EMCymbal: the electromagnetically prepared cymbal

Contents

Praise him with sounding cymbals,
praise him with clanging cymbals.
Let everything that breaths
praise the LORD! Alleluia.
Psalms 150

If I speak in human and angelic tongues, but do not have love, I am a resounding gong or a clashing cymbal.
1 Corinthians 12:31

1 INTRODUCTION

The EM Bronze Ensemble is a project for electromagnetically prepared cymbals, gongs and metal sheets. The purpose of this paper is to investigate the preparation and actuation of metallic percussion instruments with a solenoid and permanent magnet attached to the instrument. Projects for the electromagnetically prepared piano [1], [2], [3], [4] and vibraphone [5] have been proposed. The technique described in this paper uses an electromagnet either as a non-contact force or torque actuator on a magnetic dipole in the form of a small permanent neodymium magnet epoxied to a metal percussion instrument.

Out of all the musical instruments that can be excited with a solenoid, perhaps the cymbal, gong and sheet is the most interesting. This is because it's possible to induce rich behavior when the nonlinear dynamics contribute. With nonlinearity comes very interesting behavior like period doubling route to chaos, subharmonics, and attractor dynamics. It's very difficult to excite strings and bars to the point where they become nonlinear. **Resonance.**

Obviously, the presence and mass of the permanent magnet will modify the dynamics of the instrument. Fortunately, we can use neodymium magnets that are very strong so they need not be massive. The usual method found in academic literature for exciting cymbals employs an electrodynamic shaker attached to the center hole of the cymbal. Electrodynamic shakers tend to be very expensive to buy and/or to rent. This paper will discuss a non-contact method that is inexpensive to implement.

The goal of this project is the following: we're after a source of oscillating magnetic fields to form a non-contact actuator with a dynamic range from 10 to 1000 Hz.

Figure 1. An electromagnetically prepared piano
An elaborate set of holding electromagnets held over piano strings [4].

2 Sources of Magnetic Fields

This paper will discuss two types of electromagnets: the industrial holding electromagnet that is readily commercially available and the straight solenoid electromagnet that is made by winding copper wire around a straight length of permeable core like iron or ferrite rods or bobbins. **There will be a brief discussion of combining two or more straight solenoid electromagnets for either push-pull or torque actuation or in a Helmholz coil arrangement for producing large magnetic field gradients for push-pull actuation**. The two types of electromagnets are shown in Figure 2.

Need table of materials and permeability and saturation frequency.

2.1 Permanent Magnets

come in all sizes and shapes such as discs, truncated pyramids, cones, rods, and cubes. The most convenient shape for our purposes is a disc magnet that we can attach to the cymbal edge using either glue or double-sided tape. The size of magnet should be chosen so as to produce sufficient force to excite all the dynamic modes of the cymbal, but as light (mass) as possible so as to affect those dynamic modes as little as possible.

An arbitrary source of magnetic fields such as a permanent disc magnet can be expressed as a sum of basic sources of fields known as multipoles. This is known as a multipolar expansion. There is no known example of a magnetic monopole. The field of a dipole drops as 1/r^2, the quadrupole drops as 1/r^3. The higher the order, the faster its field drops away. So, the field far away (compared to its physical dimensions) from the permanent magnet is dominated by the dipole. We're going to approximate the field of a disc magnet with a perfect magnetic dipole. A perfect magnetic dipole is by definition an infinitesimally small loop of current. The best macroscopic approximation of a perfect magnetic dipole is a small sphere magnetized along a single axis. The sphere's magnetic dipole moment where the magnetic moment

$$\vec{m} = \vec{M}\mathrm{V},$$

where $\vec{m}$ is the magnetic moment in $\mathrm{A} \cdot m^2$ and $\vec{M}$ is magnetization in $\mathrm{A/m}$ and V is the volume of the magnet in m^3. In general, magnetic dipole moment increases with volume, so torque forces will be large for large volume magnets, but large volume magnets are more massive than smaller ones and will modify the dynamics of the cymbal more than a smaller magnet. The size of magnet should be chosen according to the amount of excitation desired and no more to keep the mass to a minimum. Neodymium N42 magnets have magnetization of $\vec{M} \approx 1.0 \times 10^6$ A/m (order of magnitude) and N52 $|\vec{M}| \approx 1.15 \times 10^6$ A/m (about 10–15% higher than N42), so a 3/16″ × 3/16″ × 1″ bar with $\mathrm{V} \approx 5.8 \times 10^{-7}$ m³ will have magnetic moments of $|\vec{m}| \approx 0.6$ A·m² with N42 and $|\vec{m}| \approx 0.7$ A·m² (roughly 10–15% larger for the same bar size) with N52. So, for a given bar size, N52 has a slightly larger magnetic dipole moment than N42, but in both cases the moment scales linearly with bar volume. Physical parameters of various permanent magnet shapes can be found on the K&J Magnetics website [6].

