An Analysis of Linear Motors

Ryan Sheldon

Adviser: Leon Cole

Abstract

This project was designed to observe and understand the underlying mechanics and properties of linear motors, unrolled variants of the traditional rotary motor. These motors are commonplace in today's world, but largely go unnoticed unless they are attached to grand design, such as a maglev train. In order to further understand the theory, design, and application of these motors, research was conducted into the physical properties that allow the motors to work, and test models were constructed in order to observe these principles firsthand. Although the motors unfortunately did not function exactly as intended due to technical constraints, a great deal was learned about the theory of the linear motor, as well as electromagnetism in general.

Introduction

This project was initially designed to investigate what factors correspond to pulling speed and power in a linear motor, specifically the linear induction motor variant, although research was done into both the linear induction motor and the linear synchronous motor. The interest in this project stemmed from a lifelong interest in rail transit, specifically the high-speed maglev trains that are currently in use in several countries. The goal was to have a model track set up with a functioning motor that could have its current, voltage, and frequency altered so that different combinations could be tested in order to understand what factors play the biggest role in determining the speed and potential pull force of a linear motor.

In performing primary research on this topic, the applications of linear motors became readily apparent, and actually, they are commonplace in everyday life. Aside from powering maglev trains, linear motors are most notably found in industrial manufacturing machines (for their precision), and roller coaster braking systems. The benefit of using the linear motor as opposed to a rotary motor with an axle is simple: there are no physically moving parts in the motor, and thus the motor itself requires less maintenance.

The decision to use a linear induction motor as opposed to a linear synchronous motor was one borne out of sheer curiosity – linear synchronous motors are simply unrolled three-phase rotary motors, and their use is widespread. Linear induction motors, on the other hand, are less common as a propulsion device, and are mainly found on the high-speed maglev trains as mentioned previously. In addition, the linear induction motor operated on several principles I was familiar with in theory, but the idea of seeing them in action was also quite appealing. Because of this, constructing a small model seemed the best course of action.

Theory

Learning how linear motors work was the first course of action I had to undertake. The principles of the linear synchronous motor are quite apparent, based on knowledge of how a rotary motor works. That is, to say, that three electromagnets are wired 90 degrees out of phase with one another, and the alternating current passing through them will, at various points, be attracted the permanent magnets situated around the stator, causing a rotational motion. Translated into a linear fashion, this is just a matter of physical layout – the passive stator becomes flat and the active rotor containing the three-phase electromagnets is then supported above it (for the remainder of this paper, I will refer to the rotor as the primary, due to its active electronics, and the stator as the secondary). Figure 1 has a visual representation of this translational movement.

Understanding the linear induction motor, however, was a bit more of an undertaking. To achieve this end, I read from a variety of sources, but David J Griffith's *Introduction to Electrodynamics* had the most concise way of describing the electromagnetic forces at work in the linear induction motor. In addition to the most basic concept that an electrical current will induce a magnetic field (Amperé's law), what it ended up being was condensed into were the two components of Faraday's Law of Induction:

1. A time-changing magnetic field will induce an electrical current.
2. An electrical field in the presence of a magnetic field will induce magnetic eddy currents which will repel any motion by the electrical field.

The eddy currents in particular are key to the function of the linear induction motor. With these principles in mind, the function of the linear induction motor becomes clearer. The goal is to use electromagnets that are powered through alternating current (and thus, changing with time) to induce an electrical current in a conductor plate. The current in this conductor plate will then react to the same moving, time-changing magnetic field that induced it, causing magnetic eddy currents to form normal to the surface of the conductor plate (Figure 2). The interaction of the eddy currents with stationary permanent magnets situated along the track is what ultimately drives the motor forward.

Amperé's Law gives us the relationship between the current and the magnetic field generated: $= \frac{\mu_{0I}}{2\pi r}$, where μ_0 is the permittivity of free space, I is the current measured in amperes, and B is the magnetic field strength located at a distance r located normal to the axis of the current-carrying wire. From this, it can be seen that the field strength diminishes with respect to distance, and thus it becomes necessary to keep the components of the motor as close to each other as possible in order to get the most strength from the magnetic field.

Faraday's Law of Induction states that the electromotive force ε is defined by $\varepsilon = -\frac{\partial \Phi_B}{\partial t}$, where Φ_B is the magnetic flux through an open surface. The negative sign is significant because it displays mathematically the opposing magnetic field generated by the eddy currents in response to the change in magnetic flux, which is essential to the operation of the linear induction motor. This flux is calculated through the double integral $\iint_S \; B \cdot dS$, showing that the magnetic flux is equal to the surface area of an open surface times the magnitude of the external magnetic field normal to that surface.

