EMCymbal: the electromagnetically prepared cymbal

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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 two passages from scripture suggest that we learn a different way to play the gong or the cymbal. This paper describes my attempt to learn a new way. It's been a labor of love spanning over 20 years.

In any introductory Electricity and Magnetism text, one can always find a discussion of how magnetic fields do no work juxtaposed with an image of a massive crane lifting a pile of steel trash. With that wisdom in mind, this paper will describe an electromagnetic actuator that produces oscillating magnetic fields and field gradients to force a small permanent magnet attached to a mechanical object to vibrate, thus vibrating the object. We will apply such an actuator to vibrate various bronze and other metal percussion instruments such as cymbals, gongs and sheets. A system for setting up self-sustained oscillation with a cymbal as resonator will be discussed as well as some of the rich dynamics of a cymbal. Another tendency of E&M texts is to refer to a cylindrical coil of wire (possibly wrapped around a permeable material like soft iron) as a "solenoid", but in the vernacular a "solenoid" is understood to refer to a mechanical electromagnetic device that pushes, pulls, or turns an armature to actuate some other mechanical device like a door latch or fluid valve. This paper will refer to "solenoid" in the first sense.

In the following two sections we'll investigate the solenoid as a non-contact force actuator, then as a lumped component in driven resonant electromechanical circuit. Figure 1 and Figure 2 show two solenoid/magnet arrangements considered for this study.

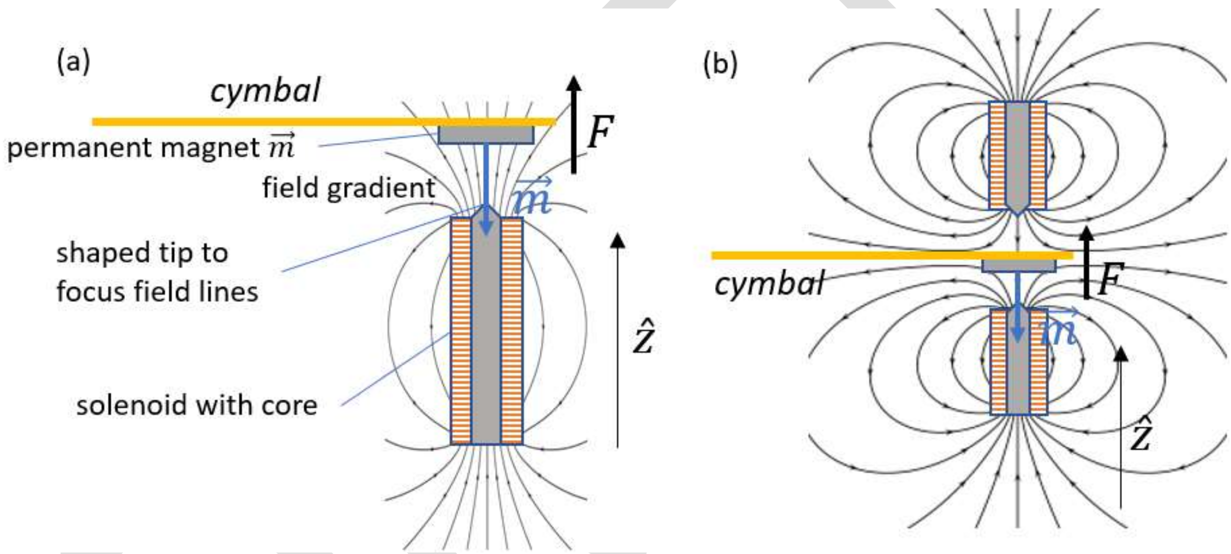


Figure 1. Gradient force arrangement
Two arrangements for using a field gradient to produce force on a permanent magnet with dipole moment $\vec{m}$. (a) gradient produced by a single solenoid, (b) a strong gradient produced by two opposing solenoids.

