# A STUDY INTO THE FUNDAMENTALS AND ENHANCEMENTS OF SOLENOID BASED ACCELERATORS

by

William Poole

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Advisory Committee:

David Kotecki, Associate Professor

Nuri Emanetoglu, Associate Professor

Donald Hummels, Professor

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ABSTRACT

Initial research into coilgun projects determined that they have a common issue of low efficiency and design complexity. This research aims to cover the topics of solenoid applications, magnetic fields, wires properties, and more for specific task optimization. There are many factors that come into the design and operation of solenoids which make them complicated to utilize effectively. These points will be combined for the overall system aspects dependent on application. These applications can be steady state for solenoid valves, high force for coil guns, and response time for chemistry applications. Coilguns have been studied for their unique ability to accelerate an object without adding weight or manipulating their design to allow for launches by alternative means. This advantage is purposely exploited for either a satellite launcher or another projectile accelerator. To get this data and review its interpretation my Honor’s Thesis committee shall be utilized. To prove some of this data, the ECE capstone project coilgun will use these concepts to enhance its optimization.

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An acknowledgments page is optional but recommended. This is a place to thank anyone who helped you and your project get where you are. Like with the dedication page, include a lowercase Roman numeral page number, with page numbering starting on the title page.

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List of Definitions

|  |  |
| --- | --- |
| Current |  |
| Efficiency |  |
| Projectile |  |
|  |  |
|  |  |
|  |  |

### Equations

ω=Angular frequency [Radians]

L=Inductance [Henrys]

L=μAN2/L [H/m \* m^2 / m]

N=#of turns [unitless]

ZL=jωL

TL=L/R

[1] V=L\*di/dt

[2] F=q V x B

[3] H=I\*N/m

[4]

[5]

[6] F=qE + q V x B

[7] m=n^NIA

[8] T=m x B

[9] F=∇ (m . B)

# Introduction

A coil gun is a complex device that has many aspects which can be varied for specific applications. The following is a theoretical and experimental insight into many of these variables and how to utilize them in understanding these devices. These variables can be combined into the following groups, Electromagnetic Principle, Technologies, System design, and Losses. These groups explain the function and method of any coil gun operation. With these aspects of a coil gun theory the application can be optimized.

# History

This technology is quite old starting in the early 1900’s with a patent by a Norwegian scientist in 1904 being one of the earliest documents [3]. Past this earlier variant it has fallen into 2 main categories projectile or vehicle acceleration. Projectile acceleration is the gun designed to throw a projectile with the intent to have it destroy something, usually military. An example of this is the Darpa project to enhance mortar systems by replacing propellant weight and increasing distance [1]. Whereas the alternative is something that accelerates a container to deploy something at a distance. One of the vehicle launchers was the NASA super-cooled coil gun or quench gun project for launching liquid oxygen off of the moon for use in spaceships [2]. Allowing this technology to be used for new purposes whenever an object needs to be thrown.

# Research

## Electromagnetics

To start the discussion on coil guns their operational principles must be established. The first of which is what generates the force in a coil gun, then how that system is manipulated in order to facilitate the usage. After which will be a discourse into problematic effects of these devices and what can be done to mitigate their losses.

#### Electromagnetic Principles

The coil gun relies upon electromagnetic fields and ferromagnetic materials to generate force. This type of force is called the *Lorentz Force* which can broken down to *Magnetic Force*. This is the equation 2 where a moving charge [q] with velocity vector [V] is multiplied with a perpendicular vector of magnetic flux density [B].

##### B and H fields

The fields that magnets emit are known as magnetic fields but are broken down into two fields, B and H fields which measure magnetic flux density and magnetic field intensity. B-fields’ SI unit is that of a Tesla (T) which has a definition of N/(C\*m/s) which allows it to translate it between a charge to a force [**BOOK**]. H-fields’ SI unit is that of A/m or Am/m2 as it is based off the current through a length conductor with a surface profile area, however this field is not used in the force calculation directly. These two fields are related to each other and are used with the Biot-Savart Law to get these fields. These equations are [4] and [5] given earlier in the equations section.