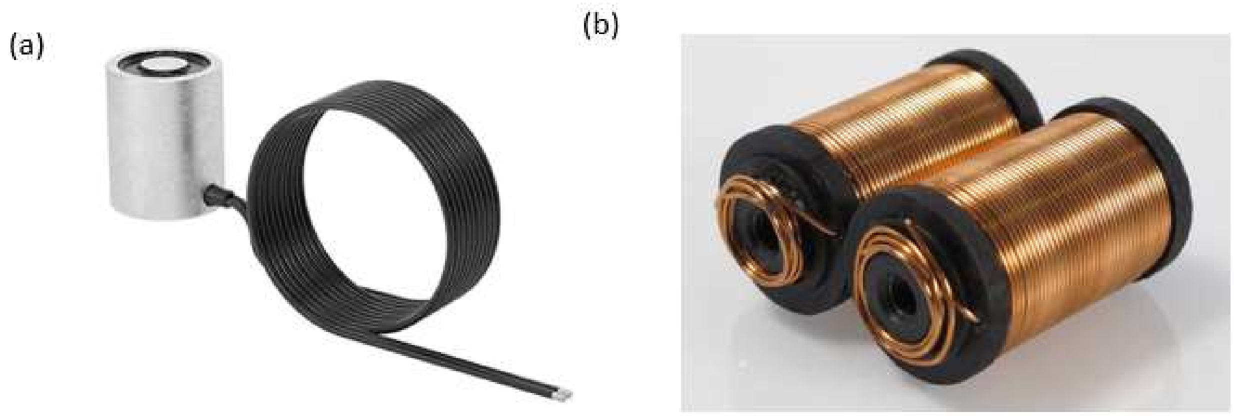

Figure 2. Types of electromagnets
(a) an industrial holding-type electromagnet; (b) a set of straight solenoid electromagnets (tattoo coils)

2.2 A Holding Electromagnetic

The holding electromagnet is quite popular probably because it's readily and commercially available. The electromagnetic piano preparations of Backer and Berdahl [1] [2] and McPherson [3] both employ the holding magnet. Its round geometry produces a circularly symmetric pattern of magnetic field lines about its axis. Field lines emanate from the center and terminate at the periphery or vice-versa depending on the polarity of voltage across the device. Both piano and vibraphone projects make use of a holding-type electromagnet. It's not the best choice especially for actuating a piano wire because only the fields in the vertical plane of the wire do any work, while fields not in plane do no work and are wasted. E-core type electromagnets would be improvement over the round "pot" style currently in vogue because its geometry concentrates field lines in the vertical plane of the wire. It should be mentioned that the holding EM for actuating piano wires is actually a reluctance actuator where "reluctance" is the magnetic analog to resistance for electricity. The reluctance actuator works on the basis of minimizing the path of resistance to the magnetic lines of force produced by the electromagnet by pulling on the string which is more permeable (conductive to magnetic fields) than air toward the electromagnet thus closing the gap between the wire and the electromagnet. The reluctance actuator can only pull on the string and can't push.

The holding EM can be used as part of a push-pull force actuator, but since its magnetic field strength drops with distance squared, the permanent magnet mustn't be too far away, but the permanent magnet is ferromagnetically attracted to the steel body of the holding EM, so that the two can easily stick together. This becomes especially problematic for large vibration amplitudes. Admittedly, large vibration amplitudes aren't an issue with piano wires nor with vibraphone bars [5], and a mechanical gap can be maintained with a proper mounting fixture. Yet another drawback of the holding-electromagnet is its large lumped inductance which yields a weak response everywhere except a narrow band around its resonant frequency.

2.3 A Solenoid Electromagnet

The solenoid electromagnet is shown in **Error! Reference source not found.**b. It is simply a long length of enameled solid copper wire wrapped around a straight ferrous steel or ferrite core. Field lines have to wrap around the solenoid from one pole to the other pole. The air which the fields span reduces the overall inductance. It has a few advantages over the holding electromagnet because as will be shown the solenoid electromagnet can be used to build a non-contact push-pull or torque actuator.

Firstly, the solenoid can be positioned very closely to the permanent magnet since in that orientation the solenoid won't interfere with the cymbal as it vibrates; secondly, the magnetic field drops off with distance squared, so the gap between one of the solenoid's ends and the permanent magnet should be kept as small as possible. The geometry of the situation will dictate which of the two actuation methods is the most practical; for instance, the authors of [5] express their intention to actuate a steel drum which for which only the first method is practical, and the lujon and mbira for which either method would work. One drawback to Method 2 is that it can only be implemented at the edge of the cymbal. This is particularly effective at exciting axisymmetric modes.

2.4 Short Discussion on I, U or C shaped cores

Permeability and reluctance in magnetics play roles analogous to conductivity and resistance in electronics. Air has nearly unit permeability, so it does not concentrate magnetic flux the way ferromagnetic materials do. Wrapping the coil around a high-permeability core concentrates the magnetic flux so that a strong field and gradient emerge at the pole face, where they can efficiently interact with the small permanent magnet attached to the cymbal. Cores come in a variety of shapes referred to the letters they resemble. Figure 3 shows examples of ferrite I-, E-, U- and C-shaped cores available online.

Figure 3. Ferrite Cores
Shown are various shapes of ferrite cores available online [7].

