on the same fundamental technology: a solenoid electromagnet consisting of multiple turns of wire around a ferromagnetic core. Electromagnets have been used for well over a century, but they prove remarkably adaptable to the challenges of modern acoustic/digital instrument design. This paper will present techniques and design guidelines for creators of new electromagnetically-actuated instruments. The material presented here partly reflects the author's own experience developing multiple generations of the magnetic resonator piano, but the techniques are broadly applicable to many acoustic instruments.

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2. THEORY OF OPERATION

In this paper, an *electromagnetic actuator* (actuator for short) is defined to be a solenoid-configuration electromagnet which consists of multiple turns of wire around a central core made of iron, steel or other ferromagnetic material. The magnetic flux density B_a within a solenoid actuator is proportional to its current i:

$$B_a(t) = \frac{\mu N}{\ell} i(t) \quad (1)$$

where N is the number of turns of wire, μ is the permeability of the core, and ℓ is the length of the solenoid [7]. In the context of musical instrument design, we use actuators to exert time-varying force on an acoustic body, so we are particularly interested in relationship between flux density B_a and force. We will consider two cases that commonly occur in augmented instruments.

2.1 Force on a Magnetized Object

In the first case, consider using an actuator to drive a permanent magnet attached to the instrument (Figure 1). Permanent magnets are useful in situations where the instrument itself is not made of a ferromagnetic material: for example, in the EMvibe, the aluminum bars of the vibraphone do not respond to magnetic fields, so permanent magnets are affixed to each bar [4].

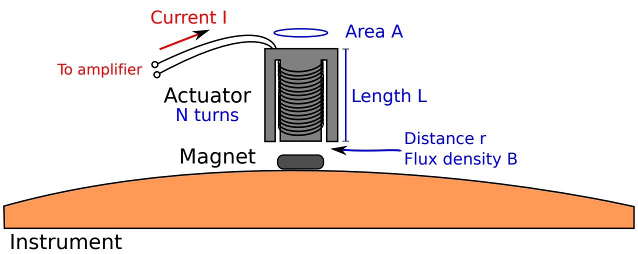

Figure 1: Actuation of an instrument through an attached permanent magnet.

A complete model of the force between two magnetized objects is complex, depending on the shape, orientation and magnetization of each object and the distance between them. For our purposes, Coulomb's Law, though it does not accurately model the underlying physical processes for real magnets, provides a starting point [7]. It gives the force between two magnetic poles spaced r meters apart:

$$F = \frac{\mu m_1 m_2}{4\pi r^2} \quad (2)$$

where m_1 and m_2 are the pole strengths in Ampere-meters and μ is the permeability of the intervening material (generally $\mu_0 = 4\pi 10^{-7} N/A^2$ for air).

Classically, a permanent magnet is modeled with point magnetic charges on either end. A solenoid electromagnet can be represented similarly, with the pole strength m_e given as a function of current I, number of turns N, length ℓ and area A:

$$m_e = \frac{NIA}{\ell} \quad (3)$$

We thus arrive at the force between a permanent magnet with pole strength m_p and an electromagnet:

$$F = m_p \frac{\mu NIA}{4\pi \ell r^2} \quad (4)$$

It is worth repeating that this is a simplified approximation of real-world systems. However, for purposes of musical instrument actuation, it demonstrates several important results. First, force is linearly proportional to current and number of turns (and hence to flux density B_a), and inversely proportional to the square of the distance between actuator and permanent magnet. It also suggests that coils with larger area and shorter length will produce a stronger force for the same current.

Since the goal is to induce vibrations in a musical instrument, the minimum distance r will be constrained by the need for the instrument to vibrate without contacting the actuator. Equation 4 appears to argue for actuator design favoring the largest possible number of turns, but we will see shortly that this design choice comes with a cost.