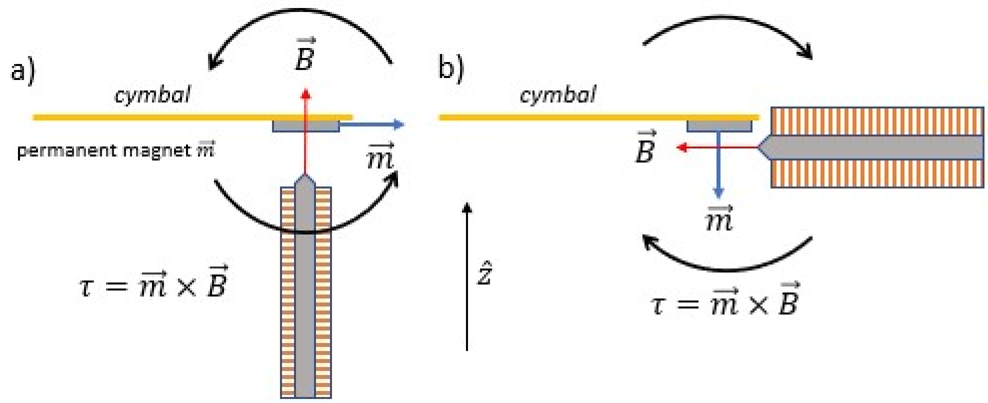


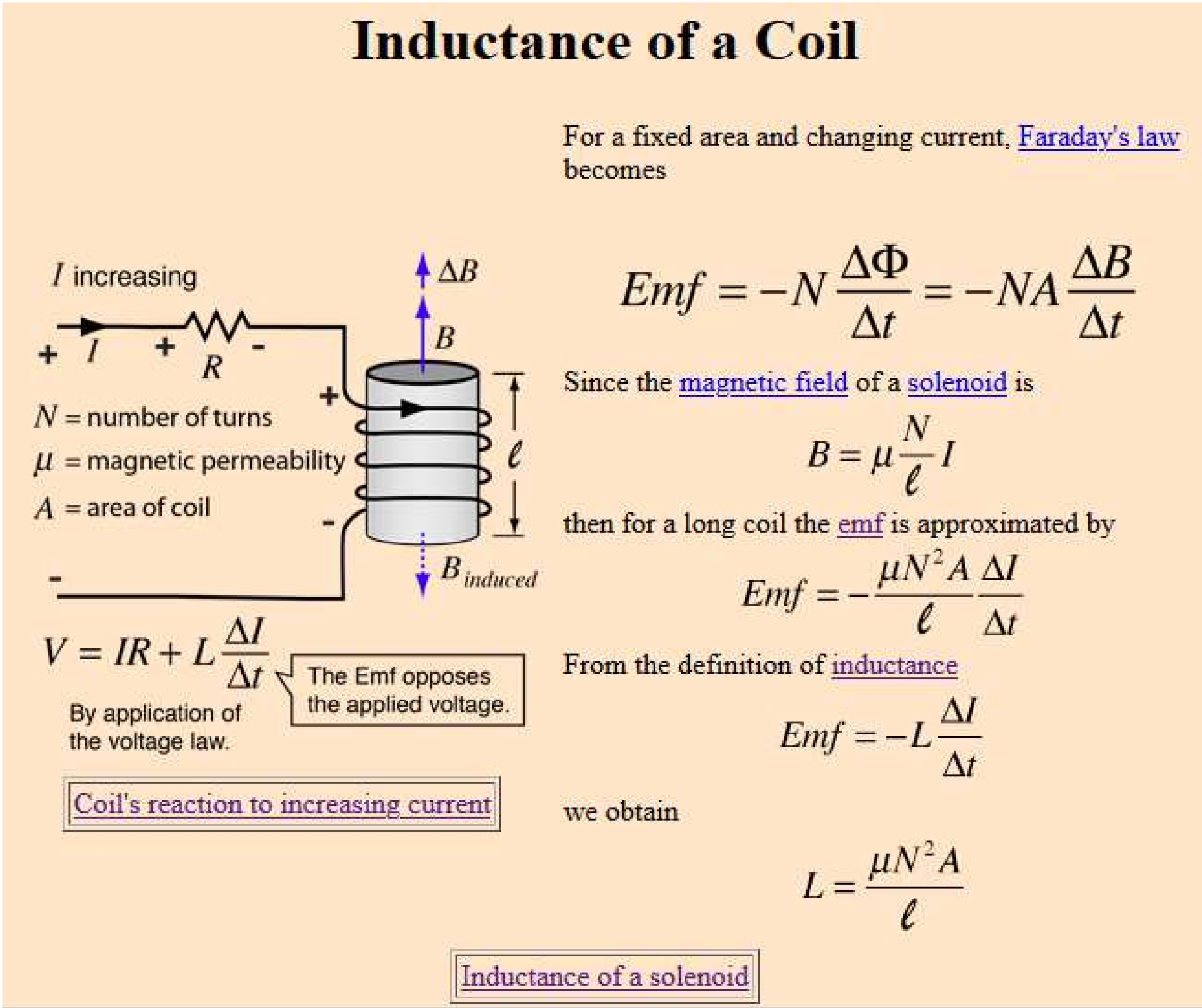
Figure 2. Torque arrangement
Two arrangements for actuating a permanent magnet using the torque produced by the cross product of the magnetic moment and the magnetic field. (a) will limit the mechanical oscillation amplitude as does the arrangement in Figure 1