3 NON-CONTACT ELECTROMAGNETIC ACTUATORS

The field generated by a finite solenoid of finite length [8] a short distance z from one of its ends is

$$B(z) = \frac{\mu_0 NI}{2\ell}\left[\frac{\ell + z}{\sqrt{R^2 + (\ell + z)^2}} - \frac{z}{\sqrt{R^2 + z^2}}\right], \quad z \geq 0 \tag{1}$$

where N, I, ℓ, R and z are the number of turns, electrical current, length and radius of the solenoid, and distance away from one of the solenoid's ends where $z = 0$ at the end face. Force on a magnetic dipole increases with field gradient strength; whereas torque on a dipole varies with the field magnitude. We'll see that force increases the strength of the field gradient and torque increases with the strength of the magnetic field. Both force and torque vary with the magnetic dipole moment of the permanent magnet. The field, in turn, increases with the number of turns and current. We'll see that the number of turns is restricted by the coil's inductance because as the inductance increases its frequency response become concentrated around a resonant frequency as inductance increases. Before we discuss electromagnets, we'll take a look at permanent magnets.

$$B(u, \alpha) = \frac{\mu_0 NI}{2L}\left[\frac{1 + u}{\sqrt{\alpha^2 + (1 + u)^2}} - \frac{u}{\sqrt{\alpha^2 + u^2}}\right], \quad u = z/L,\ \alpha = R/L \tag{2}$$

EM actuators can excite both asymmetric and axisymmetric modes in the cymbal. The push-pull EM actuators can only excite axisymmetric modes in the cymbal. EM torque actuators can excite both axisymmetric and asymmetric modes. **Error! Reference source not found.**c and **Error! Reference source not found.**c show geometries that will excite asymmetric modes. The geometries shown in a) and b) of

Error! Reference source not found. and a) and b) of **Error! Reference source not found.** show geometries appropriate for exciting axisymmetric modes.

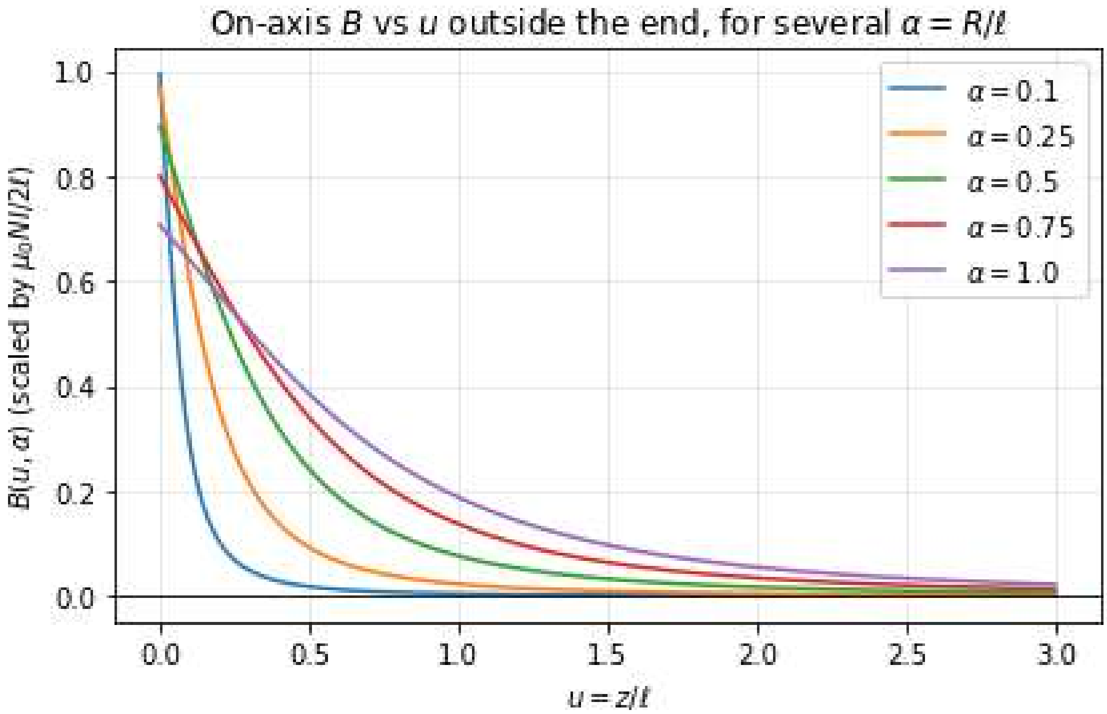

Figure 4. ***B*** **Field**
The magnetic field versus normalized distance ($u = z/\ell$) from the end face of straight solenoid electromagnet for five different values of α.

3.1 Linear Force Actuators

Both the method employed by Thomas et al. to investigate the nonlinear vibrations of thin spherical shells [9] and the EMVibe project [5] are examples of the push-pull force actuator where a small permanent magnet is attached to a cymbal in the former case and a vibraphone bar in the latter case. Thomas et al. used an air core electromagnet and the EMVibe project used holding electromagnets. The analysis in this section will focus on straight solenoid electromagnets, but similar physics applies to holding magnets [10]. A "solenoid electromagnet" is an electromagnet formed by wrapping wire around a straight permeable core. The setup in **Error! Reference source not found.**a was employed by a different group for electromagnetically actuating vibraphone keys [5].

The force $\vec{F}$ on a fixed magnetic dipole with dipole moment $\vec{m}$ in a non-uniform field $\vec{B}$ [11] is

$$\vec{F} = \nabla(\vec{m} \cdot \vec{B}). \quad (3)$$

We're only interested in the z component of this force, i.e., the force along the axis of the solenoid F_z

$$F_z = m_z \frac{\partial B}{\partial z}, \quad (4)$$

where m_z is the z-component of the permanent magnet's magnetic moment.

