

Electromagnetic Train

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Abstract

This experiment tested how the spacing between windings affects the magnetic field of a coil, which in turn affects the speed of an electromagnetic train. This can help one understand how the windings in a coil influence the magnetic field, and can be applied to creating more efficient transportation systems. Three different coils with different spacing in between the windings were made for this experiment. A battery with neodymium magnets attached to its terminals (referred to as the Battery Electromagnetic Train, or BEMT for short) were run through the coil, and an Arduino was used to calculate the time it took for the BEMT to travel from point A to point B using an innovative technique of utilizing coils as magnetically induced sensors. Other factors such as remaining voltage and battery temperature were also measured. Coil 1, which had windings spaced out at 3 mm, had the fastest time. Coil 2, which had the windings spaced out at 4 mm, had the second fastest time. Coil 3, which had the coils spaced out at 5 mm, had the slowest time.

Project

Experiment, Physics

Background

We chose this topic because we both have an interest in engineering, especially in the form of transportation. Our project is very similar to an electrical device in real life: a linear motor. Linear motors are like rotary motors, except the stator is laid out in a straight line rather than in a round shape. Linear motors are used in trains, and we wanted to understand how they can deliver a payload faster than rotary motors when transporting. Furthermore, we wanted to test what kinds of factors affect the speed of the train.

Purpose/Problem

The purpose of this experiment is to determine how the distance between windings in a copper coil affects the speed of the BEMT passing through it. The following spacings will be compared: windings spaced at 3 mm, 4 mm, and 5 mm.

Hypothesis

If the windings are made at intervals of 3 mm, then the BEMT will move the fastest, since the coils will be the tightest wound group compared to the rest. The strength of the magnetic field is related to the spacing of the windings. With smaller distances between windings, there will be more coils, leading to a larger current density, which then amplifies the magnetic field. This creates more force and therefore the speed of the BEMT increases.

Control

Coil 2 (spacings of 4 mm) was used as the control group. It is in the middle of the two coils, and is used to see how making the windings tighter (in 3 mm) or farther apart (5 mm) would affect the speed.

Variables

Independent Variable: Distance between windings

Dependant Variable: Speed of the BEMT

Control Variables: Travel distance, elevation, magnetic interference, battery life, permeability of core (air), number of magnets, strength of magnet, material of the coil, thickness of coil

Materials

- 6x neodymium magnets (1.3mm in diameter and 2mm thick)
- 1x AAA battery (rechargeable NiMH)
- 59 m 18 gauge bare copper wire
- 6x 30 cm 25 gauge insulated solid core telephone wire
- Scotch tape
- Styrofoam trough
- 4x alligator cables
- 4x male to female jumper cables
- I2C 16x2 LCD screen
- USB 2.0 type B cable

Apparatus

- Copper pipe
- Arduino board
- Mac computer running Arduino software
- Infrared thermometer
- Voltmeter
- High-speed camera (iPhone 5s camera was used)