Figure 2(a) will limit the mechanical oscillation amplitude as does the arrangement in Figure 1; however, the situation is worse in Figure 1 because in that arrangement if the magnet swings close enough to the solenoid armature, the two will stick together, thus kill actuation; whereas, in Figure 2(a) the two aren't attracted to each strongly since the magnetic moment points perpendicular to the solenoid armature.

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. 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.

2 SOLENOID AS A LUMPED INDUCTOR

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.



Inductance of a Coil

For a fixed area and changing current, Faraday's law becomes

$$Emf = -N\frac{\Delta\Phi}{\Delta t} = -NA\frac{\Delta B}{\Delta t}$$

Since the magnetic field of a solenoid is

$$B = \mu\frac{N}{\ell}I$$

then for a long coil the emf is approximated by

$$Emf = -\frac{\mu N^2 A}{\ell}\frac{\Delta I}{\Delta t}$$

From the definition of inductance

$$Emf = -L\frac{\Delta I}{\Delta t}$$

we obtain

$$L = \frac{\mu N^2 A}{\ell}$$

2.1 ELECTRICAL DRIVEN SOLENOID ACTUATOR

In this section we will discuss the physics of driving a solenoid with an audio signal. We want to know the requirements of the circuit that drives the solenoid, and we will want to know the bandwidth or range of frequencies over which the two together will generate appreciable force or torque. We will discuss the use of an audio amplifier for driving a solenoid.

2.2 TEMPORAL RESPONSE

We need the actuator to keep up with our drive.

$$V(t) = I(t)R + L\frac{dI(t)}{dt}$$

Let $V(t) = V_o \sin(2\pi f t)$, where f is the drive frequency and V_o is the amplitude, we get

$$V_o \sin(2\pi f t) = I(t)R + L\frac{dI(t)}{dt}$$

A solution to this is to assume the current take the form $I(t) = I_o \sin(2\pi f + \phi)$, so that

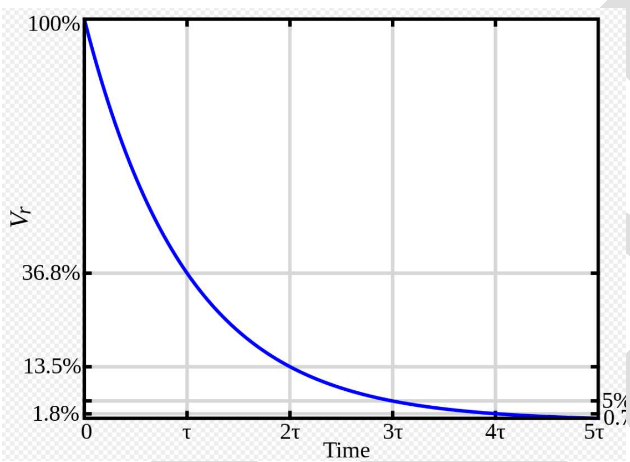
$$V_o \sin(2\pi f t) = I_o \sin(2\pi f t + \phi) + 2\pi L \cdot cos(2\pi f t + \phi)$$

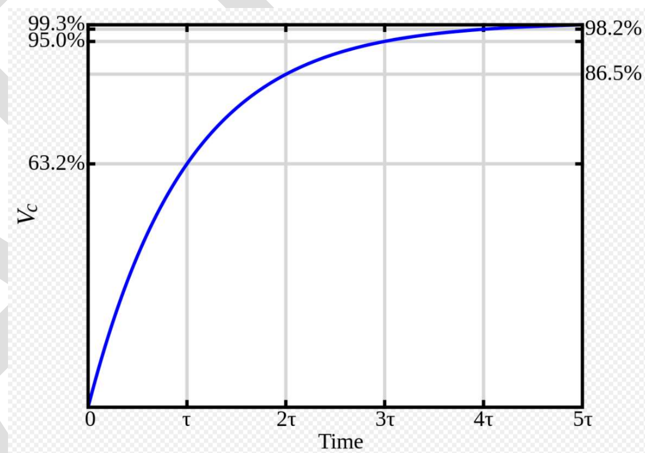
Where ϕ is a phase shift introduced in the solenoid.