If we take the derivative of Eq. (1) with respect to z we get

$$\frac{dB}{dz} = \frac{\mu_0 NI}{2\ell}\left[\frac{R^2}{(R^2+(\ell+z)^2)^{3/2}} - \frac{R^2}{(R^2+z^2)^{3/2}}\right]$$

and make this dimensionless by introducing $u = z/\ell$, $\alpha = R/\ell$

$$\frac{dB}{du} = \frac{\mu_0 NI}{2\ell}\alpha^2\left[\frac{1}{(\alpha^2+(1+u)^2)^{3/2}} - \frac{1}{(\alpha^2+u^2)^{3/2}}\right], \quad u = z/\ell,\ \alpha = R/\ell \tag{5}$$

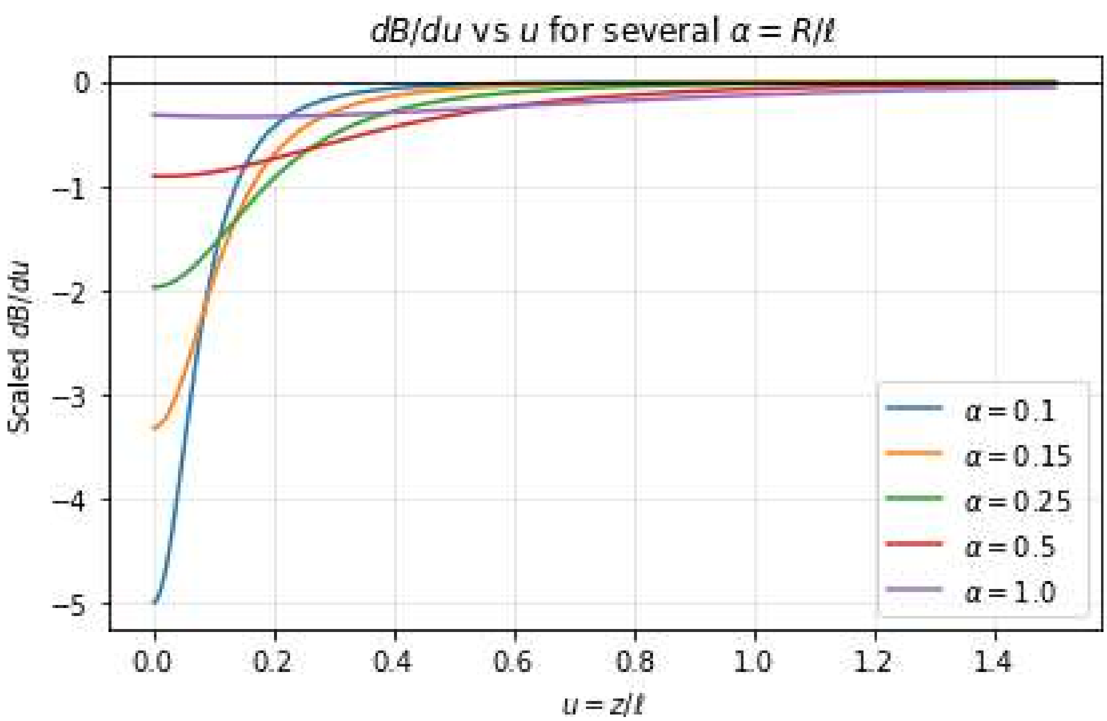

Figure 5. Plot of dB/du
Plot of Eq. xx

Figure 5 shows a plot of Eq. (5) versus u for five different values of α. It can be seen that for a given axial position $u = z/\ell$ outside the end, thinner / longer solenoids give a steeper field gradient and therefore larger force, while fatter solenoids ($\alpha \sim 1$) produce a more uniform field and a gentler gradient and smaller force.

Note that the force is proportional to how the field changes with respect to z (the distance between the solenoid and the disc magnet) known as the field gradient. A uniform field produces no force; large forces are associated with large gradients, so our challenge is to set up large gradient *fluctuations* in order to vibrate the cymbal. Also, the expression tells us that if we should choose a permanent magnet with largest value of m_z as possible. There is a built-in gradient inside the solenoid, i.e., the field at the ends of the solenoid are about 50% what the field strength is at the center of the solenoid. We won't have access to the built-in gradient because we are going to fill the solenoid with a permeable material (known as an armature or core) of ferrite or soft iron to increase the field just above the solenoid at the location of the permanent magnet.

This figure shows that a solenoid with a large radius (compared with its length L) produces a gradient that is smaller than the gradient produced by a solenoid with a small radius. The strongest field gradients are produced by two opposing solenoids. The opposite of a Helmholtz coil. Etc. If we restrict ourselves to a single coil what do the design restraints tell us about producing the strongest possible gradients and therefore the best non-contact force actuator based on an electromagnet?

There are two sets of constraints that we must consider in order to build the best solenoid for actuating a metallic percussion instrument (or for any other spring-mass mechanical system). We must consider the ability of the solenoid to produce large gradients since force is proportional to gradient strength (not field strength) and the challenge of electrically driving a solenoid over a broad range of audio frequencies. We want the time constant $\tau = {}^{R}/_{L}$ to equal the reciprocal of the largest frequency of interest. Simultaneously meeting these two constraints will lead to a compromise in the performance of the actuator.