Safety Precautions

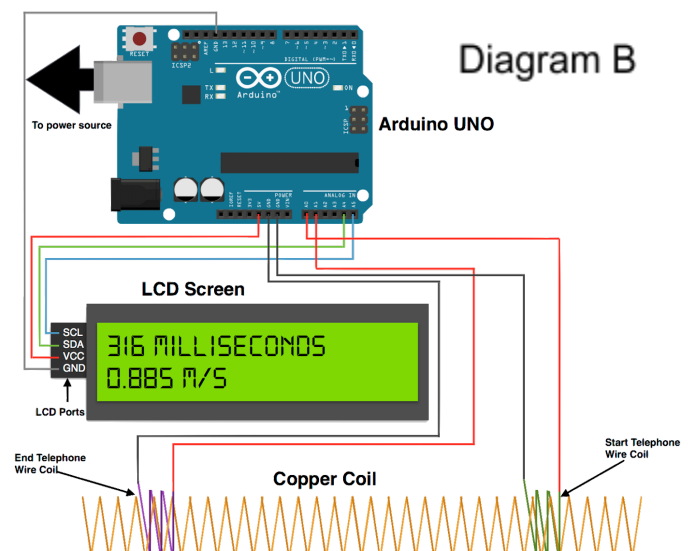
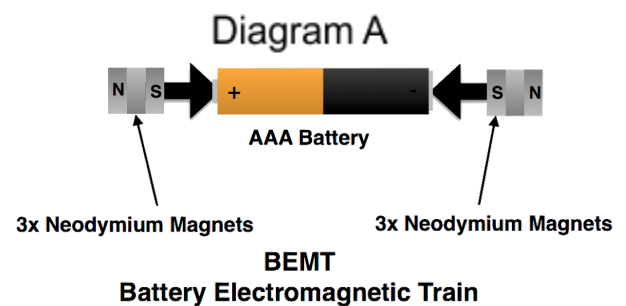
- Be cautious when using neodymium magnets. Two idle magnets can attract each other at high speeds up to 5 cm away from each other. The impact from the two magnets can be harmful to anything in between the two magnets. Do not consume magnets. There will be severe damage done to internal organs in the digestive system.
- Similarly, do not leave any magnetic objects near the coil while doing the experiment. The BEMT will be attracted to the magnetic object and the coil will be pinched between the two objects. This is not as much of a safety precaution to the experimenters, but rather, it is to prevent damage of the coil, which is also important to keep in mind.
- Do not leave the BEMT in the coil. This will short out the battery, and may cause overheating and fires. For this reason, one should not use lithium AAA batteries. If the battery gets stuck in the coil, remove it as quickly as possible.

Procedure

1. The BEMT was created with 3 magnets attached on each end of the battery with the North polarities of the magnets pointing outward as shown in diagram A.

2. 3 different coil tubes were made by wrapping the copper wire around a copper pipe. One had coils spaced out at 3 mm each, the next one had coils spaced out at 4 mm each, and the last one had coils spaced out at 5 mm each.

3. An interval of 28 cm was measured on the styrofoam trough. This is where the speed of the battery was measured. 2 insulated telephone wires were made into small coils and taped down on each end of the 28 cm intervals. These were attached to the Arduino to precisely measure the time it took for the



BEMT to travel from one point of the coil to the other. As the BEMT travelled through the telephone wire, the magnetic field of the BEMT's magnets was detected by it.

4. The copper coil was inserted through the two telephone wire loops. It was made sure that the telephone wire did not seep into the actual copper coil, or else it would block the BEMT.

5. An Arduino was set up as shown in diagram B. Alligator clips were used to make the system more convenient. Before writing the code, an Arduino plugin^[1] was downloaded to drive the 16x2 Serial LCD display. Then the following program was written for the Arduino to measure the time the BEMT took to travel between the two insulated telephone wire coils. The Arduino had a free-running 64 bit timer measured in milliseconds counting from the reset of the device. When the BEMT passed through the first telephone wire, it induced a voltage, which was read by the Arduino and recorded the start time. When it reached the second telephone wire, the voltage was detected, and the endtime was recorded. The time difference was displayed in both milliseconds and meters/second on the LCD. The numbers were recorded on the serial monitor on the computer, making it easier for the numbers to be transferred into a spreadsheet. This measurement was very accurate and was instantaneously triggered when the BEMT passed through.

