Analysis of the Limits of Electromagnetic Induction in Object Detection

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Abstract

Object detection has useful applications in areas like security, manufacturing, or even athletics. Many of these devices implement some form of computer vision and can be costly. By using simple electromagnetic induction, it is also possible to detect a specific item passing through a hoop, given that the item is magnetic and the hoop is bounded by a loop of wire. The ability to detect the object diminishes rapidly, however, as the size of the hoop increases. This paper proposes methods by which to address this issue and constructs a three-foot hoop to test them, resulting in a device which can accurately detect the passing of a volleyball through a plane. This suggests that the practical applications of electromagnetic induction for object detection have yet to be uncovered and further research may reveal even more uses for this simple concept.

1 Introduction

There are many applications of electromagnetic induction in modern technology, including electric generators, wireless charging, and MRI machines. Faraday's Law of Induction states that the electromotive force generated by a changing magnetic field is proportional to the change in flux over change in time. However, as the size of the coil increases, a stronger magnetic field is required to produce the same current, making this concept difficult to scale up in practice. In the case of detecting a magnetic object moving through a plane, the induced current is extremely limited by the area of the planar surface. This project aims to analyze the effect of several factors on the strength of the induced current and optimize them accordingly in order to achieve the maximal area of the planar loop while maintaining a detectable change in current.

2 Methods

2.1 Initial testing

The device used for the initial data collection was a Helmholtz coil demonstration tool borrowed from the Harvard Physics Department. It consists of two coils oriented in the same direction measuring 24 inches in diameter, spaced 12 inches apart. Each coil has approximately 20 turns (the exact number cannot be measured without disassembly of the device), but only one coil was used for the voltage measurement. This device provided a simple and convenient way to take measurements without building a hoop from scratch.

The coil ends were connected to an oscilloscope to read the voltage over time. A long aluminum tube was positioned through the plane of the hoop at a sharp angle to act as a ramp for an N52 magnet to slide down with its field aligned parallel to the direction of travel. A velocity sensor was also installed at the top of the ramp.

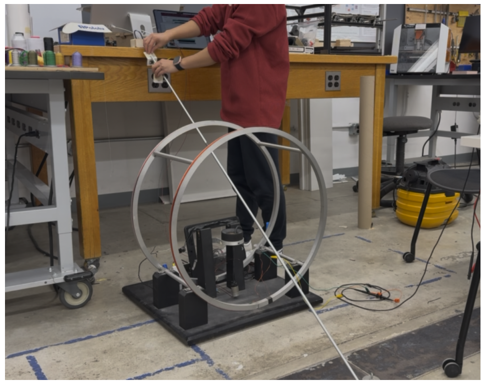

Figure 1: Helmholtz coil repurposed for data collection.

2.2 Construction of hoop

To construct a hoop of larger diameter, a frame was designed in CAD software and laser cut from cardboard and eventually wood. Two identical annular regions were assembled in eight-piece segments then attached with small posts, which allowed for everything to be fabricated in a laser cutter with a 18×36 inch bed size with minimal waste production. This model measures 36 inches along its outer diameter. Magnet wire was wrapped around the circumference of the hoop, totaling approximately 60 turns in the coil.

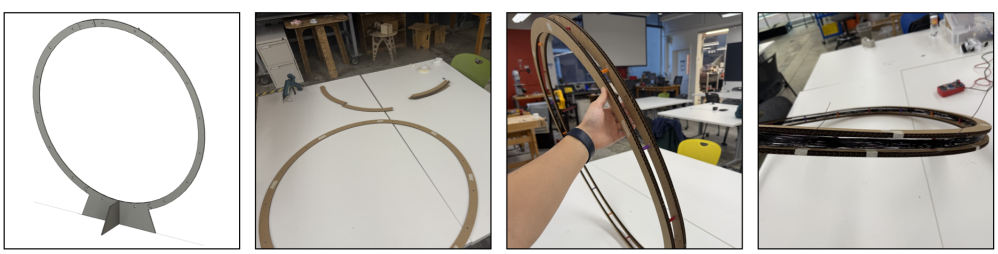

Figure 2: Hoop is constructed from cardboard and plastic tubing.

For the electronics measurement, an ESP-WROOM-32 Devkit board was used, along with the AD620 Instrumentation Amplifier (Gain Range 1 to 10,000) and EcoSmart LED Strip

Lights. The ends of the hoop coil were inputted into the amplifier and the gain range was calibrated using the Arduino IDE (see Appendix A). This setup was used to create a portable and presentable form of the device. However, for the data collection used in this paper, the oscilloscope was used instead of the ESP-32, for the sake of consistency and because it provided more accurate voltage readings at higher sampling rates than the ESP-32.

