

Velocity Monitoring via Magnetic Interaction¹

A Mechatronics Demonstration Project

by

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Abstract

In order to demonstrate Faraday's Law ($\varepsilon = -N d\Phi/dt$), a simple interaction between coils of wire and a magnet mounted on the top of a toy car racing down a track was constructed. The project can be used to show high school students that a changing magnetic flux produces an induced emf (electromotive force) and for more advanced physics students how this emf can be used, with some approximations, to determine the velocity of the car. The emf of the car is measured using mechatronics, the synergistic integration of mechanical engineering, computer science and electronics.

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1. Curriculum Standards Correlation

This project deals with Electromagnetic Induction which is a topic in Physics—The Physical Setting⁽¹⁾. Electromagnetic induction (including Faraday’s Law and Lenz’s Law) constitute 5% of the Advanced Placement Physics (B) syllabus and 8% of the Physics (C) syllabus⁽²⁾.

This project also supports the following New York State Core Standard content and process skills:

STANDARD 1—Analysis, Inquiry and Design, Mathematical Analysis

Students will use mathematical analysis, scientific inquiry, and engineering design as appropriate, to pose questions, seek answers and develop solutions.

STANDARD 6---Interconnectedness:Common Themes

Students will understand the relationships and common themes that connect mathematics, science and technology and apply the themes to these and other areas of learning.

STANDARD 7----Interdisciplinary Problem Solving

Students will apply the knowledge and thinking skills of mathematics, science and technology to address real-life problems and make informed decisions⁽³⁾.

2. Introduction

Historical

The discovery that an electric current in a wire is produced by a changing magnetic field was a turning point in physics and the technology that followed. The question arose as to whether magnetism could produce electric current in a wire. In 1831, two physicists, Michael Faraday in England and Joseph Henry in the United States, independently discovered that the answer to this question is yes. Up until their discovery, the only current-producing devices were voltaic cells, which produced small currents by dissolving expensive metals in acids. These were the forerunners of our present-day batteries. The discovery of Faraday and Henry provided a major alternative to these crude devices. Their discovery was to change the world by making electricity so commonplace that it would power industries by day and light up cities by night⁽⁴⁾.

Theory

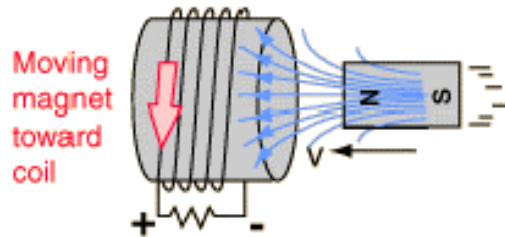
Faraday and Henry both discovered that electric current could be produced in a wire by simply moving a magnet in or out of a wire coil. They discovered that a voltage was induced by the relative motion between a wire and a magnetic field. This is now known as electromagnetic induction which can be summarized in a statement that is called

Faraday's law: the induced voltage in a coil is proportional to the product of the number of loops and the rate at which the magnetic field changes within the loops. This statement can be expressed in a differential form as⁽⁵⁾:

$$\varepsilon = -N \frac{d\Phi}{dt} \quad (1)$$

where N is the number of loops of wire, Φ is the magnetic flux and t is time. The magnetic flux, is given by:

$$\Phi = \int \mathbf{B} \cdot d\mathbf{A} \quad (2)$$



In equation (2) \mathbf{A} is the area vector of magnitude A that is perpendicular to the area.