--START OF PROGRAM--

```
// Code written by Andrew Pun
#include <Wire.h>
#include <LiquidCrystal_PCF8574.h>
LiquidCrystal_PCF8574 lcd(0x27); // set the LCD address to 0x27 for a 16 chars and 2 line display
int show;
// the setup routine runs once when you press reset:
void setup() {
  // initialize serial communication at 9600 bits per second:
  pinMode(13, OUTPUT);
  int error;
  Serial.begin(9600);
  Serial.println("LCD...");
  while (! Serial);
  Serial.println("Dose: check for LCD");
  Wire.begin();
  Wire.beginTransmission(0x27);
  error = Wire.endTransmission();
  Serial.print("Error: ");
  Serial.print(error);
  if (error == 0) {
    Serial.println(": LCD found.");
  } else {
    Serial.println(": LCD not found.");
  }
}
```

```

} // if
lcd.begin(16, 2); // initialize the lcd
show = 0;
lcd.setBacklight(255);
lcd.home(); lcd.clear();
  lcd.print("BEMT");
  delay(3000);
} // setup()
// the loop routine runs over and over again forever:
void loop() {
  digitalWrite(13, LOW); // LED is turned off
  int sensorValue = analogRead(A0); // A0 is hooked to the first telephone wire
  while(sensorValue < 10) { // A loop that continues until the A0 value is more than 10
    sensorValue = analogRead(A0); // Reads voltage from port A0
    digitalWrite(13, LOW);
  } // If the value of A0 is less than 10 then it will keep reading the voltage until it is more than 10
  digitalWrite(13, HIGH); // After the loop is exited then the LED is turned on
  int long startTime;
  startTime = millis(); // The start time is recorded
  int sensorValue2 = analogRead(A1); // A1 is hooked to the second telephone wire
  while(sensorValue2 < 10) { // A loop that continues until the A1 value is more than 10
    sensorValue2 = analogRead(A1); // Reads voltage from port A1
    digitalWrite(13, HIGH);
  } // If the value of A1 is less than 10 then it will keep reading the voltage until it is more than 10
  int long endTime = millis() - startTime; // Subtracts start time from the current time and sets it as the
variable "endTime"
  digitalWrite(13, LOW); // Turns off LED
  Serial.println(endTime); // Prints the time in milliseconds on the serial monitor
  if (show == 0) {
    lcd.setBacklight(255);
    lcd.home(); lcd.clear();
    lcd.print(endTime); // Prints the milliseconds on the LCD
    lcd.print(" ms");
    lcd.setCursor(0, 1);
    lcd.print(((double)28 / endTime * 10)); // Calculates meters per second from the milliseconds and prints it
on the bottom of the LCD.
    lcd.print(" m/s");
    delay(1000);
  }
}

```

--END OF PROGRAM--

6. The BEMT was put in the end of the coil that had the insulated sensor rigged to the A0 port. The BEMT travelled through the coil. Results were recorded from the serial monitor (they could also be recorded by writing the numbers displayed on the LCD, but it is easier to copy and paste the numbers on the monitor).
7. Every 20 times the BEMT passed through, the temperature and the voltage of the battery were measured using the infrared thermometer and the voltmeter.
8. The BEMT was passed through at least 100 times for all the coils.

9. A high-speed camera recording at 270 fps was used to record 2 trials for each coil with the battery fully charged. Each frame was analyzed to see how much the velocity changed to calculate the acceleration. The number of frames it took before passing the first telephone wire (in this case it was 10 cm) was recorded, and the number of frames it took to travel the remaining 28 cm was also recorded. The full length of the coil was recorded. The following formula was used:

Let A be frames taken to travel first 10 cm.

Let B be frames taken to travel the next 28 cm.

$$\left(\left(\frac{0.28}{(B/270)}\right)-\left(\frac{0.10}{(A/270)}\right)\right)/\left(\frac{A+B}{270}\right)$$

Observations

<u>Trial#</u>		<u>Coil 1</u>	<u>Coil 2</u>	<u>Coil 3</u>
Baseline	Voltage	1.486	1.488	1.447
Baseline	Temperature (°C)	26.6	26.6	26.2
1	Time taken (milliseconds)	296	372	710
2		260	334	651
3		332	317	516
4		303	392	714
5		265	376	335
6		328	407	514
7		329	317	479
8		329	286	609
9		324	385	474
10		354	308	449
11		328	291	486
12		340	343	368
13		323	330	454
14		333	311	542
15		346	320	381
16		300	314	391
17		319	314	339
18		344	329	408
19		309	342	468