2.3 Construction of magnetic field

To create magnetic fields which can easily be detected in the hoop, six N52 magnets were attached to the surface of a volleyball measuring 8.2 inches in diameter. The spherical shape allowed for the magnets to be positioned symmetrically for equal weight distribution. The magnets were disc-shaped with fields oriented in the axial direction, with strengths ranging from 2598 to 4440 Gauss. The discs were oriented such that the six vector fields would be added constructively, resulting in a single field pointing outwardly from the surface of the ball.

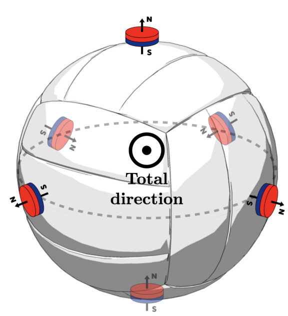

Figure 3: Orientation of magnets on the surface of the ball.

2.4 Data collection

The data collection from the large hoop was performed using an oscilloscope. The ends of the coil were connected as channel input and voltage was measured over time as the ball was thrown through the hoop. A total of 12 trials were performed, for both a slow toss and a fast-paced throw. A separate measurement was also observed for trials of the ball passing parallel to the plane of the hoop, as this also produces a change in the magnetic flux passing through the surface.

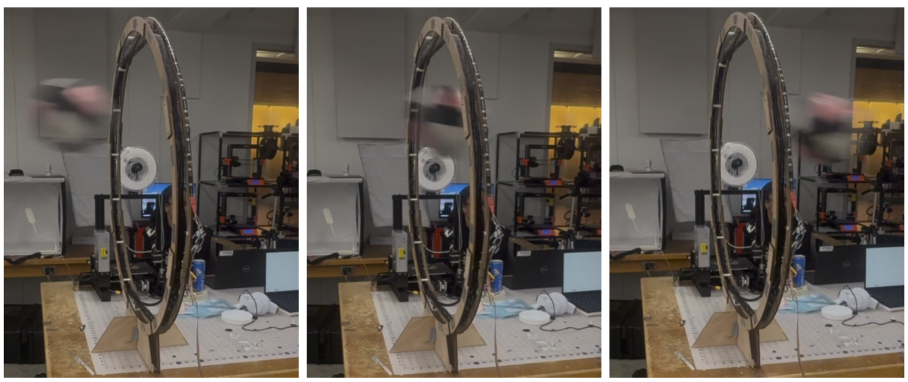

Figure 4: Captured frames of ball being thrown through the hoop.

2.5 Difficulties

Several difficulties were encountered before reaching a setup configuration which produced usable results. Limitations of the hardware proved to be the main source of many issues. The VL53L0X time-of-flight sensor was originally implemented to measure velocity for a straight-line trajectory but could not be used for trials when the ball was thrown. An Adafruit Metro board was at first used to measure voltage, but the analog input interval is $\frac{3.3V}{1023} = 0.0032V$ or 3.2 millivolts, which was not precise enough for the measurement required. Additionally, only a positive voltage could be measured, which would not be able to detect if the magnetic field is oriented in the opposite direction or the magnet travels the other way through the hoop. In order to address this issue, a full wave rectifier was incorporated into the circuit, but this introduced a significant amount of noise and mitigating these types of effects can potentially be the topic of another study.

3 Results

3.1 Initial testing

The 24-inch hoop produced, on average, a maximum voltage change of 16.8mV over 10 trials with the DX06-N52 magnet. The peak velocity of the magnet sliding down the ramp was 4.83 meters per second.

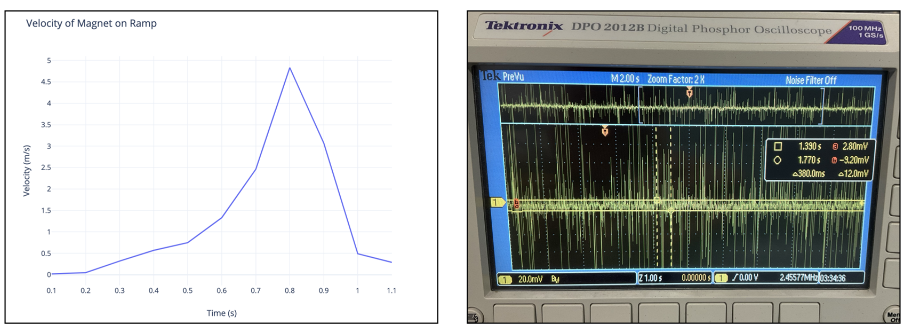

Figure 5: Readings from the 24-inch hoop.