Methods

The first track that I constructed consisted of a 3-foot long 1x4 with a 3-foot long section of OO gauge model train track (roughly one inch wide). Along the track on both sides I attached two lines of neodymium permanent magnets with alternating poles (Figure 3 for a diagram) to serve as the secondary for the motor. For the car, I cannibalized an OO gauge model caboose car to serve as the base. Fortunately, the car came with an iron plate affixed to the bottom, which I decided to use as my conductor. To make the electromagnets, I used two 2 ½ inch zinc-iron alloy carriage bolts threaded with approximately 15 feet of magnet wire (100 turns on each).

The quadrature circuit was constructed quite simply with an inductor and resistor in series, situated between the two electromagnets. This worked due to how voltage and current are split in phase when passing through either a capacitor or inductor; in this case, the current would lag the voltage by ¼ of a wavelength, or 90 degrees. The resistor was put in as a means to prevent the voltage from overloading the power supply. This circuit was assembled on a small proto-board, and was placed directly on the car for ease of access.

To simplify the process of making adjustments to my linear induction motor circuit, I decided on using an AC function generator that would generate a sine wave. The function generator in question allowed for the voltage, the frequency, and the wave type to be controlled through one unit. The function generator was then hooked up in series to the quadrature circuit to create the phase shift necessary for the motor to function. This phase shift is absolutely crucial to the function of this motor; as without an electromagnet leading in phase, the best one could hope for would be a slight back-and-forth motion.

Once the track and circuit were assembled, I connected the circuit to the electromagnets on the car and powered the circuit using a function generator outputting a sine wave to simulate alternating current. This method was chosen due to its ease of use, as well as its ability to adjust the peak-to-peak voltage and frequency of the wave without having to muck about with reconnecting various pieces of equipment.

This first model was unable to produce a working motor, unfortunately, and I deduced its failure to a number of construction errors, which I will go over in the next section. In light of this, I built a second test track that corrected these construction errors, as well as a few minor adjustments to pieces to facilitate the operation of the motor, but most notably the scale was increased.

This secondary was constructed out of a three foot section of a 1x6 plank with O-gauge track (roughly 1 ½ inch wide) acting as the base for the car. This gauge was chosen due to its accessibility and material composition – the OO gauge I had used previously had many imperfections in it, which caused unnecessary friction between the wheels of the car and the track. Along each side of the track I stacked ½ inch high yardsticks to create a U-channel, a sort of trough that contained the track. The rationale behind this was to provide a platform for the permanent neodymium magnets so that they could be as close as possible to the conductor plate, as on actual high speed maglev trains, the air gap between the primary and secondary

The car used was a flatbed O-gauge model train car, with a number of differences applied to it. After some research I ordered copper plates to act as the conductor plate, due to the higher conductivity of copper when compared to iron ($5.95 * 10^7$Siemens/meter as opposed to iron's $1.03 * 10^7$Siemens/meter). This conductivity is important to the function of the motor because the electrical field within the conductor needs to be as high as possible to allow the magnetic fields generated by the eddy currents to be of sufficient strength to move the motor. In addition, the size of the electromagnets was increased significantly, as this model used 2 ½ inch bolts wound with 40 feet of magnet wire for a total of 250 turns on each, again for the purposes of making the magnetic field as strong as possible. This new car was again hooked up to the function generator, with the quadrature circuit designed for the first car placed between the two electromagnets.

Results

The first component I tested was the quadrature circuit, as I knew that this would be key to making sure the eddy currents were generating properly in the correct directions. Since there was no readily available means to measure current like one can through an oscilloscope, I used a more old-fashioned method of holding compasses up to the electromagnets while they were connected in quadrature, with the frequency of the oscillations reduced so that I could more easily see the movements of the needle. The circuit was a success: as one needle moved from its equilibrium position towards the magnet, the other needle moved away from the magnet towards the equilibrium point; a 90 degree phase split.

Unfortunately, the motor was unable to propel itself. This stemmed from a technical limitation of getting the current high enough to create a magnetic field of sufficient strength, which in turn stunted the size of the induced electrical current and resultant eddy currents. However, I did gather some useful data that can display these errors mathematically.

Using a 10 ohm resistor measured at 10.4 ohms, I found that when the voltage on the function generator was set to its highest setting of 10 volts peak-to-peak, the voltage measured across the resistor was approximately 8.6 volts. An application of Ohm's law ($V = IR$) quickly revealed the current through the resistor to be .827 amperes.