As a special case suppose that the loop lies in a plane and that the magnetic field is perpendicular to the plane of the loop. Then we can write the dot product of equation (2) as $BdA \cos 0 = BdA$. If the magnetic field is also uniform then B can be brought out in front of the integral sign. The remaining integral of dA then is just the area A of the loop,

$$A = \pi r^2 \quad (3)$$

Substituting, (2) and (3) in (1) we get,

$$\varepsilon = N\pi r^2 \frac{dB}{dt} \quad (4)$$

In order to evaluate the change in the magnetic field with time we assume that it can be written as,

$$\frac{dB}{dt} = Bv/L \quad (5)$$

In (5) v is the velocity of the magnet and L is the length of the loops measured in the direction of motion of the magnet. Substituting (5) in (4) we get,

$$\varepsilon = N\pi r^2 Bv/L \quad (6)$$

In (6) ε can be measured using a microprocessor, r , N , L can be measured and thus v can be calculated. Given the approximations made in arriving at (6) it can be rewritten as

$$\varepsilon = K v \tag{7}$$

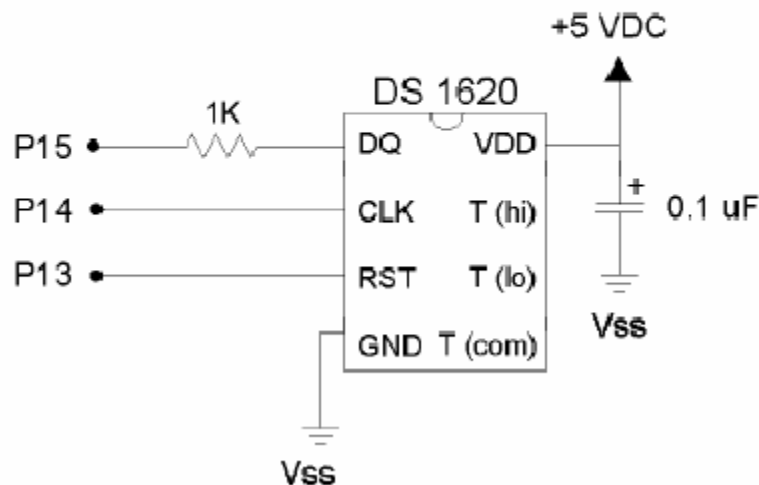
where K is the proportionality constant which is equal to $N\pi r^2 B/L$. In our project K was evaluated and then used to determine the unknown velocities from measurements of induced emfs. This velocity calculated from (7) is then compared to the velocity measured using a photogate..

3. Equipment List

Components: ADC0831

To experimentally measure the emf generated the BASIC Stamp and ADC0831 integrated circuit (microprocessor) is used. An integrated circuit is a circuit with microscopic components implanted on the surface of a silicon wafer. This microprocessor uses 8 bits to describe the analog voltage it samples. 8 bits is also its resolution which means that it can measure upto 5 V as one of 255 levels. Thus each level is approximately 20 mV.

DS1620 with BS2



Light Emitting Diodes

Diodes are semiconductor devices that allow current to flow only in one direction. A typical use for diodes is rectifying alternating current to direct current. This project uses a form of diode called a Light Emitting Diode (LED). These diodes give off light when there is a potential difference across the diode in the forward (conducting) direction. The LED's used for this project have an output in the infrared range.



Figure 1 Schematic diagram of LED



Figure 2: LED

Phototransistors

Transistors are semi-conducting devices which serve two main functions: as amplifiers and as switches. All transistors have three inputs: a base, an emitter and a collector. There are two types: NPN and PNP depending upon the types of materials used to make the transistor. The nature and operation of transistors are well documented. This project uses a type of NPN transistor called a phototransistor. If the transistor receives a potential at its base that is higher than the potential at the emitter, a current flows between the collector and the emitter. The transistors used in this project are very sensitive to infrared light. Receiving light keeps the base high compared to the emitter. When the light is blocked the base goes low, turning off the current. The combination of the LED and phototransistor serves as a “photogate” which detects the car as it passes through the gate by changing the state of a pin on the BS2 IC from high to low.