3.2 Constructed hoop

The 36-inch hoop produced, on average, a maximum voltage change of 24.8mV over 10 trials with the DX06-N52 magnet.

With the magnetic ball, the 36-inch hoop produced, on average, a maximum voltage change of 11.3mV for a slow toss, 42.4mV for a fast toss, and 10.1mV for a toss parallel to the plane of the hoop.

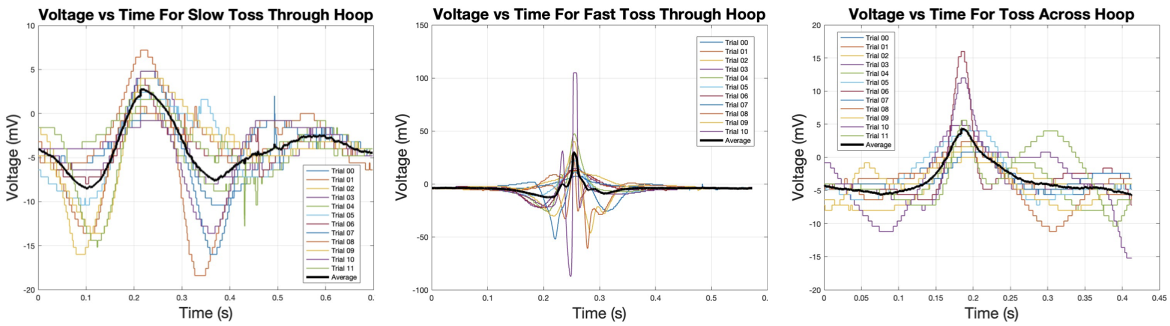

Figure 6: Readings from the 36-inch hoop.

4 Discussion

4.1 Induced voltage

Faraday's Law of Induction, in its simplest form, reads that induced voltage ε is calculated by the following:

$$\varepsilon = -N\frac{\Delta\Phi}{\Delta t}$$

where N is the number of loops, Φ is the magnetic flux, and t is time. Magnetic flux is typically given by $\vec{B}\cdot\vec{A}$ where $\vec{B}$ is the magnetic field and $\vec{A}$ is the area of the loop in the direction of the normal vector. However, this assumes a constant field through the entire plane of the loop. In scenarios where the magnetic field varies, flux is given by $\Phi_B = \iint_A \vec{B}\cdot d\vec{A}$. A permanent magnet which is much smaller than the hoop will only create a magnetic field in a small area, and the rest of it is negligible. Let the magnetic field's area be given by a_0. Then we can approximate total flux as

$$\Phi = \iint_A \vec{B}\cdot d\vec{A} \approx a_0\|\vec{B}\| + (\|A\| - a_0)\|\vec{0}\| = a_0\|\vec{B}\|$$

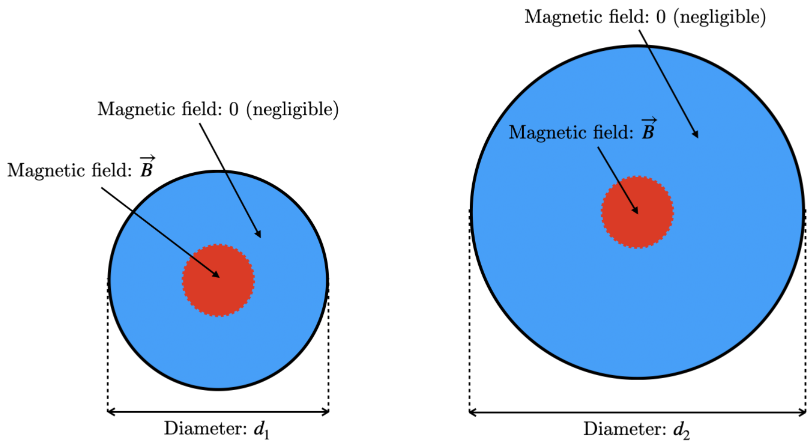

Figure 7: As hoop size increases, only the area which has negligible magnetic field increases.

For the 24-inch hoop and the 36-inch hoop, which differed in number of coils, we would expect

$$\frac{\varepsilon_{36}}{\varepsilon_{24}} = \frac{N_{36}}{N_{24}} \cdot \frac{24^2}{36^2} \approx \frac{60}{20} \cdot \frac{24^2}{36^2} \approx 1.33$$

Based on our data, $\varepsilon_{36} = 24.8\text{mV}$ and $\varepsilon_{24} = 16.8\text{mV}$, so $\frac{\varepsilon_{36}}{\varepsilon_{24}} = 1.48$, which is an error of about 11%.