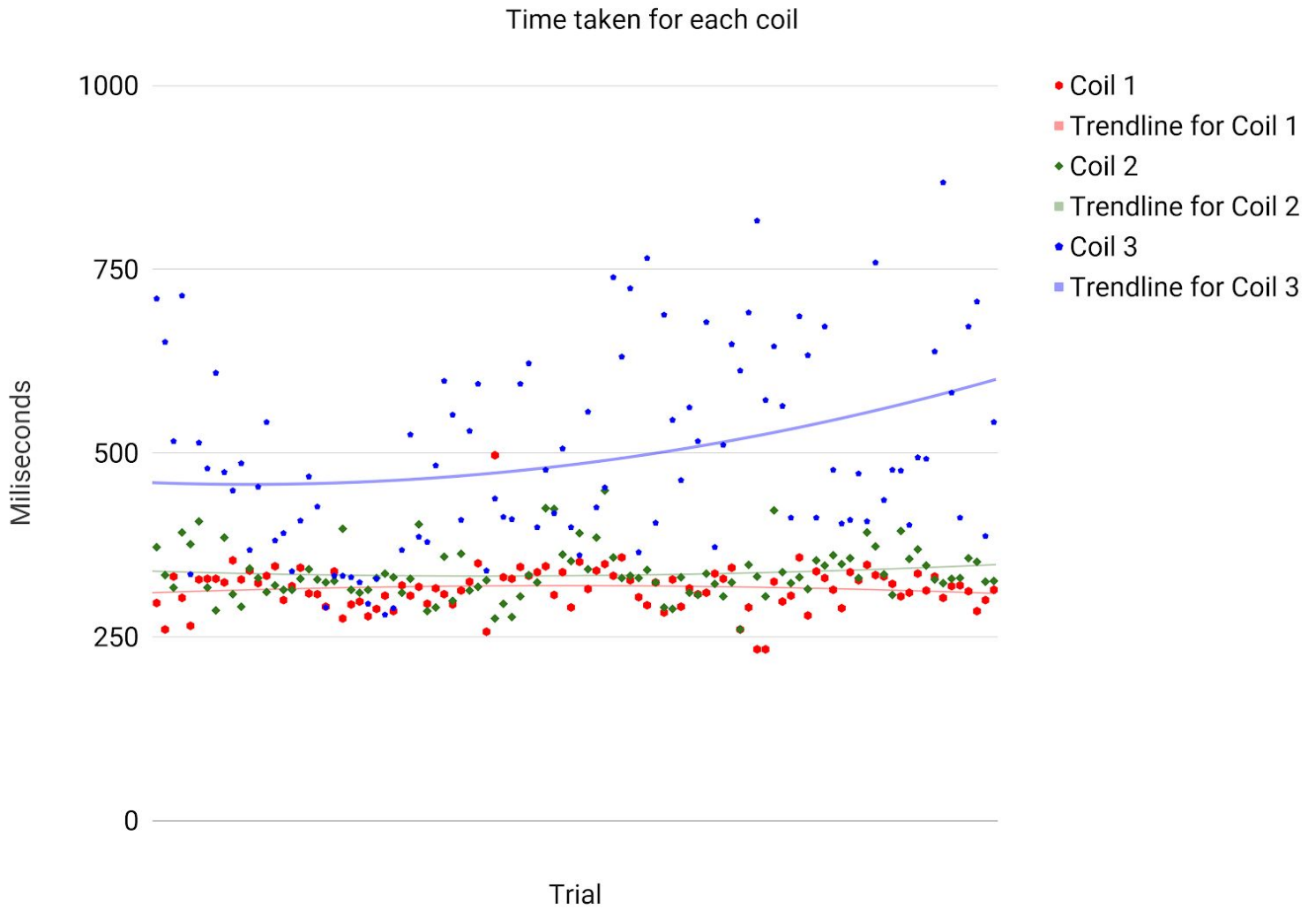
20		308	328	427
After trials 1-20	Average time (milliseconds)	318.5	335.8	485.75
After trials 1-20	Voltage	1.419	1.368	1.308
After trials 1-20	Temperature (°C)	26.6	27.2	31
21	Time taken (milliseconds)	291	324	290
22		339	326	333
23		275	397	333
24		294	314	331
25		298	310	324
26		278	314	295
27		288	330	329
28		306	336	280
29		285	331	289
30		320	310	368
31		306	329	525
32		318	403	386
33		295	285	379
34		316	290	483
35		308	359	598
36		294	299	552
37		313	363	409
38		325	313	530
39		350	318	594
40		257	327	340
After trials 21-40	Average time (milliseconds)	302.8	328.9	398.4
After trials 21-40	Voltage	1.39	1.332	1.27
After trials 21-40	Temperature (°C)	26.8	27.4	35.2
41		497	275	438
42		331	295	413
43		329	277	410
44		345	305	594
45		333	334	622
46		338	324	399