The working distance is the distance between the end of the solenoid and the permanent magnet. It's desirable to have a working distance > 5 mm to accommodate large amplitude fluctuations of the cymbal. If the working distance is too small the permanent magnet and the armature will get so close during large swings of the cymbal that they will stick together and oscillation will stop. I have had some success fixing a small permanent magnet to the armature/core with the opposite polarity of the magnet attached to the cymbal so that the two repel. This can tend to dampen cymbal vibrations if the two are brought sufficiently close. A long slender solenoid will make for a long working distance.

Let's look at the first terms of Eqs. X and XX, i.e., ${}^{\mu NI}/_{2}$ and ${}^{\mu N^2 A}/_{l}$. The former (from the magnetic field and gradient expressions) suggests that we should make our solenoid with lots of turns per unit length; whereas the second the term varies as the square of N and suggests that in order to keep inductance low we should keep turns N small. Note that current I multiplies the first term, so we can make N small (to lower inductance) and current I large to generate large field gradients. We are forced to trade appreciable field gradients with inductance (and therefore bandwidth). The second term suggests that we make the solenoid long and narrow (small diameter) and use small gauge (heavy) wire to reduce the number of turns, but reducing turns reduces field gradient strength, so compensate reduced N with large currents I. Reducing the wire gauge will necessarily increase current since resistance per unit length (resistivity) goes down with the inverse of wire gauge.

3.2 TORQUE ACTUATORS

The torque on a magnetic dipole is

$$\vec{\tau} = \vec{m} \times \vec{B}\,, \qquad (6)$$

where $\vec{m}$ is the magnetic dipole moment of the small permanent magnet attached to the cymbal, and $\vec{B}$ is the magnetic field produced by the solenoid. This is illustrated in **Error! Reference source not found.**b. Torque on the magnetic dipole reverses direction as the magnetic field reverses its direction.

Discuss all the possible geometries for a torque actuator. Depending on choice of geometry, torque actuators will excite either asymmetric or axisymmetric modes as shown in **Error! Reference source not found.**. When the torque vector is aligned with the cymbal's axisymmetric axis, axisymmetric modes will be excited, and when the torque vector is aligned along the asymmetric axis, asymmetric modes will be excited.

4 EM ACTUATOR ELECTRODYNAMICS

We're using a solenoid as an electromagnetic actuator which means that we're going to drive the electromagnet by reversing its polarity rapidly at the excitation frequency. The inductance of the solenoid is going to resist changes that we try to impose in the current. In designing an electromagnetic actuator, we need to consider the electrical performance and its magnetic performance and balance these the requirements of each of these.

The holding electromagnet body is made from ferrous steal which tends to saturate at frequencies above 100 Hz or so.

4.1 EM ACTUATOR INDUCTANCE

A coil of wire acts as a lumped inductor. The inductance of the solenoid is proportional to the number of turns N squared, so that the more turns, the more inductance and the greater the magnetic field produced. While a large magnetic field is desirable, large inductors tend to exhibit a strong resonant frequency and a weak response away from its resonant frequency. We must consider the temporal response of the solenoid since we want to be able to vibrate the object to which the permanent magnet is attached over at least two orders of magnitude from 10 to 1000 Hz which is a range that contains most cymbal and gong resonant frequencies. The solenoid's frequency response will guide us on deciding how many turns to put on our solenoid. The best way to know our solenoid's inductance is to build it and measure it using a LCR meter or calculate it using an online calculator [12]. The inductance of a solenoid L with an iron core can be approximated using Wheeler's multi-layer formula [13] accurate to ≲1 % for near-square cross-sections, i.e., $(r_2 - r_1)/_{\mathrm{l}} \sim 1$:

$\mathrm{L} \approx \mu_0 \mu_{\mathrm{eff}} \frac{N^2 r_{\mathrm{mean}}^2}{6r_{\mathrm{mean}}+9\mathrm{l}+10\,t}$ in units of μH, where

$$r_{mean} = \frac{r_1 + r_2}{2} = \text{mean winding radius}$$

and

- $\mathrm{t} = r_2 - r_1 = \text{winding thickness}$
- N = total number of turns,
- r_1 = inner radius of the winding (m),
- r_2 = outer radius of the winding (m),
- l = coil length (m),

- $\mu_0 = 4\pi \times 10^{-7}\, {}^{H}/_{m}$
- $\mu_{eff} \sim 20 - 50$ for a 10 mm diameter iron core.

Where μ is the magnetic permeability of the armature/core, L is inductance, l is the end-to-end length of the solenoid, and N is the number of turns of wire.

It can be seen from the expression that inductance increases with the square of number of turns. So, for low inductance use small gauge (fat) wire. Using heavier wire will reduce the DC resistance, so that current will increase for a given voltage across the solenoid. Inductance can be decreased by making the solenoid long and small in diameter (A/L). This also makes for a good working distance.

The following table gives the inductances of three solenoids each with a 10 mm iron core ($\mu_{eff} = 30$) and with a different number of turns.

***N* = turns**	**Inductance [µH] air-core**	**Inductance [mH] iron-core**
100	5	0.15
200	20	0.60
300	45.1	1.35

There are also online calculators for estimating multi-layer coil inductance [12]. Once we know our solenoid's inductance, we can investigate its electronic frequency response.