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. The EMF tends to oppose any change in field flux, and therefore, any change in the applied voltage through Eq. xx. Work is required to "fight" EMF to produce a fluctuation in the magnetic field, and work is proportional to inductance L.

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.

Differential equation. Importance of time constant < 1/driving frequency, e.g., 1/1000 Hz = 1 msec. Need L/R = 0.001.





fjfjfjfjf

2.3 Spectral Response

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.

What is the power in the inductor?

3 Electromagnetic Actuator

We are going to use an electromagnet as an actuator. To actuate a small permanent magnet attached to the cymbal. We want to know how to design the actuator. How do the dimensions of the electromagnet determine its ability to actuate? We can get an idea of the field generated by a finite solenoid by looking at the field generated by a single loop of current or even better yet the field generated by a finite single layer coil.

The DC field generated by a finite solenoid of finite length [1] and without a core is given by

$$\mathrm{B}_z(R, \mathrm{z}) = \frac{\mu_0 NI}{2}\left[\frac{L/2 - z}{L\sqrt{R^2 + (L/2 - z)^2}} + \frac{L/2 + z}{L\sqrt{R^2 + (L/2 + z)^2}}\right]$$

where N, I, L, R and z are the number of turns, (DC) current, length and radius of the solenoid, and distance away from one of the solenoid's ends.

A non-contact force actuator can be arranged by attaching a small (so as not to affect the dynamics of the cymbal; mass magnet << mass cymbal) permanent magnet to the cymbal and bringing one end of a finite solenoid close to the permanent magnet. The force on a permanent magnet is proportional to the gradient in the magnetic field.

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

$$m = \frac{B_r V}{\mu_o}$$

The approximation improves with distance from the disc, i.e., in the far field. Up close the approximation fails. Since we need a gap of at least 5 mm between the disc and the solenoid to allow the cymbal to flex up and down, we are operating somewhere in between up close and the far-field.

3.1 Gradient Force

The setup in Figure 1a was employed by a different group for electromagnetically actuating vibraphone keys [2]. One nice feature of the first method is that it can be applied anywhere on the radius of the cymbal and not just at the edge, so as to excite both radial and circumferential modes. However, the working distance weakens the interaction between magnet and solenoid and results in weaker actuation.

The force on a magnetic dipole with dipole moment $\mathbf{m}$ in a field $\mathbf{B}$ [3] is

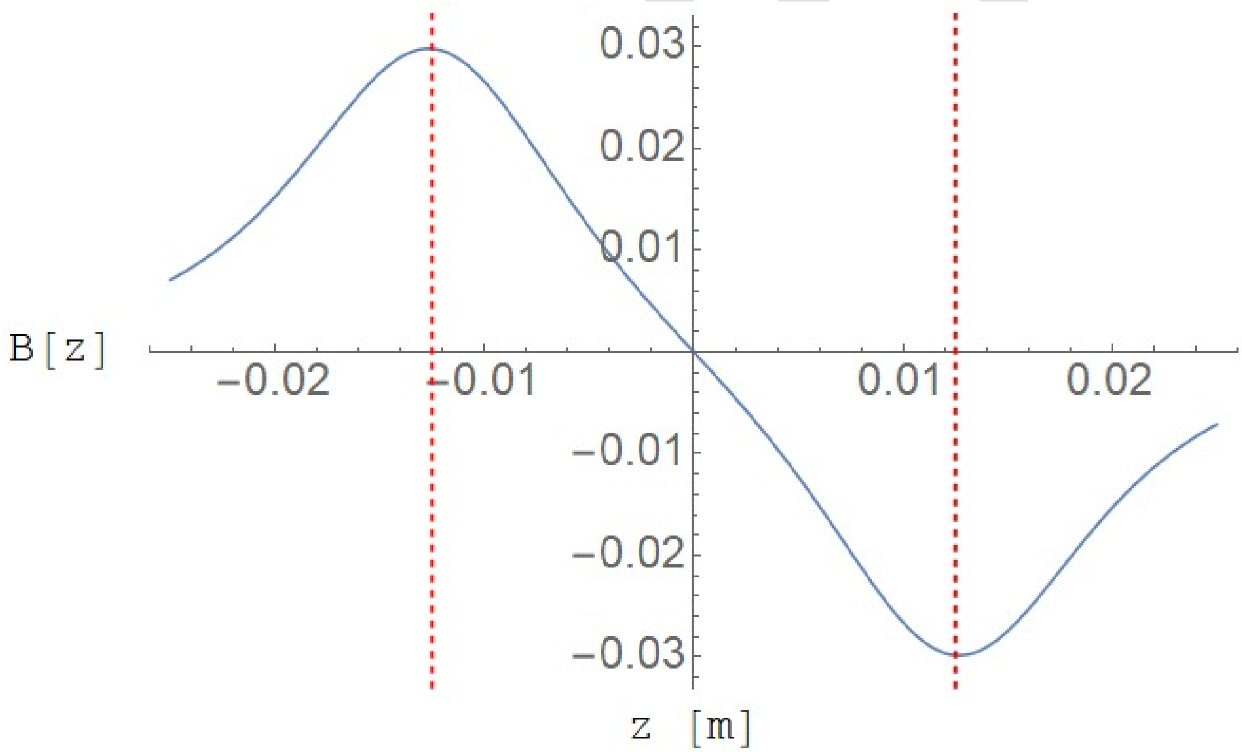
$$\mathbf{F} = \boldsymbol{\nabla}(\mathbf{m} \cdot \mathbf{B}) = (\mathbf{m} \cdot \boldsymbol{\nabla})\mathbf{B}$$