Figure 3: Schematic Diagram of phototransistor



Figure 4: Phototransistor

Board of Education and Basic Stamp 2 Chip

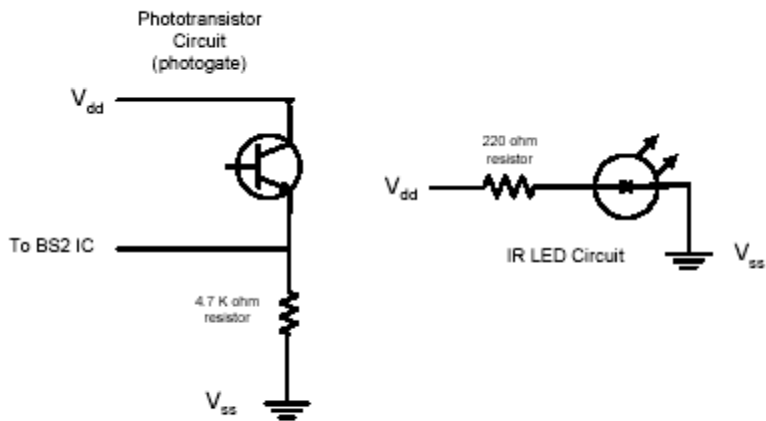


Figure 5: Board of Education and Basic Stamp

The Basic Stamp 2 circuit and the Board of Education project board are the microcontroller used for this project. The Basic Stamp is a special purpose mini computer that contains a microcontroller chip and a small amount of memory to hold interpreters and programs. The BOE provides regulated +5 volts (V_{dd}) and ground (V_{ss}) as well as connections to the 16 pins of the Basic Stamp IC. There is a small breadboard for circuitry and a DB9 connector for programming the BS2 IC and for serial communications while programs are running. Using a programming language, Pbasic, the Stamp can be programmed to perform a variety of operations.

4. Experimental Procedure

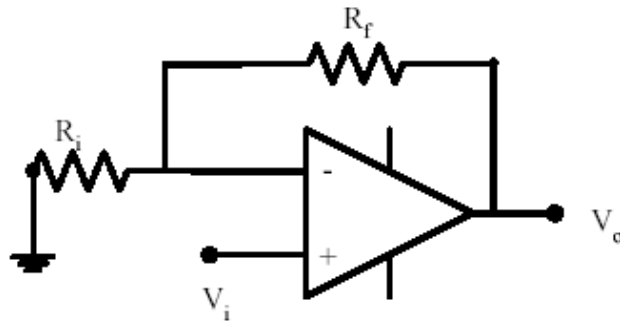
450 turns of copper wire was wrapped around a plexiglass cylinder and the assembly connected to a track. A car raced through this track going through the coils of copper wire generating an induced voltage. The velocity of the car was obtained using photogates. The induced voltage should be linearly related to the velocity. A schematic diagram of the layout is shown below. The circuit diagram for the phototransistor and the IR LED is shown on the next page.



The circuit diagram for the ADC and the noninverting amplifier is shown below.

Non-Inverting Amplifier

- Gain = $\frac{V_o}{V_i}$
 $= 1 + \frac{R_f}{R_i}$



Program Logic

Velocity Calculation

This program uses one set of photogates. The program checks the status of the first gate, looping until it detects a “0” or blocked state. It then branches to a For...Next routine that checks the status of the second gate and increments a variable. When the second gate goes to zero indicating that the car has reached there, the value of the variable is stored and used to calculate the time. Since the distance between the photogates is known the velocity can be calculated. In this program the velocity is given in m/s times a factor of 10.

Voltage Calculation

The induced voltage coming from the experiment is multiplied by a factor of 10 in the op amplifier and is then measured in the ADC chip. To get the voltage in volts, the computer reading must be multiplied 5 and this answer divided by 2805.