4.2 EM Actuator Frequency Response

The solenoid, modeled as an inductor L with a series resistance R, has a complex impedance given by:

$$Z_{\text{sol}} = R_{\text{sol}} + \mathrm{j}\,\omega L \tag{7}$$

where $\omega = 2\pi f$ is the angular frequency.

The current is:

$$\mathrm{I}(\omega) = \frac{V_s}{Z_{\text{sol}}(\omega)}.$$

Substituting the expression for $Z_{\text{comp}}(\omega)$, we have:

$$\mathrm{I}(\omega) = \frac{V_s}{R_{\text{sol}} + j\omega L}. \tag{8}$$

The magnitude of the current is:

$$|I(\omega)| = \frac{|V_s|}{\sqrt{{R_{\text{sol}}}^2 + (\omega L)^2}}. \tag{9}$$

The power dissipated in the solenoid is:

$$P_{\text{sol}}(\omega) = |I(\omega)|^2\,R = \frac{|V_s|^2\,R}{{R_{\text{sol}}}^2 + (\omega L)^2} \tag{10}$$

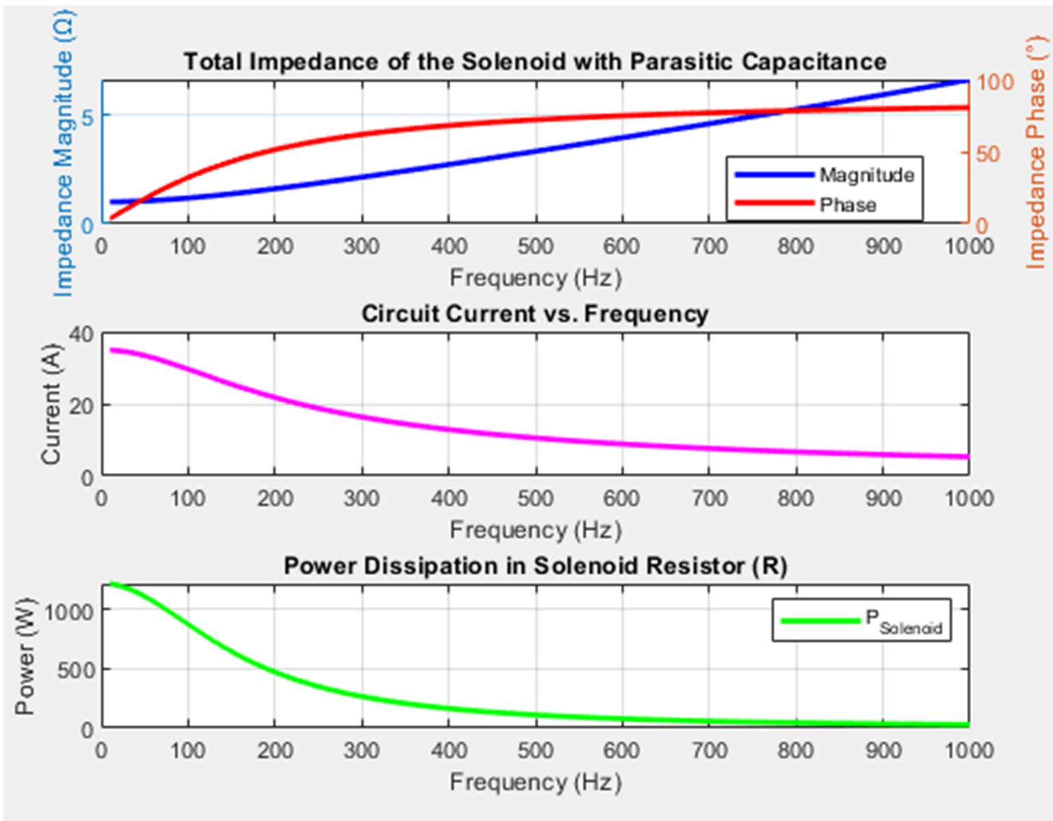

Figure 6. Solenoid RL Response
Plots of with R_{sol} = 1 Ohm (winding loss); L = 1 mH with a 10 mm ferrite core; V_s = 35 Volts

4.3 Passive Compensation Network

The solenoid and the electronics including the waveform generation and amplifier driving the solenoid should have an appreciable response that covers the interesting resonances of the cymbal which is usually less than 1 kHz for medium to large ride and crash cymbals.