2.2 Force on a Ferromagnetic Object

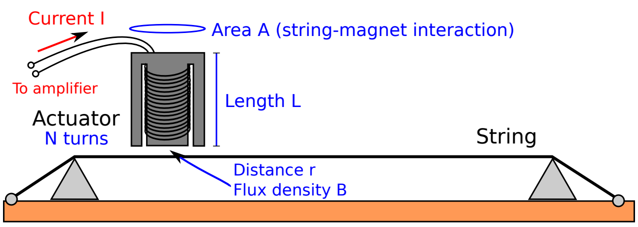

Figure 2: Electromagnetic actuation of unmagnetized ferromagnetic string.

Figure 2 shows the case of an actuator driving a steel instrument string. This is the configuration used in the magnetic resonator piano [11]. An important distinction from the previous case is that the string is not magnetically polarized. However, steel is ferromagnetic, with a permeability $\mu \gg \mu_0$ significantly larger than that of free space.

The complete system of actuator and string can be seen as a magnetic circuit containing two air gaps of length r (the distance between actuator and string). The system will try to minimize the total stored magnetic energy, and the force F_s on the string can be written as the derivative of stored energy with respect to distance [15, p. 508]:

$$F_s = -\frac{\partial W_m}{\partial r} \quad (5)$$

where the stored energy is a function of the field strength H_{gap} in the gaps and the area A of each area of interaction:

$$W_m = 2[\frac{1}{2}\mu_0 (H_{gap})^2 Ar] \quad (6)$$

Assuming a very high permeability core, [15] shows that the field strength in the gaps can be written as a function of number of turns N, current I and distance r:

$$H_{gap} = \frac{NI}{2r} \quad (7)$$

which gives

$$W_m = \frac{\mu_0 N^2 I^2 A}{4r} \quad (8)$$

and thus the force (the negative sign indicating direction):

$$F_s = -\frac{\partial W_m}{\partial r} = -\frac{\mu_0 N^2 I^2 A}{4r^2} \quad (9)$$

This is again an idealized system, but it shows that ignoring core saturation effects, the force between actuator and string is proportional to the *square* of the current. To see the implications of this, let us rewrite Equation 9 for a time-varying current $i(t) = I\cos(\omega t)$:

$$|F_s(t)| = i(t)^2 \frac{\mu_0 N^2 A}{4r^2} = I^2 \cos(\omega t)^2 \frac{\mu_0 N^2 A}{4r^2} \quad (10)$$

$$|F_s(t)| = I^2 \frac{1+\cos(2\omega t)}{2} \frac{\mu_0 N^2 A}{4r^2} \quad (11)$$

This result shows that applying an AC actuator current will result in a frequency-doubling effect on the string. Intuitively, this can be seen as the result of both positive and negative half-waves attracting the string, since ferromagnetic objects are attracted to a magnetic field regardless of polarity. For augmented instrument designers, two solutions are possible. One is to use permanent magnets placed immediately next to the actuator to create an offsetting field as Berdahl does with the Electromagnetically-Prepared Piano [1]. The other is to drive the actuator with a single-ended current (always positive or always negative):

$$i(t) = I_{off} + I_{sig}\cos(\omega t) \quad (12)$$

$$i(t)^2 = (I_{off})^2 + 2I_{off}I_{sig}\cos(\omega t) + (I_{sig})^2\cos(\omega t)^2 \quad (13)$$

$$i(t)^2 \approx (I_{off})^2 + 2I_{off}I_{sig}\cos(\omega t), \text{ when } I_{off} \gg I_{sig} \quad (14)$$

The greater the offsetting current I_{off}, the more linear the resulting system. Musically speaking, we have found that perfect linearity is not necessary, and excessive offset current results in wasted power and heating of the actuator. The magnetic resonator piano uses I_{off} slightly greater than I_{sig}: in other words, the troughs of the signal approach ground but never go negative (Figure 7). A circuit to achieve this result is presented in Section 3.2.