Considering that in the model constructed I used O scale (1:48), and with these numbers in mind, I can calculate the resultant magnetic field produced by the electromagnets. $B = \frac{\mu_{0I}}{2\pi r}$ with:

- $\mu_0 = 8.85 * 10^{-12}$
- $I = 0.827$
- R = 0.0254 meters (one inch at its furthest point)

This comes out to equal $4.58 * 10^{-11}$ Tesla. Research shows that the MLX01 (the current land speed record holder maglev train) uses coils with upwards of 700,000 amperes that are capable of generating magnetic fields of 5 Tesla, or 100,000 times the earth's own magnetic field. If we are to assume linear scaling with these values, then to make an equivalent model at scale would require approximately 14,600 amps of current generating a 0.1 Tesla magnetic field, which is several orders of magnitude larger than I am capable of producing.

Though almost immeasurable with my resources, if the primary was pushed opposite to the direction of its movement if the motor worked, the car could be observed to slow to a stop slightly faster than if the circuit was off. Unfortunately, I could not provide any consistency for the force applied to the car, so this result is at best inconclusive.

Discussion and Conclusions

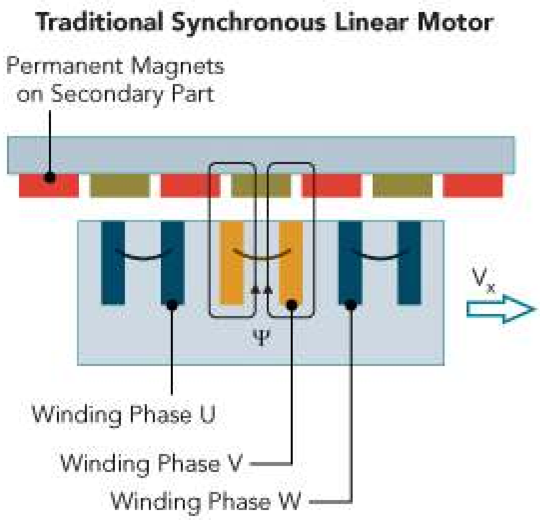
The first motor constructed had a number of design flaws related to its construction, the first and foremost being that the air gap between the conducting plate on the primary and the permanent motors on the secondary was much too great. Research shows that on the MLX01, the minimum air gap between the two is on the order of 7 millimeters, increasing as the train accelerates to a maximum of 40 millimeters. By comparison, my initial model had an air gap of roughly 3 centimeters, which facilitated the weakness of the magnetic field at that point. In addition to this air gap, the track I had used was also wrought with imperfections, and had a lot of friction even after polishing the track and car wheels. These issues were rectified in the second model I constructed. By lowering the distance between the conducting plate and the secondary I was able to increase, however minutely, the resultant magnetic eddy current generated within.

Although the motor did not function, that is not to say that this project was entirely without results. With access to a high-current power supply, the motor could work. In addition, through research, I found out that the linear induction motor is not often scaled down due to its immense power supply, and that it actually becomes beneficial to use on larger scales because of this limitation. Linear synchronous motors are traditionally the small-scale linear motor, only overtaken by the linear induction motor due to the immense heat that would be generated in the three-phase coils of a large-scale linear synchronous motor.

In summation, this project taught me a great deal about how electrical motors work, and all of the variables that go into fine-tuning them. I also learned a great deal about construction techniques, and how scaling is incredibly important; what works on one scale might not work on another.

Appendix

Figure 1



A diagram showing the phase windings of a linear synchronous motor.

Figure 2

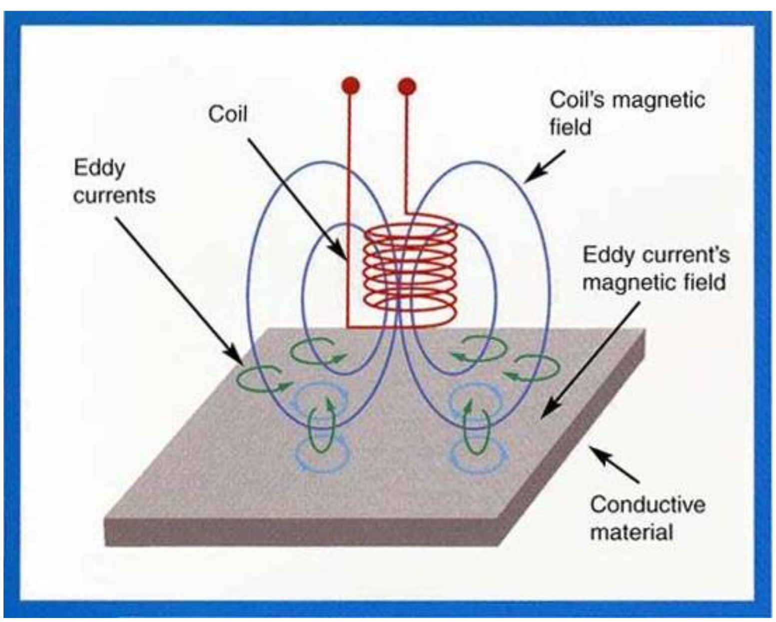
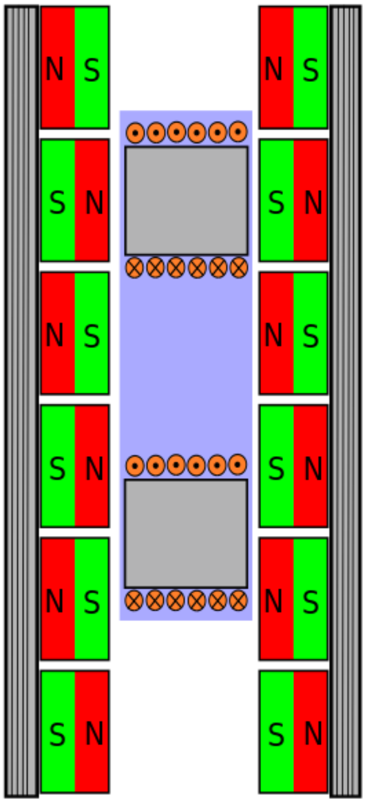