##### Force Calculation

To get a model B-field a lot must be considered in advance such as the current through the solenoid [I], wire properties such as spacing diameter, number of turns [N], and number of layers. For that a solenoid properties document was Smade and was used to estimate a best option early on which was 16awg wire at 30amps, the number of turns can easily be adjusted so it matters less but it was 200 turns at 5 layers. However to get force another magnetic property is needed, which is magnetic moment units of A/m^2 which indicates current flow around an area of a material. This gives us a charge and its velocity which is utilized to calculate the force generated by the certain solenoid design, when incorporated with armature parameters.

### Circuits

To start the discussion of circuit design an iteration is shown going from an ideal circuit to what is an accurate model of an existing device showcasing parasitics and compensation devices.

#### Ideal Circuit

A diagram of a control system

Description automatically generated

Figure 1: Ideal Circuit layout

The above circuit showcases how an ideal circuit for solenoid will look. The major feature of this circuit is infinitely fast switching, zero resistance, zero capacitance, perfect DC source, and the ideal inductor.

A diagram with a red line

Description automatically generated

Figure 2: Ideal Circuit Inductor Current Response

The figure above showcases the current flowing through the inductor or what is the solenoid. This current would theoretically approach infinity as the impedance of an inductor approaches zero as the frequency of the input voltage decreases. The reason it does not reach infinite current in the signal time, is that the frequency experienced by the inductor does not last long enough.

A green line with blue text

Description automatically generated

Figure 3: Ideal Circuit Supply Node Response

The above figure highlights something unique to this design, a stable supply voltage. This will be important as fluctuations in voltage have influences on inductors and capacitors. Another issue is that DC sources struggle handling transients resulting in transients.

A graph with a line

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Figure 4: Ideal Circuit Inductor Voltage Drop

The figure showcases what happens with an infinitely fast switch and an inductor. As when the current through the inductor is interrupted instantly it causes an extreme voltage surge due to the relation of inductors showcased in equation [1]. Since the equation has the derivative of current and the switch causes an infinitely fast cutoff there is a near infinite negative voltage surge.

#### Realistic Circuit

A diagram of a pulse

Description automatically generated

Figure 5: Realistic Circuit-Resistances

The circuit above showcases the first step towards realism of a solenoid circuit. The step being the added wire resistances these begin have large effects on the circuit operation due to its limits on the current

A graph showing a line

Description automatically generated with medium confidence

Figure 6: Realistic Circuit-Resistances Inductor Current Response

This rate change is due to the resistance limiting current through the inductor, this **becomes a charging circuit with a limit defined my time constants later explained in electromagnetic principles.**

A green line graph with blue text

Description automatically generated

Figure 7: Realistic Circuit-Resistances Supply Node Response

The figure above showcases the small voltage dip at the supply node from the voltage drop of the “incoming” resistor the slope of which is correlated the inductor current response shown in FIGURE [6].

A diagram of a diagram

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Figure 8: Realistic Circuit-Resistances Inductor Voltage Response

The figure above still showcases the inductor has the massive transient due to high speed turn-off.

#### Realistic Circuit Capacitance

A diagram of a circuit

Description automatically generated

Figure 9: Realistic Circuit with Resistance and Capacitance

The added capacitor is a model of the capacitance generated by all the wires near each other in a solenoid. This capacitance {L3\_C} adds a Voltage dip at 2mS where the switch closes. This is due to the capacitor shorting the power around the inductor, but, the dip is limited by the transition time of the switch. This is due to the switch causing an AC state where the current fluctuates which capacitors short to. However, since this switch is instant the drop is limited.

A diagram of a graph

Description automatically generated

Figure 10: Realistic Circuit-Capacitance Inductor Current Response

The figure above shows the first case of LC oscillation, in which the inductor discharging feeds back through the parallel capacitance resulting in AC signal. This causes a couple issues especially with the force output the coil gun.

A green line graph with blue text

Description automatically generated

Figure 11: Realistic Circuit- Capacitance Supply Node Response

The above figure shows that the parallel capacitor shorts the supply node which causes a large voltage drop on the supply node. This is synonymous with “inrush current” as it is a large instantaneous current draw.