2.3 Actuator Design

Given the preceding discussion, how should the augmented instrument designer choose an actuator? For the same current, more turns of wire will produce a stronger field (hence more force). However, for musical signals, we need to be able to modulate the current at audio frequencies, and changes in current are limited by actuator inductance L [14]:

$$L = \mu \frac{N^2 A}{\ell} \quad (15)$$

$$\frac{\partial I}{\partial t} = \frac{V}{L} = \frac{V\ell}{\mu N^2 A} \quad (16)$$

where A is the area of the solenoid. Equation 4 shows that

$$\frac{\partial F}{\partial t} = m_p \frac{V}{4\pi r^2 N} \quad (17)$$

In other words, the goal of strong force for a given current and extended high-frequency performance are opposed. Actuator selection should thus take into account the specific musical situation (the frequency range needed) and the available amplifier output voltage swing V.

2.4 Lorentz Force Actuation

For metal-stringed instruments, an alternative approach exists to solenoid electromagnetic actuators. The *Lorentz force* describes the force on a charged particle due to a magnetic field. A special case of the Lorentz force gives the force on a current-carrying wire from a magnetic field:

$$\mathbf{F} = I\mathbf{L} \times \mathbf{B} \quad (18)$$

where $\mathbf{F}$, $\mathbf{L}$ and $\mathbf{B}$ are vector quantities representing the force, length of the wire as it interacts with the magnet, and magnetic field, and I is the current. To use Lorentz force actuation in a musical instrument (Figure 3), strong permanent magnets are placed next to the string and current is passed through the string itself. Alvin Lucier's 1977 piece *Music on a Long Thin Wire*[1] uses this form of actuation. The Lorentz configuration can also be used to measure string vibrations by monitoring current induced in the string; this technique has been used for detailed studies of the violin [10] and the piano [6].

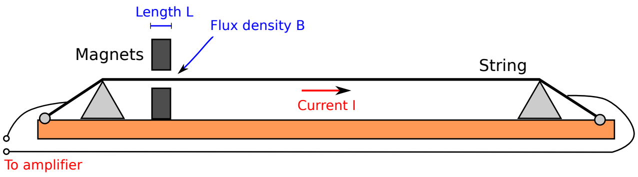

Figure 3: Lorentz force actuation of a musical instrument string.

In comparison to solenoid electromagnetic actuation, Lorentz actuation can have much better linearity and better high-frequency performance since the string lacks the inductance of a solenoid actuator. However, the maximum force exerted on the string is limited by the amount of current that can be passed through it: informal experiments with Lorentz actuation on steel guitar strings showed that large currents heat the string and cause its pitch to drop. String materials with higher conductivity, such as brass, may be better suited to this form of actuation, but in general, amplitude limitations mean that it is best used with amplified instruments.

2.5 Case Study: Magnetic Resonator Piano

The magnetic resonator piano (Figure 9) uses electromagnetic actuators to drive unmagnetized steel piano strings. Lorentz force actuation is impossible on the piano because the frame electrically connects both ends of all strings. The first generation magnetic resonator piano used hand-wound actuators: 600 turns of 30AWG copper wire on a 3/8" steel threaded rod. Actuators were approximately 0.6" in length, 0.8" in diameter, and had a resistance of 9Ω and an inductance of 20mH.

We recently built a second-generation instrument, one of the goals being to produce a design that can be replicated in larger quantity. Prefabricated actuators were thus necessary. Several actuators were evaluated from Magnetic Sensor Systems[2]. The variables available to the designer are overall size, number of turns and wire gauge, with two of these parameters determining the third.

We found that small-diameter (0.38") actuators performed well on the highest strings of the piano (frequencies above 2kHz) but that the total available power was limited before the actuators overheated. Moreover, the field from the smallest actuators was too localized to simultaneously activate the three strings of a given piano note. The best compromise between size, power and high-frequency performance was found to be an actuator of 0.82" diameter (0.77" length). Within this size, we evaluated multiple choices of wire gauge. The performance did not vary as strongly with wire gauge as with size, and we settled on 28AWG as a compromise between number of turns and low inductance. The actuators in the current magnetic resonator piano have an average resistance of 5.3Ω and an inductance of 19mH.