47	Time taken (milliseconds)	346	425	477
48		307	424	418
49		338	362	506
50		290	353	399
51		352	391	361
52		315	342	556
53		340	385	426
54		349	449	453
55		333	358	739
56		358	330	631
57		327	333	724
58		304	330	365
59		293	341	765
60		324	324	405
After trials 41-60	Average time (milliseconds)	337.45	347.85	505.05
After trials 41-60	Voltage	1.352	1.304	1.236
After trials 41-60	Temperature (°C)	26.6	24.6	35
61	Time taken (milliseconds)	283	290	688
62		328	288	545
63		291	331	463
64		316	310	562
65		308	307	516
66		310	336	678
67		336	322	372
68		329	305	511
69		344	324	648
70		260	260	612
71		290	348	691
72		233	332	816
73		233	305	572
74		325	422	645
75	298	338	564	
76	306	323	412	
77	358	331	686	

78		279	315	633
79		339	354	412
80		330	347	672
After trials 61-80	Average time (milliseconds)	304.8	324.4	584.9
After trials 61-80	Voltage	1.322	1.289	1.225
After trials 61-80	Temperature (°C)	27.2	25.2	32
81	Time taken (milliseconds)	314	361	477
82		289	349	404
83		338	357	409
84		327	330	472
85		348	392	407
86		334	373	759
87		332	335	436
88		322	307	477
89		305	394	476
90		310	356	402
91		336	369	494
92		313	347	492
93		332	328	638
94		303	323	868
95		319	329	582
96		320	330	412
97		312	357	672
98		285	352	706
99		300	325	387
100		314	326	542
After trials 81-100	Average time (milliseconds)	317.65	347	525.6
After trials 81-100	Voltage	1.298	1.273	1.212
After trials 81-100	Temperature (°C)	25.4	25.6	28.8-
Final results	Average time of all readings:	316.24	336.79	499.94

Final results	Average temperature:	26.53	26.1	31.37
Final results	Estimated acceleration (m/s²):	0.7679	0.3563	0.3009

Mathematical Analysis



Theoretical Analysis

Coil 1 had the shortest average time of 316.24 milliseconds to travel 28 cm, or 0.885 m/s. Coil 2 had the second shortest average time of 336.79 milliseconds, or 0.831 m/s. Coil 3 had the slowest average time of 499.94 milliseconds, or 0.560 m/s. This was the expected result, since the closer the coils were, the larger the current density became, and thus the magnetic field was increased, creating more force to increase the battery's speed. However, coil 1 and 2 had very similar results. This may be because as the windings got closer, the more windings the electricity needed to pass through, and the more resistance there was. Coil 1 was nearing the limit of how many windings could be made in a short distance before causing too much resistance. If another coil was made with windings less than 3 mm apart, the experimenters suspect that it may have the same results as coil 1 or 2, or even start to slow down.

Acceleration was also calculated. As expected, coil 1 had the fastest acceleration of 0.7679 m/s^2 , coil 2 had the second fastest acceleration of 0.3563 m/s^2 , and coil 3 had the slowest acceleration of 0.3009 m/s^2 . These results are not very distinct, and may show how eventually the change in speeds reach a plateau after a while due to friction.