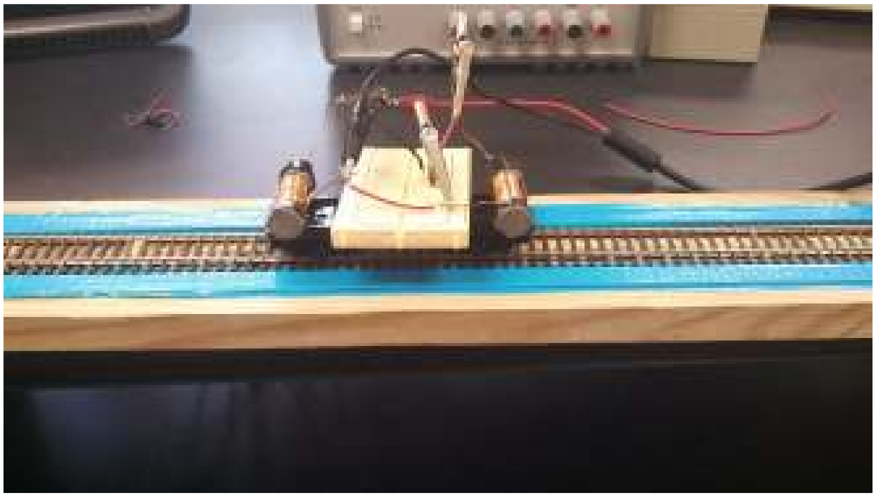
Diagram detailing the induced magnetic eddy currents.

Figure 3



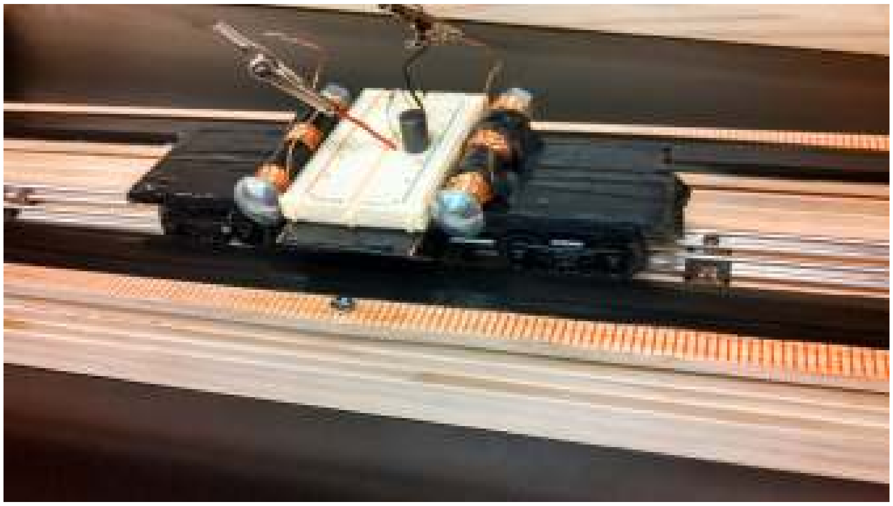
A diagram of the basic setup of the linear induction motor I built.

Figure 4



The first track constructed, note the air gap between the electromagnets and the track. The iron conducting plate is located underneath the protoboard.

Figure 5



The second track constructed. Note the proximity of the conducting plate (covered with electrical tape) to the permanent magnets on the secondary.

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