2.6 Recommendations

Even the highly simplified models above show that many factors affect actuator design. With the caveat that experimentation is always important, we offer the following suggestions:

- Actuator size usually dictates power handling, regardless of wire gauge. Choose a size first based on required output level, geometry and cost, then explore winding parameters (wire gauge vs. number of turns).
- Choose winding parameters based on amplifier capabilities, especially maximum output voltage swing. Fewer turns require less voltage swing but higher current to achieve the same performance. Also consider the minimum load impedance the amplifier can drive, especially when using amplifiers intended for speakers.
- Within reasonable limits, small variations in actuator design (e.g. 20% change in size, 2AWG in winding) do not appear to significantly affect musical results.
- Lorentz actuation can be useful where high-frequency performance is more important than overall amplitude, and it is the only option for non-ferromagnetic strings (e.g. brass). None of these forms of actuation will work with non-conductive strings.
- When a permanent magnet is used, actuator force also depends on its strength. Neodymium (rare-earth) magnets provide the highest field strength per unit mass; low mass minimizes any alteration to the instrument's natural resonance.

3. CIRCUITS

Just as important as the actuator design is how it is driven. This section presents circuits designed specifically for electromagnetic manipulation of acoustic instruments.

3.1 Power Amplifier

Actuators require significant amounts of power. While some actuators can be driven with commercial audio amplifiers, not all have suitable impedance to be used this way. Driving a large number of actuators with a collection of pre-made amplifiers can also become bulky and expensive. Moreover, most modern audio amplifiers are *voltage* amplifiers: for most of the audio range, the output voltage is proportional to the input voltage.[3] Equation 1, however, shows that the flux density of an actuator (and hence its force) is proportional to the *current* through its windings.

[1] http://www.lovely.com/albumnotes/notes1011.html
[2] http://www.solenoidcity.com

[3] Current amplification is occasionally used in an audio context. See, for example, `http://www.firstwatt.com/pdf/art_cs_amps.pdf` (accessed 04/2012).

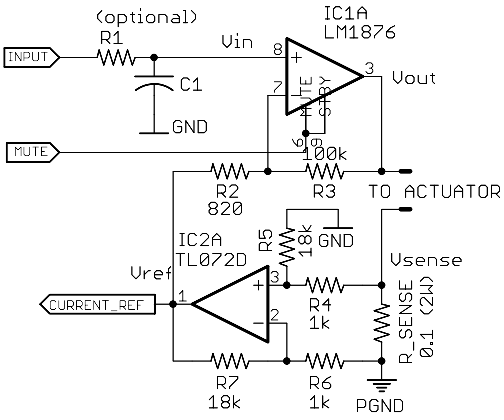

Figure 4: Transconductance amplifier for driving electromagnetic actuators.

Figure 4 shows a schematic for an amplifier designed for electromagnetic actuation. It is a *transconductance amplifier*: the output current is proportional to the input voltage. This amplifier design, repeated 88 times, powers the latest version of the magnetic resonator piano.

Current-output amplifiers are used extensively in haptics for the same reason they are valuable here: output actuator force (or motor torque) is linearly proportional to current [5]. Haptic systems often require strict feedback control but lower bandwidth than audio systems [9].

3.1.1 Operation

The heart of Figure 4 is a National Semiconductor LM1876 integrated two-channel power amplifier. Many similar amplifier chips have become available in recent years, with varying specifications on output power, supply voltage, and number of channels. These chips offer short-circuit, overcurrent and thermal protection, and many offer mute and low-power standby modes as well. These features make them highly robust in live performance where wires can come loose and unexpected signals can arrive at the inputs.