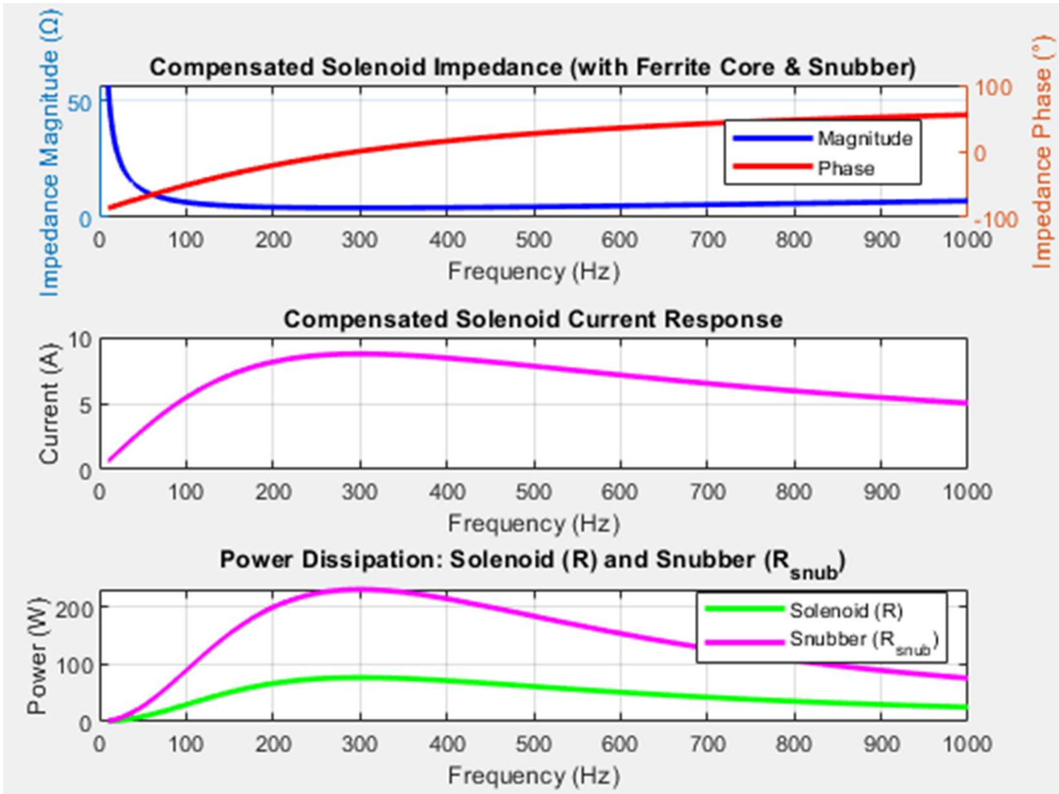

Figure 7. Compensated Response
R_comp = 3 Ohms; f_0 = 300 Hz; C = 1/(L*omega0^2)

When a capacitor C and a resistor R_{comp} (the damping resistor) are added in series with the solenoid, the overall series impedance becomes:

$$Z_{\text{comp}}(\omega) = \left(R + R_{\text{comp}}\right) + \mathrm{j}\left(\omega L - \frac{1}{\omega C}\right).$$

$$\left|Z_{\text{comp}}(\omega)\right| = \sqrt{\left(R + R_{\text{comp}}\right)^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}.$$

At resonance, the inductive and capacitive reactances cancel:

$$\omega L = \frac{1}{\omega C}$$

Solving for the resonant angular frequency:

$$\omega_0 = \frac{1}{\sqrt{L\,C}}$$

which in Hertz becomes:

$$f_0 = \frac{1}{2\pi\sqrt{L\,C}}.$$

The quality factor (or Q) of the circuit is defined as:

$$Q = \frac{\omega_0 L}{R + R_{\text{comp}}}.$$

Comment on the Q factor.

If the circuit is driven by an applied voltage V_s, the current through the solenoid is given by Ohm's law in the frequency domain:

$$I(\omega) = \frac{V_s}{Z_{\text{comp}}(\omega)}.$$

Substituting the expression for $Z_{\text{comp}}(\omega)$, we have:

$$I(\omega) = \frac{V_s}{(R + R_{\text{comp}}) + j\left(\omega L - \frac{1}{\omega C}\right)}.$$

The magnitude of the current is:

$$|I(\omega)| = \frac{|V_s|}{\sqrt{(R + R_{\text{comp}})^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}}.$$

This expression shows how the current varies with frequency and depends on both the resistive losses and the net reactive impedance.

Power dissipated in the solenoid (internal) resistor:

$$P_{\text{sol}}(\omega) = |I(\omega)|^2 R = \frac{|V_s|^2 R}{|Z_{\text{comp}}(\omega)|^2}$$

Power dissipated in the compensation resistor:

$$P_{\text{comp}}(\omega) = |I(\omega)|^2 R_{\text{comp}} = \frac{|V_s|^2 R_{\text{comp}}}{|Z_{\text{comp}}(\omega)|^2}$$

where

$$|Z_{\text{comp}}(\omega)| = \sqrt{(R + R_{\text{comp}})^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}.$$

4.4 Electromagnet Design Intuition

Now that we've discussed the field generated by electromagnets and their electrodynamics, we're in a position to consider optimum electromagnet design. The optimal design depends on whether the electromagnet is to be used as a linear force or torque actuator.

4.4.1 EMs For Linear Force Actuators

Figure 5 **Plot dB/dz versus R/L here for force actuators**

Need to discuss electrodynamics: inductance, current, wire gauge, turns, etc

4.4.2 EMs for Torque Actuators

Figure 4 shows that

- Long, thin coils ($\alpha \ll 1$) concentrate field *right at* the opening but it collapses very rapidly outside.
- Shorter, fatter coils ($\alpha \sim 0.5$–1) produce a stronger *B* field at practical stand-off distances (fixed *u*), and the field extends further out along the axis.