A diagram of a graph

Description automatically generated with medium confidence

Figure 12: Realistic Circuit-Capacitance Inductor Voltage Response

The figure above showcases 2 major details the on transient and the off transient or AC signal. The on transient showcases the large voltage drop is not surging across the inductor rather it is in parallel with the capacitor short which results in the voltage drop being across the resistances Incoming, L3\_C\_r, and Outgoing. Also the oscillation in the inductors current response in **Figure 10** comes into effect with the voltage at that node.

#### Realistic Circuit Switch

A diagram of a circuit

Description automatically generated

Figure 13: Realistic Circuit with Power MOSFET

This switch is an NMOS HEXFET which has many parasitics which causes feedback issues at the transition times of the switch. This will be mostly beneficial as it tries to fight the existing LC oscillator of the inductor.

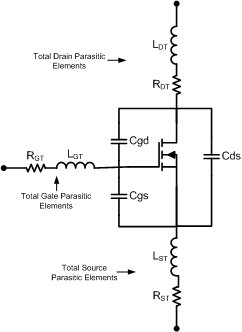


Figure 14: MOSFET Parasitics ***Add reference***

A graph of a graph

Description automatically generated with medium confidenceFigure 15: Realistic Circuit-Switch Inductor Current Response

The figure above showcases that the large current oscillation of the parallel capacitance is mitigated however it is not eliminated as it resumes at a lower power.

A green line graph with blue text

Description automatically generated

Figure 16: Realistic Circuit-Switch Supply Node Response

The figure above showcases the major transient at turn on, capacitor short, and another at cutoff inductor voltage surge, then a new one a delay to the resumed supply voltage. However, a major note is that the capacitor voltage dip has significantly decreased going from ~40V to ~58V. The middle voltage value before 4mS is still roughly the same. However the response after is different, this is caused by the LC oscillation of the inductor being disturbed significantly. As showcased when comparing **figures 15 to 10** the oscillation is disturbed greatly.

A diagram of a graph

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Figure 17: Realistic Circuit-Switch Inductor Voltage Response

The above figure showcases a very interesting response. As the signal turns on these is a large voltage across the inductor from allowing a positive derivative of current through it as it approaches DC. But as this voltage grows more positive it begins to charge the nearby capacitors causing a voltage drop across the inductor. Also at turnoff the large voltage transient of the inductor still persists but it is mitigated from reaching large voltages by the capacitor on the switch chocking it out and slowing the derivative by its turn off time.

#### Realistic Circuit Diodes

A diagram of a circuit

Description automatically generated

Figure 18: Realistic Circuit with Flyback Diode

The above circuit is a realistic circuit with a flyback diode this device is commonly used to discharge the inductor by having it not charge through the capacitor and oscillate out. However, with the values currently used, the voltage drop is solved but the current through the inductor suffers slightly.

A graph with a red line

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Figure 19: Realistic Circuit-Diode Inductor Current Response

The current here has a longer release time this likely due to the diode’s junction capacitance coming into effect and some principle of RLC circuitry being snubbed by the diode. **What is known is that this current is not ideal as it is likely causing a pulling force after to projectile gets through the halfway.**

**A green line graph with blue text

Description automatically generated**

Figure 20: Realistic Circuit-Diode Supply Node Response

With the diode the voltage resuming to nominal supply levels is faster but still has a small buffer after getting close to the supply voltage. This is due to the diode turning off due to little voltage driving it.

A graph showing a line

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Figure 21: Realistic Circuit-Diode Inductor Voltage Response

The diode helped here by mitigating the current ringing in figure **19** which also speeds up the flyback voltage release of the inductor.

Another Diode is added to prevent something I call backdraft, as the solenoid turns off it generates a voltage pulling current through the MOSFET which harms the nature of device operation. To mitigate this a backdraft diode is used.

A diagram of a circuit

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Figure 22: Realistic Circuit-Backdraft

A graph showing a curve

Description automatically generated with medium confidence

Figure 22: Realistic Circuit-Backdraft Inductor Current Response

The current peak is choked here from ~75amps to ~45amps however the turn off response is narrower.

A green line graph with white text

Description automatically generated

Figure 23: Realistic Circuit-Backdraft Supply Node Response

The supply node voltage resumes instantly and is stable immediately after turn off. This works by the high voltage from flyback allowing the current to loop around in the inductor without interfering with the MOSFET parasitics, or its protective diode.