The transconductance design works as follows: current through the actuator produces a voltage across resistor R_{sense}. IC2A, a standard op-amp in a differential amplifier configuration[4], amplifies this voltage by the ratio R_5/R_4.The gain of IC1A is set quite high ($R_3/R_2 = 122$), which means that for finite output voltage, the output of IC2A should be approximately equal to the input on pin 8 of IC1A (exactly equal as R_3/R_2 approaches infinity). Therefore,

$$V_{in} \approx V_{ref} = \frac{R_5}{R_4}(I_{out}R_{sense}) \tag{19}$$

$$\frac{I_{out}}{V_{in}} \approx \frac{R_4}{R_5 R_{sense}} \tag{20}$$

3.1.2 High-Frequency Performance and Stability

Equation 16 demonstrates that *voltage swing*, and not total output power, determines the maximum change in current (slew rate). The LM1876 is specified for supply rails up to ±32V, with an output swing within 3V of each rail. Other integrated amplifiers are rated for even higher supply voltages. The magnetic resonator piano uses ±28V rails.

R_2 and R_3 are necessary to limit the maximum gain of the LM1876. Electromagnetic actuators are inductors, with increasing impedance with respect to frequency; as frequency increases, it will take an ever-greater voltage swing to achieve the same current output. The maximum gain of IC1A is given as:

$$G_{max} = 1 + \frac{R3}{R2} \tag{21}$$

Every actuator has both resistance and inductance. At DC, only resistance is relevant. From Equation 20 we can find the DC voltage gain of IC1A:

$$G_{DC} = \left(\frac{V_{out}}{V_{in}}\right)_{DC} \approx \frac{R_4(R_a + R_{sense})}{R_5 R_{sense}} \tag{22}$$

where R_a is the actuator resistance. By comparing Equations 21 and 22, we find the maximum *boost*, or the extent to which the gain increases with frequency (Figure 5).

Normally, the actuator acts as a lowpass filter with corner frequency $R_a/2\pi L_a$. The amplifier acts a shelving first-order highpass filter, with the result that the *effective corner frequency* of the actuator is pushed upwards:

$$f_{rolloff} = \frac{G_{max}}{G_{DC}} \frac{R_a}{2\pi L_a} \tag{23}$$

For the magnetic resonator piano, the actuators have a natural corner frequency of $1/(2\pi(L/R)) = 44$Hz; with the component values given, the gain at DC is 3.0 and the maximum gain is 122. This produces a theoretical closed-loop corner frequency of 1800Hz (i.e. output transconductance is flat until 1800Hz). In practice the corner frequency is measured closer to 3000Hz, which suggests that the apparent inductance of the actuator drops at higher frequencies, most likely due to losses in the steel core.

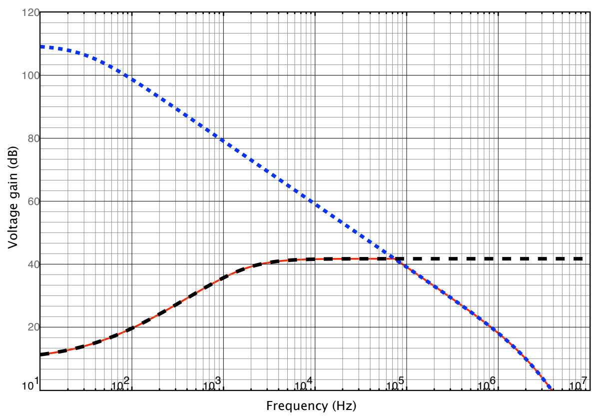

Figure 5: Voltage gain for open-loop (blue, short dashes) and inverse feedback path (black, long dashes). The closed loop voltage gain (solid red) is the minimum of the two. Where the curves intersect, the total phase offset must be less than 180°.

The stability criterion is shown in Figure 5. The open-loop gain is derived from the LM1876 datasheet, showing standard dominant-pole compensation. At the point where the open-loop gain of IC1A intersects the (inverse) gain of the feedback path, the total phase shift must be less than 180°. This requires that the feedback gain be approximately flat before the point of intersection, placing an upper bound on the ratio R_3/R_2 which is dependent on the specific properties of the actuator. The given component values produce a stable design for most electromagnetic actuators, but not for low-impedance purely resistive loads (e.g. Section 2.4) where artificial high-frequency rolloff must be added.