5. **Results**

Coils of copper wire was wrapped around a pexiglass tube and a toy car was set in motion on a track that goes through the tube. The toy car carries a magnet and the magnetic interaction with the loops of wire generates an induced voltage. The magnitude of the induced voltage depends upon the velocity of the toy car. Preliminary results indicate that there is a linear relationship between the voltage and the velocity thus proving equation 7. For example for a velocity of 17.3 m/s we got a voltage of 180 volts and a velocity of 8.5 m/s a voltage of 107 volts. Unfortunately due to time, the velocity of the car could not be controlled by resistors and thus the calibration curve has few values. Further work must be done in this direction. However, our initial results do demonstrate the validity of equation (7).

6. **Conclusion**

Using coils of copper wire and a toy mounted on a track Faraday’s law was demonstrated. Preliminary results appear to indicate that the relationship between the induced emf and velocity is linear, though further work must be done in this regard. This work applied the principles of mechatronics in showing how the voltage can be measured, velocity can be computed using photoresistors and LED’s. .

7. **Suggested Projects**

Additional experiments covering a wider range of velocities to establish the linear relationship between emf and velocity. Altering the design and having a magnet mounted on a cart passing a copper wire. The equations relating induced voltage to velocity are more precise in this case. Another example would be to pass a rectangular loop of wire in a magnetic field and evaluating the current and its direction as the loop enters and exits the magnetic field.

8. **Project Cost Analysis**

1. Hot Wheels Starter Set (Amazon.com \$20)
2. Magnet 1" x 1" x 3/8" (KJMagnetics.com \$6)
3. ADC Chip
4. Non-inverting amplifier
5. Light Emitting Diodes
6. Phototransistors

Total Cost \$26

9. **Acknowledgements**

We would like to thank Project Director Professor Vikram Kapila, Project Instructor Sang-Hoon Lee, Teaching Assistant Anshuman Panda for their assistance and patience. We would also like to thank Alessandro Betti for his assistance and allowing us to use his workshop.

Finally we would like to thank Parallax Inc. for donating a "Homework Board", and a "What's a Microcontroller" text and part kits to each teacher involved in the project and Polytechnic University and the National Science Foundation for making this program possible.

9. Appendix

PBasic Programs

```
' {$STAMP BS2}
' {$PBASIC 2.5}

'veLOCITY monitoring via magnetic interaction
'this program gives the velocity as measured by photogates
'and the velocity measured from the induced emf

'declarations:defines variables used in program

adcbits VAR Byte
emf VAR Byte
C VAR Word
vel VAR Word
r VAR Byte
r1 VAR byte
v1 VAR Byte
vemf VAR word
vemf1 VAR Word

'declarations:defines constants used in the program
' con is the distance between the photogates, in cm times 100
'kprop is the proportionality constant from equation 7 in our report

dist CON 800
kprop CON 77

INPUT 3
INPUT 4

'veLOCITY from photogate

Main:

IF IN3 = 0 THEN COUNT1
'DEBUG HOME, ? IN3
GOTO main

COUNT1:
FOR c=1 TO 65000
PAUSE 1
c=c+1
IF IN4 = 0 THEN EXIT
'DEBUG HOME, ? c
'endif
NEXT

'calculates the velocity in m/s from photogate

vel=dist/c
r=dist//c
v1=10*r/c
```

```

vel=(10*vel)+v1
vel=vel/100
r=vel//100

'veLOCITY from from emf

emf=0
DO
HIGH 0
LOW 0
LOW 1

PULSOUT 1,10
SHIFTIN 2,1, MSBPOST, [adcbits\8]
'DEBUG ? adcbits
'PAUSE 10
IF adcbits > = emf THEN
emf=adcbits
ENDIF
IF adcbits < emf THEN EXIT

LOOP

'calculates velocity from emf

vemf=emf/kprop
r1=emf//kprop
vemf1=10*r1/kprop

DEBUG HOME, "vel. photogate (m/s) = ", DEC vel, ".", DEC r, CR
DEBUG "vel. emf= (m/s) ", DEC vemf, ".", DEC vemf1
'DEBUG DEC vemf, ".", DEC vemf1
PAUSE 1000
'GOTO main
END

```

10. **References**

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