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

$$\boldsymbol{F_z} = m_z \frac{\partial B_z}{\partial z} \hat{\boldsymbol{z}}$$

where m_z is the z component of the disc magnetic moment. 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. 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 as possible. In general, larger magnets have larger values of m, but we mustn't add any more mass to the cymbal as is required to actuate the cymbal.

In general, 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.



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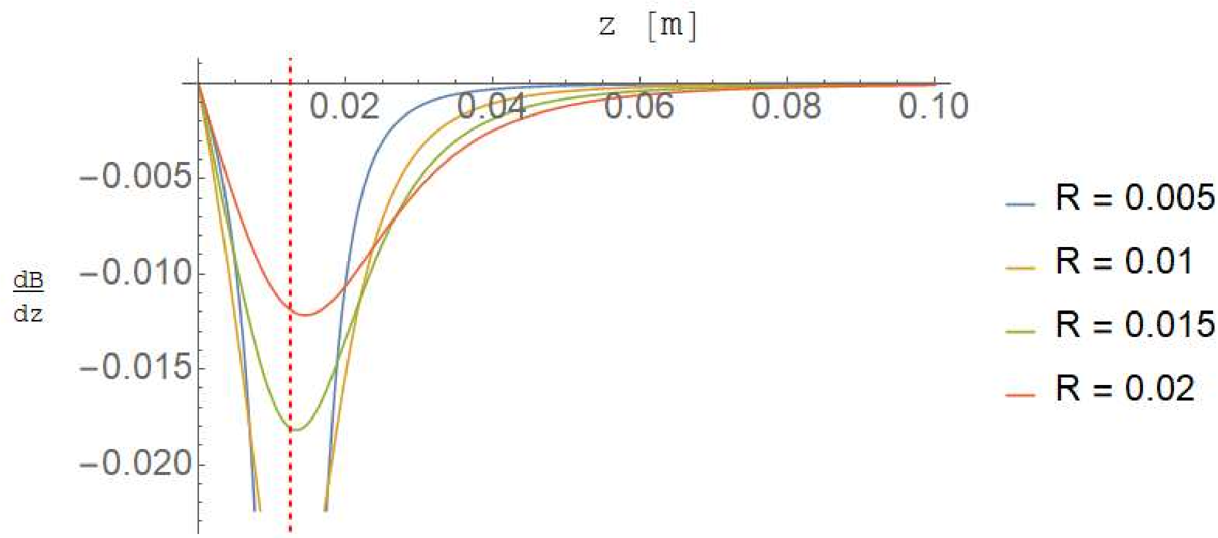


This figure shows that a solenoid with a large radius (compared with its length L) produces a gradient that is smaller than the gradient produced by a solenoid with a small radius.

Need plots in R/L.