[4]The differential configuration is used so that power and signal grounds can be separated; voltages induced in the power ground by other amplifiers will be canceled out.

3.1.3 Current Monitoring

A useful feature of this amplifier design is that the output of IC2A (V_{ref}) provides a voltage proportional to the actuator current, even in cases where IC1A saturates or distorts. Additionally, by connecting R_2 to ground rather than to the output of IC2A, the amplifier can be converted into a voltage-output (low output impedance) design while retaining current monitoring capability.

Current monitoring is useful for interference cancellation. When magnetic actuators and magnetic pickups are used simultaneously, the actuator signal can bleed directly into the pickup. By subtracting a scaled version of V_{ref}, this interference can be significantly attenuated. However, core saturation and hysteresis effects prevent V_{ref} from being an exact measure of the magnetic flux density in Equation 1.

3.1.4 Construction Notes

Schematics and board layouts are available from the author online.[5] The roles of R_2-R_7 have been previously discussed. R_1 and C_1 form an optional low-pass filter on the input signal to reduce the output swing from high-frequency noise. 1% resistors should be used, particularly for R_4-R_7 and (if possible) R_{sense}. R_{sense} should be rated for sufficient power to handle the maximum possible load current. As with all amplifier designs, proper supply bypassing and heatsinking are required.

Traditional or switching power supply designs are possible for the rails of IC1. If the rails exceed ±15V, a separate supply is required for IC2. Both IC1 and IC2 are dual amplifier parts, so a complete design consists of two amplifiers.

3.2 Polarity and Offset Adjustment

Section 2.2 showed that driving (unmagnetized) ferromagnetic objects requires a single-ended output current. The amplifier in Section 3.1 can be used for either bipolar or single-ended signals, as there is no DC blocking capacitor at the input. The circuit in Figure 6 provides a comprehensive means of adjusting the offset and polarity (phase inversion) of an input signal.

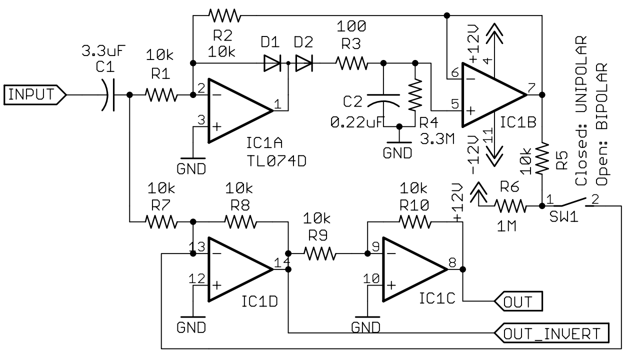

Figure 6: Circuit for selecting single- or dual-polarity inputs. Single-polarity signals are useful for driving unmagnetized ferromagnetic objects.

3.2.1 Single-Ended Mode

When SW1 is closed, the output is single-ended: positive on signal 'out', negative on 'out_invert'. The troughs of the shifted waveform approach but do not cross ground, as shown in Figure 7. This is a superior configuration to a fixed voltage offset because the average DC value is never any higher than needed, conserving output power (and heat).

[5] http://www.eecs.qmul.ac.uk/~andrewm/

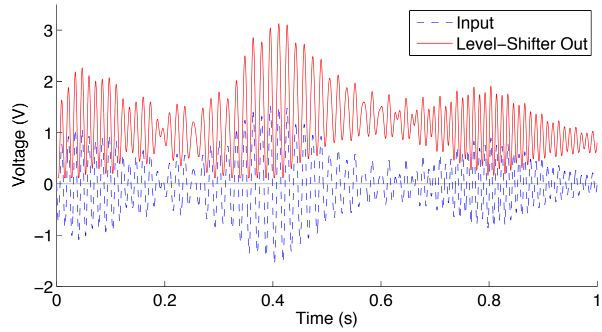

Figure 7: Output of level-shifter circuit.