By increasing the number of coils, we were able to balance out the effect of increasing hoop size. Other factors which could also be adjusted are magnet strength and wire type.

4.2 Distinguishing types of movement

Another aim of this research is to distinguish whether the magnet has passed through the hoop or across it. Both of these produce a change in magnetic flux, but when the magnet passes through the hoop, we would expect a gradual change in flux, whereas when the magnet passes across, we would expect a sharp change in flux as it enters the region of the hoop. Additionally, after the magnet passes through the hoop and travels out the other side, we would expect a negative voltage as the magnetic flux switches from increasing to decreasing. These distinctions can be observed in 6.

In order to numerically distinguish these two types of throws, we can align all the graphs by their peaks and read the voltage over time as a vector. Taking the average vector over all trials of each type gives us $\vec{v}_{\text{through}}$ and $\vec{v}_{\text{across}}$. Then we define $\vec{v}_{\text{proj}} = \vec{v}_{\text{across}} - \vec{v}_{\text{through}}$, which extends to line l_{proj}, onto which we project all the vectors and mark the midpoint between the means. These points can be visualized in 8, where red markers are the trials from tossing across the hoop, blue markers are the trials from tossing through the hoop, and the green star is the midpoint between the means. This gives us a visualization of these 10,000+ dimensional vectors and whether there exists a separation between them.

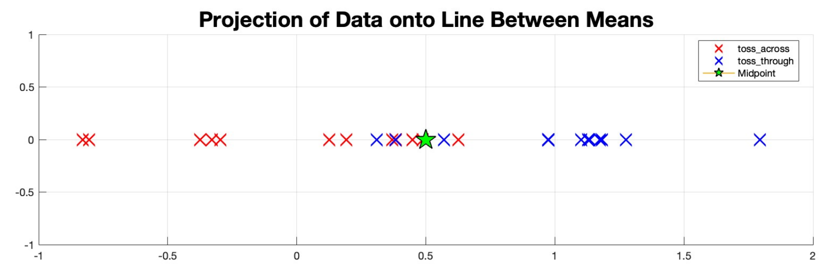

Figure 8: Trials of two types of throws, projected into one dimension.

To test the accuracy of this approach, we implement leave-one-out cross-validation, as presented in Appendix B. This is done in two ways, either finding the closest other vector in the set and looking at its type or simply the closer mean vector ("closest" is defined using standard Euclidean distance). Suppose $\{\vec{h}\}_1^N$ is the set of trials where the ball is thrown through the hoop, and $\{\vec{a}\}_1^N$ is the set of trials where the ball is thrown across the hoop. Then some $\vec{h}_i$ is selected and the following values are calculated

$$d_h = \min_{k\neq i}(\|\vec{h}_i - \vec{h}_k\|) \quad \text{and} \quad d_a = \min_{k\neq i}(\|\vec{h}_i - \vec{a}_k\|)$$

and if $d_h < d_a$ then the classification is correct, otherwise it is not. Or, if we use mean vectors, we simply have

$$d_h = \|\vec{h}_i - \vec{v}_{\text{through}}\| \quad \text{and} \quad d_a = \|\vec{h}_i - \vec{v}_{\text{across}}\|$$

and go from there. Performing the first test across all $\{\vec{h}\}$ and $\{\vec{a}\}$ gives 79.2% accuracy, while the second test gives 75.0% accuracy.

4.3 Further discussion

The increase of loop size poses a difficult problem in practical applications of Faraday's Law. Motivated by being able to detect a ball passing through a circular hoop, this research aims to analyze and optimize the effect of other factors on the induced voltage, namely the number of coils. Two loop sizes were compared, and it was shown that in order to compensate for a 50% increase in hoop diameter, the number of coils has to increase by around 300%. This was relatively feasible for the hoop constructed in this research, and as a result, the induced voltage remained at a detectable level. An even bigger hoop would require many more coils (which also becomes more difficult to manage, physically, when the circumference grows large, and introduces the issue of wire resistivity) and possibly the use of a stronger or larger magnetic field. Taking these factors into consideration gives us a good idea of the physical limitations of such a configuration in practice.

Another limitation in this method of object detection comes from being able to distinguish if the object has in fact passed through the hoop or simply traveled across it. By processing samples from the two types of graphs, we propose an algorithm to make such a distinction. Though its accuracy was only 75-80%, we must consider that only twelve trials were performed and there was no formal device in place to ensure constant velocity of the ball across these trials. Another consideration is that the induced voltage for a throw across the hoop is only at a detectable level when the object passes very close to the plane of the hoop, which is rare in practice.