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 $\mu N^2 A/\ell$. 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

The setup in Figure 1b produced the best results for actuating cymbals, gongs and sheets. It has three advantages over Method 1: firstly, the electromagnet can be positioned very closely to permanent magnet since in that orientation the attractive force between the permanent magnet and the solenoid core is small, and such close proximity makes for large torque, and thirdly because the solenoid in the horizontal orientation doesn't mechanically limit or impede the cymbal during large amplitude swings. A vertical oriented solenoid limits cymbal travel mechanically and adds a persistent DC magnetic force between the cymbal and solenoid in the direction of the solenoid core. These effects become worse as the gap between the two pieces becomes smaller. It must be said that the geometry of the situation will dictate which of the two methods is the most practical; for instance, the authors of [2] 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 radial modes.

The torque on a magnetic dipole is

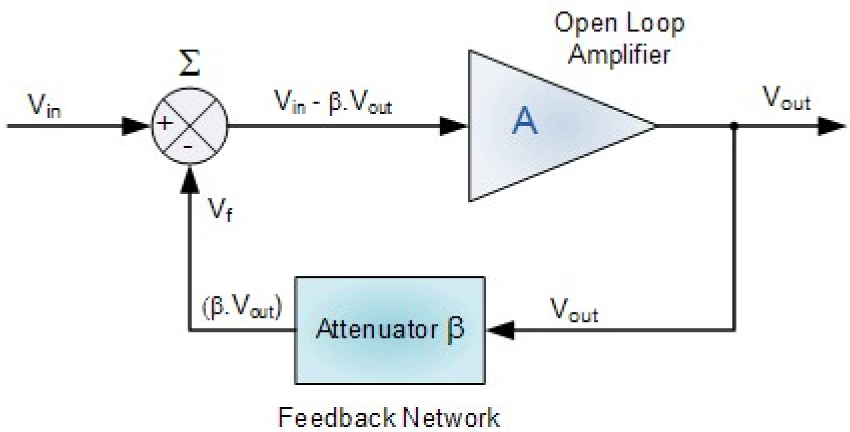
$$\vec{\tau} = \vec{m} \times \vec{B}$$

This is illustrated in Figure 1b. Torque on the magnetic dipole reverses direction as the magnetic field reverses its direction.

$$\vec{\tau} = E\overrightarrow{m} \times \overrightarrow{B}ronze$$
$$Ensemble$$

4 Feedback Oscillator

Describe the "feedback oscillator". We're going to insert a force actuator into a positive feedback loop as shown below. We can combine the rich nonlinear dynamics of a cymbal and some electronics to form a closed loop to set up self-sustaining resonances in the cymbal. The system is shown below in Figure xx.



Inside the loop we have a programmable delay for controlling the resonant frequency of the circuit (including the cymbal resonator) and an auto-gain control for maintaining stable oscillation and to prevent the oscillation amplitude from growing out of control.

5 Dynamics of a Cymbal

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.

Map the dynamics of the cymbal (like solitons). Discuss the nonlinear dynamics of a cymbal. Period doubling route to chaos. Duffing eq. The goal of this project is identify parameters of the loop like delay and gain so as to operate a particular point in the phase space of the cymbal resonator. Self-sustaining resonance. Choose parameters to visit/explore the regions of phase space (amplitude versus frequency).

Warbling, flutter, chime, splash, washing, seashore lapping,

6 Tuning and Timbre

Timbre is determined by the location and strengths of resonant frequencies. Map the resonances of each cymbal and compare the spectra. Sweep a tone generator or excite the cymbal with white noise and calculation DFT. Look where the resonances overlap; look for consonant intervals, e.g. octaves, fifths, etc. Arrange on a MIDI keyboard. Play.

7 Bio

Matthew O'Donnell grew up and lives in Los Angeles with wife and daughter and works as a Research Scientist in the aerospace industry. Starting from the age of sixteen when he bought is his first drum kit, Matthew played drums in various garage bands until about the age of thirty when he became aware of experimental music and sound art by listening to late night college radio. Matthew became disillusioned with playing drums conventionally and started to experiment with vibrating his drums and cymbals at their resonances. His first approach was to use bare speakers to excite drum heads or to attach the voice coil of a speaker freed from its cone directly to a cymbal. Matthew got involved in the thriving experimental music scene in Los Angeles in the early 2000's and performed his new electro-acoustic instrument around town. Matthew truly appreciates the patience that most of his audience exercised in these early days. Since then, he’s been perfecting a contactless technique using electromagnets.

8 CONCLUSION

The smallest magnet that “does the job” should be selected.

9 REFERENCES

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

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

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