Apart from the readings, the voltage and temperature were important to keep in mind. Coil 1 ended up with the most remaining voltage of 1.298 v, coil 2 had a remaining voltage of 1.273 v, and coil 3 had the least remaining voltage of 1.212 volts. A potential reason for this is that when the BEMT was used in coil 3, it was slower which led to spending more time in the coil, and thus had more time to short. This would drain out the battery faster. Out of the 3 average temperatures, coil 3 had the highest temperature, of 31.37 degrees celsius. Similar to the first explanation, this heat could be the result of the battery shorting out, which would explain why coil 3 was so warm.

Conclusion

The experimenters' hypothesis was supported. Coil 1 had the fastest average speed of 0.885 m/s, coil 2 had a slightly slower speed of 0.831 m/s, and coil 3 had the slowest average speed of 0.560 m/s. As well as that, coil 1 had the highest remaining voltage, meaning that it was not only fast, but much more efficient, since its energy was spent on its speed. Coil 3 had a very high temperature, which shows how the energy was wasted on heat, instead of its velocity.

Extension

This project can be extended by comparing the material used for the coil. Only copper was used, but if this project was recreated, other metals like aluminum and silver (if cost is not an issue) could be used to make the coil to see how their conductivity affects the magnetic field. Similarly, different coil thicknesses can be tested to see how the current is altered. For example, the gauge of the wire used in the experiment was 18, but sizes of 20 or 22 are available as well. Different magnets with different strengths could also be tested for their effectiveness.

Sources of Error

- Many times, the second telephone wire did not trigger. This caused the counter to not stop, and the wire had to be unplugged to reset the timer. While these results were not recorded, this did wear down the battery.
- The farther apart the windings were, the more bumpy the surface that the BEMT had to traverse on. This caused fluctuations in the readings for the third coil, as sometimes the friction hindered the BEMT's performance.

Application

Linear motors^[27] are much more efficient at transport systems than rotary motors since the electricity is directly converted to linear movement, as opposed to giving a vehicle wheels that are driven by a regular motor. This reduces friction and makes the speed much faster. The experiment was able to test for what made a more efficient linear motor by adjusting the spacings between coils. Trains such as the Bombardier Innovia Metro^[28] and Hyperloop One^[16] already use linear motors. Some roller coasters and elevators^[32] also utilize these motors.

Apart from the coil, another aspect of the experiment has a practical application. The development of the experiment required a method to precisely record the time it took for the BEMT to travel 28 cm. Initially, the experimenters considered timing the BEMT by hand, using a stopwatch. However, this would be too inaccurate. Other ideas such as optical sensors could have been used to start and stop a timer when the sensors detected a train passing through. This idea

would have been a bit more precise. The experimenters finally settled on creating an original sensor that detects a magnetic field, which was made using a telephone wire coil. This magnetically induced sensor was very precise, inexpensive, and easy to create since it did not require any special electronic devices. A sensor like this has multiple applications, especially when applied to a magnetic motor. The sensor can measure the RPM (revolutions per minute) of the motor, and from this, a computer driving the motor can adjust the current to slow or speed up the motor to a pre-set speed based on the amount of RPM.