A graph showing a curve

Description automatically generated

Figure 24: Realistic Circuit-Backdraft Inductor Voltage Response

The figure above also indicates that the voltage across the inductor plummets this helps with power demand of the inductor and could be used in multiple aspects such as power draw and overheating.

# Applications and Manipulations

This section covers solenoid use cases, common variable of solenoid design, and what each manipulation will cause to a system. This will lend to considerations overall, but using this source will require in depth

## Applications

Solenoids are typically used in systems with short linear travels. These could be, applications such as electronic locks, air or hydraulic valves, package sorters, and more. Some other use cases involve [oscillating motions](https://www.electricity-magnetism.org/ac-solenoid/), [latching circuits](FromanYigal1975.pdf), [high force applications](High%20Velocity%20Electromagnetic%20Punch%20Presses%20-%20WinSet%20Technologies.pdf), or [coilguns](19900012490.pdf). Furthermore all of these applications have various manipulations due to system parameters. With concepts of some [Startrams or space launchers](PR_83.pdf) or [nano-satellite lauchers](5039.pdf) being created to help mitigate fuel costs or trying to optimize power loading. So, those above are designs to solve a problem, to continue on must consider concerns of a design once the process has started with research to determine the specifics of a design.

## Weighting of Variables

The specifics of a design are determined by various factors, unique to each project that are factors on what the specifications, allotment, or weight of attributes of a system.

The major consideration for this project was that of research time, as to build a system on-time for capstone limited research to a few months, which did later cause issues with various system functions. Secondly was that of budget as comparable models to the desired test specifications reached above the allotted capstone budget. Furthermore, the scope of project may allow manipulations beyond what is discussed in this document.

However, with the initial research conclusions were made in advance about the dominant factors of solenoid shape, wire size, and overall system demands. Furthermore more advance considerations can be considered like NASA’s concept of [Niobium-Titanium superconductors](19900012490.pdf), Super-large Giga-amp facilities, or flushing the solenoid with high-pressure flourinert to avoid insulation and keep the coils cold as -138°C. to continue on with this the table below showcases what parameters can be fluctuated to better optimize a system.

|  |  |  |
| --- | --- | --- |
| Category | Manipulation | Outcomes |
| Solenoid | Increase number of turns | Force increase, Resistance gain, Inductance gain, influences temperature radiation |
| Solenoid | Increase number of layers | Force increase, Resistance gain, Inductance gain, influences temperature radiation |
| Solenoid | Installed flyback diode | Discharge time reduction |
| Solenoid | Increased inductance | Field creation and destruction delay |
| Wire | Gauge | Resistance decrease, Ampacity increase |
| Wire | Insulation thickness increase | Voltage rating dependency, Inductance loss, Temperature radiation dependency |
| System | Temperature increase | Insulation loss, Ampacity loss, and potential failure |
| System | Power increase | Cost gain, radiating heat necessity, control scheme changes |
| System | Duty-cycle increase | Additional heat capacity, ampacity, control scheme requirements increase |

Table xx: Explanation of system correlations

# Simulations and Explanations

## Force Generation

For coil-guns to generate force there must be an aligned b-field to respective projectile desired to move. The force we are looking at is due to B-fields of the solenoid and the magnetic properties of the projectile. There are other things that come into effect that will reduce this but, the main force comes from the Lorentz Force, equation 6 specifically. The projectile contains moving charge in this system is typically ferromagnetic unpaired electron orbits of a material. Though the projectile could also be another electromagnet.

Of note are the two possible forces there is a radial or linear acceleration. Out of these accelerations the desired one is the linear as it is the one to accelerate the projectile forward. The radial acceleration or Torque is related to the B-field perpendicular to the magnetic moment, equation 7, so the projectile will accelerate radially due to B-field perpendicular normal to the M-field or magnetic moment. Though when the B-field and M-field are co-axial or parallel, the resultant value is going to be energy when integrated across a volume. Energy in an object at this point is potential energy, though since this field is non-uniform, it experiences an acceleration that is proportional to the gradient of the energy.

M-field is measurement of a magnet to document how their energy density fluctuates with different magnetic fields. This is correlated to magnetization and magnetic moment.

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# Appendices

# Author’s Biography