IC1A and IC1B form a precision peak detector with decay time set by the product R_4C_2. R_3 limits inrush current to C_2 and avoids op-amp instability. IC1D mixes the original and peak-detected signals, meaning the troughs of the waveform will always stay above ground. Optional R_6 adds a small voltage offset (I_{off} in Equation 12). Since IC1D is an inverting amplifier, IC1C recovers the original non-inverted (but still level-shifted) signal.

3.2.2 Dual-Ended Mode

When SW1 is open, the peak detector is disconnected from IC1C. IC1C and IC1D now act as simple inverting buffers. SW1 can be implemented as a physical switch or an analog switch IC (e.g. 74AHC1G66).

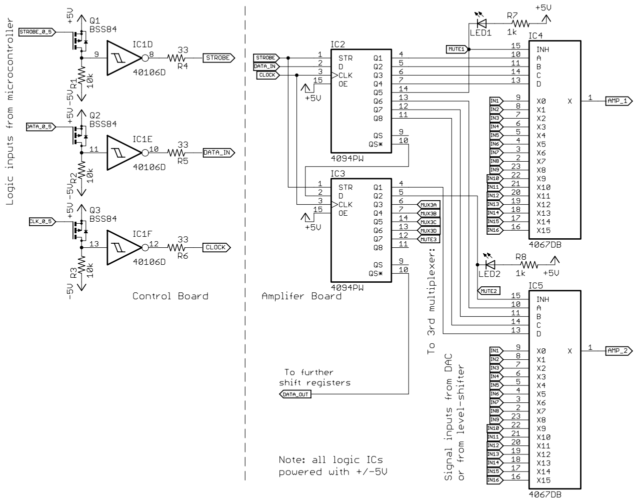

Figure 8: Signal routing from DAC channels to amplifiers. Two shift registers support 3 multiplexers (3rd not shown) and blocks can be daisy-chained to support an arbitrary number of actuators.

3.3 Multi-Actuator Signal Routing

Each actuator requires its own amplifier. However, for polyphonic instruments such as the piano, it is not feasible to have an audio output channel for every string. Figure 8 shows a circuit which dynamically routes input signals to amplifiers. Each amplifier takes its input from a 16-channel multiplexer. The control inputs of the multiplexers, as well as the standby/mute pins on the amplifiers, are driven from the outputs of a chain of shift registers. In this way, a microcontroller can easily maintain a routing matrix between up to 16 inputs and an indefinite number of output amplifiers.

The circuit is tailored to work with the amplifier of Section 3.1. The logic is powered from ±5V to allow dual-ended signals to pass (the audio inputs must be within the multiplexer supply rails). P-channel MOSFETs are used to convert standard 0-5V logic to this format. Schmitt-trigger buffers (IC1) are used to provide clean edges on slow-rising or noisy data lines. If multiple amplifier boards are daisy-chained through long cables, Schmitt-trigger buffers at the input of each board are recommended.

4. PUTTING THE PIECES TOGETHER: THE MAGNETIC RESONATOR PIANO

Figure 9: The magnetic resonator piano, showing electromagnetic amplifiers over each string. Amplifiers are inside the piano behind the actuators.

The magnetic resonator piano, an electromagnetically-augmented grand piano, was first designed in 2009 [11, 12]. It allows the performer to continuously shape the string vibrations for every note, with extended techniques including infinite sustain, crescendos, pitch bends, harmonics and new timbres. The material presented here reflects a complete redesign of the hardware. This redesign was fundamentally *musical* in motivation: composers and performers requested features that could only be addressed by hardware changes. Requests included:

1. **Louder sound**, especially in the bass: though the instrument was already quite loud, it had difficulty competing with the traditional piano when played *forte* or *fortissimo*. Making the instrument louder required higher-power amplifiers.
2. **Brighter sound** and **upper harmonics**: musicians wanted the timbre of the electromagnetic sound to more closely match the timbre of the traditional piano, which contains many upper partials. The instrument can also play individual harmonics on each string, but the upper harmonics were quite soft. Addressing both requests required a greater current slew rate and thus an amplifier with a larger voltage swing.
3. **Faster speaking time**: the actuators produce tones that speak more slowly than hammer-struck notes. Though this is inherent in the nature of electromagnetic actuation, faster response was achieved through a combination of higher-power amplifiers and a level-shifting circuit (Section 3.2) with a rapid attack time (defined by R_3C_2).
4. **88-note coverage**: the original instrument covered 48 strings. To cover the complete range of the piano, both amplifiers and actuators needed to be machine-produceable in quantity, which guided their design.

Figure 9 shows a picture of the current MRP design, which places amplifiers next to the electromagnets inside the piano. In addition to the electronic improvements described above, a rapidly-adjustable bracket allows the horizontal and vertical position of each actuator to be changed and locked using a single wing nut, greatly reducing setup time in an 88 note configuration. The instrument was recently used in performances of new music by six Philadelphia-area composers; further musical discussion can be found in [11], and videos are available online (see previous footnote).

5. CONCLUSION

This paper has presented a basic theory of electromagnetic actuator design and several circuits intended for use in acoustic instrument actuation. The techniques presented form the basis of the magnetic resonator piano, but they are broadly applicable to any augmented instrument situation. It is hoped that these ideas will accelerate the process of creating new augmented instruments by providing a procedure and toolkit for designing actuation systems.

6. REFERENCES

[1] E. Berdahl, S. Backer, and J. Smith. If I had a hammer: Design and theory of an electromagnetically prepared piano. In *Proc. ICMC 2005*.

[2] E. Berdahl, G. Niemeyer, and J. Smith. Active control of a vibrating string. In *Proc. Acoustics '08*.

[3] P. Bloland. The electromagnetically-prepared piano and its compositional implications. In *Proc. ICMC 2007*.

[4] C. Britt, J. Snyder, and A. McPherson. The EMvibe: An electromagnetically actuated vibraphone. In *Proc. NIME*, 2012.

[5] M. C. Çavuşoğlu, D. Feygin, and F. Tendick. A critical study of the mechanical and electrical properties of the PHANToM haptic interface and improvements for high performance control. *Presence*, 11(5), 2002.

[6] D. E. Hall. The hammer and the string. In A. Askenfelt, editor, *Five Lectures on the Acoustics of the Piano*. 1990.

[7] P. Hammond. *Electromagnetism for Engineers*. Pergamon Press, Oxford, UK, third edition, 1986.

[8] G. Heet. String instrument vibration initiator and sustainer. U.S. Pat. 4,075,921, 1978.

[9] K. Kuchenbecker, J. Fiene, and G. Niemeyer. Improving contact realism through event-based haptic feedback. *IEEE TVCG*, 12(2), 2006.

[10] M. Mathews and J. Kohut. Electronic simulation of violin resonances. *JASA*, 53(6), 1973.

[11] A. McPherson. The magnetic resonator piano: Electronic augmentation of an acoustic grand piano. *Journal of New Music Research*, 39(3):189–202, 2010.

[12] A. McPherson and Y. Kim. Augmenting the acoustic piano with electromagnetic string actuation and continuous key position sensing. In *Proc. NIME*, 2010.

[13] D. Overholt, E. Berdahl, and R. Hamilton. Advancements in actuated musical instruments. *Organised Sound*, 16(2):154–165, 2011.

[14] M. A. Plonus. *Applied Electromagnetics*. McGraw-Hill, New York, USA, 1978.

[15] N. N. Rao. *Elements of Engineering Electromagnets*. Prentice Hall, Upper Saddle River, NJ, USA, fifth edition, 2000.

[16] G. Shear and M. Wright. The electromagnetically sustained Rhodes piano. In *Proc. NIME*, 2011.