Bibliography

1. Plugin for Arduino: <https://bitbucket.org/fmalpartida/new-liquidcrystal/downloads/>. Version 1.2.1. was used.
2. (n.d.). Retrieved from <http://www.electronics-tutorials.ws/inductor/inductor.html>
3. A-level Physics/Forces, Fields and Energy/Electromagnetism. (n.d.). Retrieved from http://en.wikibooks.org/wiki/A-level_Physics/Forces,_Fields_and_Energy/Electromagnetism
4. Ampere. (2017, November 18). Retrieved from <http://en.wikipedia.org/wiki/Ampere>
5. Ampere hour. (2017, November 17). Retrieved from http://en.wikipedia.org/wiki/Ampere_hour
6. Coulomb's law (magnetic). (n.d.). Retrieved from [http://www.tau.ac.il/~tsirel/dump/Static/knowino.org/wiki/Coulomb's_law_\(magnetic\).html](http://www.tau.ac.il/~tsirel/dump/Static/knowino.org/wiki/Coulomb's_law_(magnetic).html)
7. DIY Electromagnetic Train Breakdown. (n.d.). Retrieved from <http://physicsgirl.org/blog/2016/7/20/diy-electric-train-breakdown>
8. Electromotive force. (2017, November 11). Retrieved from http://en.wikipedia.org/wiki/Electromotive_force
9. Faraday's law of induction. (2017, November 08). Retrieved from http://en.wikipedia.org/wiki/Faraday's_law_of_induction
10. Fleming's Left Hand Rule and Fleming's Right Hand Rule. (n.d.). Retrieved from <http://www.electrical4u.com/fleming-left-hand-rule-and-fleming-right-hand-rule/>
11. How To Build The Simplest Electric Train. (n.d.). Retrieved from <http://www.waynesthisandthat.com/How To>

Build The Simplest Electric Train.html

12. How To Build The Simplest Electric Train. (n.d.). Retrieved from [http://www.waynesthisandthat.com/How To](http://www.waynesthisandthat.com/How To Build The Simplest Electric Train.html)

Build The Simplest Electric Train.html

13. How do linear motors work? A simple introduction. (2017, May 09). Retrieved from

<http://www.explainthatstuff.com/linearmotor.html>

14. How does current affect magnetic force? | Socratic. (n.d.). Retrieved from

<http://socratic.org/questions/how-does-current-affect-magnetic-force>

15. Hyperloop One. (n.d.). Retrieved from <http://hyperloop-one.com/>

16. Hyperloop One. (2017, November 18). Retrieved from http://en.wikipedia.org/wiki/Hyperloop_One

17. INNOVIA Metro. (n.d.). Retrieved from

<http://www.bombardier.com/en/transportation/products-services/rail-vehicles/metros/Innovia-Metro.html>

18. Induction Motor | Working Principle | Types of Induction Motor. (n.d.). Retrieved from

<http://www.electrical4u.com/induction-motor-types-of-induction-motor/>.

19. LATEST. (n.d.). Retrieved from <http://www.allaboutcircuits.com/textbook/direct-current/chpt-11/battery-ratings/>

20. Linear Induction Motor. (n.d.). Retrieved from <http://www.electrical4u.com/linear-induction-motor/>.

21. Linear Motors. (n.d.). Retrieved from <http://www.linmot.com/products/linear-motors/>

22. Pololu - Understanding battery capacity: Ah is not A. (n.d.). Retrieved from

<http://www.pololu.com/blog/2/understanding-battery-capacity-ah-is-not-a>

23. Revenge of the Mummy. (n.d.). Retrieved from <http://www.birket.com/portfolio/revenge-of-the-mummy/>

24. Solenoid. (2017, November 18). Retrieved from <http://en.wikipedia.org/wiki/Solenoid>

25. Solenoid. (n.d.). Retrieved from <http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/solenoid.html>

26. S. (2015, February 23). Electromagnetic Train Explained. Retrieved from

<http://www.youtube.com/watch?v=BWuICjRU3t0>

27. T. (2015, June 26). The Sci Guys: Science at Home - SE3 - EP9: Simplest Electric Train - Magneto-Electric

Train. Retrieved from <http://www.youtube.com/watch?v=wx9n30qjYpw>

28. E. (2017, June 26). An Elevator That Actually Goes Sideways. Retrieved from <http://www.youtube.com/watch?v=kdTsbFS4xmI>

29. Here!, A. N. (n.d.). DC Motor, How it works ? Retrieved from <http://www.learnengineering.org/2014/09/DC-motor-Working.html>

30. Here!, A. N. (n.d.). Fundamentals of Turbomachinery. Retrieved from <http://www.learnengineering.org/2013/08/>

31. Thyssenkrupp – engineering. tomorrow. together. (n.d.). Retrieved from <http://www.thyssenkrupp.com/en/>