Need to discuss electrodynamics: inductance, current, wire gauge, turns, etc. Having discussed the electrodynamics of an EM actuator, we're in a position to intuitively think about one and intuit an optimal design for our application. We've seen that there are two ways to use a solenoid as an actuator. One method applies a force to a magnetic dipole (permanent magnet) along the axis of the solenoid; the other method applies a torque on the magnetic dipole according to the right-hand rule. We focus on the latter technique because it avoids interference when the vibration amplitude becomes large. In the first method, force is proportional to the magnetic field gradient; in the second method, force is proportional to the magnetic field magnitude. There are solenoid designs that will produce large fields just outside the electromagnet rather than inside the electromagnet. In general, short solenoids will tend to produce stronger fields outside the solenoid core; whereas, long coils will produce strong fields inside its core. Magnetic field strength is primarily dependent on the solenoid's inductance which is dependent on the square of the number of turns of wire around the core of the solenoid. The material of the core also effects the magnetic field magnitude because some materials are more permeable than others. Permeability tends to depend on excitation frequency. Air is much less permeable than iron, but an iron core tends to be sluggish and weakly permeable at frequencies above a few hundred Hertz, so we choose ferrite for our solenoid cores. A solenoid as actuator throws magnetic field lines out of its core to immerse a small permanent magnet 3 to 5 mm away (epoxied to the cymbal) from one of the solenoid's ends before the lines of force wrap around to the other end of the solenoid. The core should be as wide as the width of the permanent magnet. We'd like as many current carrying wire-turns as close to the magnet as possible which suggests that the solenoid should be wide but not wide enough to "spread" apart the lines of force too quickly (this is how to produce strong gradients for force actuation). Our goal is to set up a strong uniform magnetic field over the magnet, so a solenoid that is as long as it is wide should be optimal for torque actuation.

Holding electromagnets should be large enough in diameter compared to the diameter of the permanent magnet to avoid the fringing fields on the outer perimeter from interacting with the permanent magnet that should only interact with the inner fields around the center of the holding electromagnet.

5 ELECTROMAGNETICALLY PREPARED CYMBALS AND GONGS

Finally, we come to a discussion on how the actuators discussed above can be utilized to vibrate metal percussion instruments like cymbals and gongs…

6 REFERENCES

[1] S. Backer, "ElectroMagnetically-Prepared Piano," [Online]. Available: https://ccrma.stanford.edu/~sbacker/empp/. [Accessed 2026].

[2] Edgar Berdahl, Steven Backer and Julius O. Smith III, "If I Had a Hammer: Design and Theory of an Electromagnetically-Prepared Piano," in *International Computer Music Conference (ICMC)*, Barcelona, Spain, 2005.

[3] A. McPherson, "The Magnetic Resonator Piano: Electronic Augmentation of an Acoustic Grand Piano," *Journal of New Music Research,* vol. 39, no. 3, pp. 189-202, 2010.

[4] "Magnetic Resonator Piano," Augmented Instruments Laboratory, [Online]. Available: https://instrumentslab.org/research/mrp.html. [Accessed 2026].

[5] N. Cameron Britt, Jeff Snyder, Andrew McPherson, "The EMvibe: An Electromagnetically Actuated Vibraphone," in *NIME*, University of Michigan, Ann Arbor, 2012.

[6] "Magnetic Finder," K&J Magnetics, [Online]. Available: https://www.kjmagnetics.com/magnet-finder.asp. [Accessed 2026].

[7] "Ferrite Shapes Core Supplier," Magnetics, [Online]. Available: https://www.mag-inc.com/products/ferrite-cores/ferrite-shapes. [Accessed 2026].

[8] D. Jiles, Introduction to Magnetism and Magnetic Materials, 3rd. ed., CRC Press, 2016.

[9] O. Thomas, C. Touze, E. Luminais, "Non-linear vibrations of free-edge thin spherical shells: Experiments on a 1:1:2 internal resonance," *Nonlinear Dyn,* vol. 49, pp. 259-284, 2007.

[10] "Round Electromagnets," APW Company, [Online]. Available: https://apwcompany.com/round-electromagnets/. [Accessed 2026].

[11] D. J. Griffiths, Introduction to Electrodynamics, 2nd. ed., Prentice Hall, 1989.

[12] "Multilayer coil inductance calculator," Coil64, [Online]. Available: https://coil32.net/online-calculators/multilayer-coil-calculator.html. [Accessed 2026].

[13] "Multi layer air core inductor calculator," [Online]. Available: https://www.circuits.dk/calculator_multi_layer_aircore.htm. [Accessed 2026].

[14] B. Zhang, "Electromagnet Design Considerations".

[15] A. McPherson, "Techniques and Circuits for Electromagnetic Instrument," in *New Interfaces for Musical Expression (NIME)*, University of Michigan, Ann Arbor, 2012.

[16] A. McPherson, "Magnetic Resonator Piano," [Online]. Available: https://instrumentslab.org/research/mrp.html. [Accessed 2026].

[17] E. Berdahl, "Edgar Berdahl's Music Technology Page," [Online]. Available: https://cct.lsu.edu/~eberdahl/. [Accessed 2026].

[18] Olivier Thomas, Cyril Touzé, Antoine Chaigne, "Asymmetric non-linear forced vibrations of free-edge circular plates. Part II: Experiments," *Journal of Sound and Vibration,* vol. 265, no. 5, pp. 1075-1101, 2003.