5 Future Work

Developing a device to perform object detection using Faraday's Law has many useful applications, such as in security, manufacturing, or sports. But implementing a practical version requires further research into the optimal configuration of factors which affect the voltage produced. The use of an amplifier, and possibly a full wave rectifier, will likely be essential to such a device, thus adding in more factors to consider. And to distinguish between types of throws, a script must be implemented to perform the throw type analysis in real time. Another feature which could be added in the future would be the calculation of object speed using the voltage measurement, given that the magnet strength and area are known. These are merely few of many ways to extend the research of this paper into useful application.

6 Conclusion

When put into practice, Faraday's Law of Induction fails to produce a measurable change in current as a magnet passes through a very large coil. The magnetic field of a permanent magnet is limited to a small area, thus the flux through the hoop is divided out by a factor proportional to the radius squared. In order to compensate for this, either the number of coils of wire or the strength/size of the magnetic field must increase. Additionally, it is necessary to determine from the voltage graph whether the magnet has actually passed through or whether it has simply traveled across the hoop. As demonstrated by this paper, both these issues were successfully addressed in the construction of a 36-inch hoop. By increasing coil turns and a creating a separation algorithm for the voltage graphs, the hoop was able to detect the passing of a N52 magnet through its plane. This suggests that larger hoops may be constructed and supports the potential for future practical application of electromagnetic induction.

Appendix A ESP-32 Script

```
#define VOLTAGE_READ 34
#define LED 22

void setup() {
  Serial.begin(9600);
  pinMode(LED, OUTPUT);
  digitalWrite(LED, HIGH);
}

int delayTime = 1;
int sampleSize = 20;
int calibratedAvg = 96;
int threshold = 15;

void loop() {
  float avg_voltage = 0;
  int i;
  for (i=0; i<sampleSize; i++) {
    avg_voltage += 1000.0 * analogRead(VOLTAGE_READ) * (3.3 /
        4095.0);
  }
  avg_voltage = avg_voltage/sampleSize;
  Serial.print(avg_voltage);
  Serial.println(" mV");
```

```

  if (abs(avg_voltage - calibratedAvg) > threshold) {
    digitalWrite(LED, LOW);
    delay(1000);
  }
  else digitalWrite(LED, HIGH);

  delay(delayTime);
}
```

Appendix B Distance-To-Set LOOCV

```
clear; clc; close all;
load compare.mat;
N = 12;
success = zeros(1,2);

for i = 1:N
    through_vec = toss_through(:, i);
    through_indices = [1:(i-1), (i+1):N];
    distances_through_to_through = zeros(1, length(through_indices
       ));
    for k = 1:length(through_indices)
        idx = through_indices(k);
        distances_through_to_through(k) = norm(through_vec -
           toss_through(:, idx));
```

```
    end
    min_dist_through_to_through = min(distances_through_to_through);

    distances_through_to_across = zeros(1, N);
    for k = 1:N
        distances_through_to_across(k) = norm(through_vec - toss_across(:, k));
    end
    min_dist_through_to_across = min(distances_through_to_across);

    if min_dist_through_to_through < min_dist_through_to_across
        fprintf('toss_through(:, %d) is closer to toss_through set.\n', i);
        success(1,1) = success(1,1) + 1;
    else
        fprintf('toss_through(:, %d) is closer to toss_across set.\n', i);
    end
    success(1,2) = success(1,2) + 1;

    across_vec = toss_across(:, i);
    across_indices = [1:(i-1), (i+1):N];
    distances_across_to_across = zeros(1, length(across_indices));
    for k = 1:length(across_indices)
        idx = across_indices(k);
```

```
        distances_across_to_across(k) = norm(across_vec - toss_across(:, idx));
    end
    min_dist_across_to_across = min(distances_across_to_across);

    distances_across_to_through = zeros(1, N);
    for k = 1:N
        distances_across_to_through(k) = norm(across_vec - toss_through(:, k));
    end
    min_dist_across_to_through = min(distances_across_to_through);

    if min_dist_across_to_across < min_dist_across_to_through
        fprintf('toss_across(:, %d) is closer to toss_across set.\n', i);
        success(1,1) = success(1,1) + 1;
    else
        fprintf('toss_across(:, %d) is closer to toss_through set.\n', i);
    end
    success(1,2) = success(1,2) + 1;
end

accuracy = (success(1,1)/success(1,2))*100;
fprintf('Accuracy: %.2f%%\n', accuracy);
disp(success);
```