ELECTROMAGNETIC LEVITATOR

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Electromagnetic Levitator

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Abstract—**In this paper, we design magnetic levitation system that deals with the knowledge of electromagnetism and the control switching application. The concept of this design is to achieve the state of equilibrium where the magnetic attraction counterbalances the force of gravity pulling on an object. The control system in this design is formed by a PIC Microcontroller and several op-amps. Using photo sensors to provide a feedback loop, the control system employs a closed-loop control in controlling the current through the electromagnet.**

Keywords-magnetic levitation, current control circuit, feedback control loop, electromagnetism, floating object

I. INTRODUCTION

The purpose of this paper is to implement the control switching technique on floating a metallic object underneath the electromagnet. This technique is similar to the technology used by the maglev trains. These trains will float over a guideway using the basic principles of magnets to replace the old steel wheel and track trains. The Fig.1 shows the design of a maglev train and its electromagnet position placement. The maglev trains do not have an engine to propel the trains, but the magnetic field created by the electrified coil in the guideway walls and track combine to propel the train. The maglev trains are the fastest trains that can go up to 300 miles per hour [1]. The main reason of the trains can travel at this very high speed is due to the friction against the train is very small. The trains are floated and travel in the air. Thus the friction force against it is only the air friction. This is different with the conventional trains that uses steel wheels to move and experienced the rolling friction. Thus the basic principle of floating in the air by maglev is implemented to our electromagnetic levitator.

Figure 1. The placement of electromagnets on the track and train

It is designed to levitate certain amount of weight of metallic object. The levitation is a method of supporting objects which is based on the physical property which refers to the force between two magnetized bodies. An electromagnet is used to levitate metallic object when the current flows through the electromagnet and generates magnetic field. The magnetic field strength is proportional to the amount of current flows when the other conditions are remaining unchanged. Thus the larger current flows could generate stronger magnetic field strength and vice versa. However, the process requires a control system that is fast and accurate to control the position of the metallic object before it attaches itself to the electromagnet or falls to the ground. The position of the object should be controlled in line with the position infrared sensors. Since the object floats in the air, thus it is exerted by air friction only. In the later example, we will show the spinning of the object in the air.

Block diagram is used to explain the process of levitation and analyse the closed-loop control system. We also involves with the PIC, thus the program which is in C Language that will be discussed in this paper.

By the end of this paper, we should be able:

- To design electromagnetic levitator to levitate object.
- To design switching circuit by using PIC.
- To provide stable feedback control loop.
- To analyse the stability of the system.

II. PROJECT DESIGN

A. Circuit Operation

The Fig. 2 shows the block diagram of the levitation system. The position sensors used are infrared diode and infrared detector. Both the diode and detector are based LED, thus they have significant characteristics of LED. When the diode is on, it emits infrared radiation to the detector. The characteristics of output voltage of detector will act as in the Fig.3. The detector will output a voltage of V_{OC} regarded to the amount of radiation is received. The V_{OC} represents the position of the object. If the object fully blocks the radiation, the V_{OC} will be relatively very low or near to $0V$. In contrast, when there is nothing blocks the radiation, the V_{OC} becomes maximum output voltage as the detector receives full radiation

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from the diode [2]. In order to float the object, it must be partially blocks the infrared radiation and the detector will output a range of voltage, which is the position set point.

The output voltage of V_{OC} is feed into the current control circuit. The circuit consists of PIC, compensation circuit and amplifier. The circuit's function is to regulate the current flowing through the electromagnet based on the V_{OC} reading received.

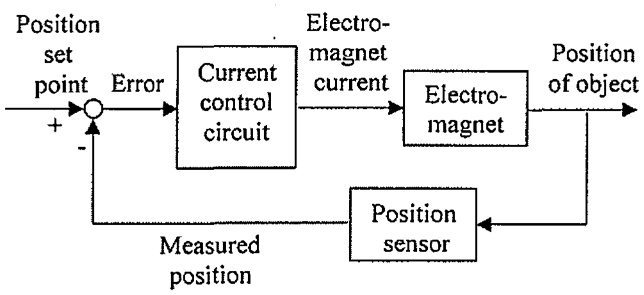

Figure 2. Block diagram of levitation system

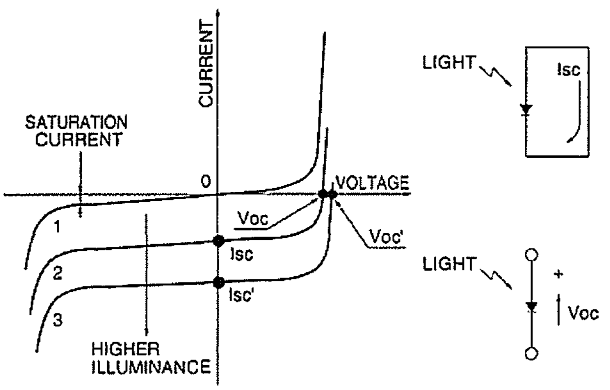

Figure 3. Voltage- current characteristics

B. Circuit Design

By referring to the block diagram, a levitation circuit is design as in Fig. 4. From the circuit, the output of infrared detector is fed to PIC. The PIC is function to switch on or off the transistor Q1. When there is present of object between the sensors and blocks the infrared radiation, the PIC switches on the transistor to keep the electromagnet coil powered on. Whenever the sensors cannot sense any opacity object, or the object is completely blocking the infrared radiation, the PIC will switch off the transistor and immediately powered off the coil. This is to prevent the coil overheating. The PIC output signal is in digital form. R-2R ladder DAC is used to convert the digital output to analog voltage and then fed to an op-amp.

The op-amp is configured for a gain of two, [(R29/R21)/R21] buffers and amplifies the analog voltage. The output signal of the op-amp is fed to a second amplifier stage thus the R-2R ladder DAC is used to convert the digital signal through the R22 and C8. The capacitor C8 forms a differentiator with the op-amp U3:B. The capacitor blocks slow voltage changes, but passes any rapid changes in the input signal and allows them to be amplified by the U3:B. The resistor of R22 and R18, R30 act to attenuate the slow voltage changes before they are amplified by the op-amp. The purpose of this compensation circuit is to perform closed-loop control using a combination of proportional and derivative modes to ensure the levitation is stable. Without it, the object would just flutter close to the electromagnet due to the system being unstable [3].

The filtered voltage is fed to second amplifier stage. The output signal drives transistor Q1 which has a dc current gain of 100 to vary the current to the electromagnet coil. Because of the transistor is switching frequently, the transistor will get very hot during operation, thus a heat sink is attached on the transistor. The signal diode D6 on the base is function to prevent reverse biasing the base. When the transistor suddenly switches off, the two diodes 1N4001 provide a path for the excess current from the electromagnet coil so that it does not damage the transistor.

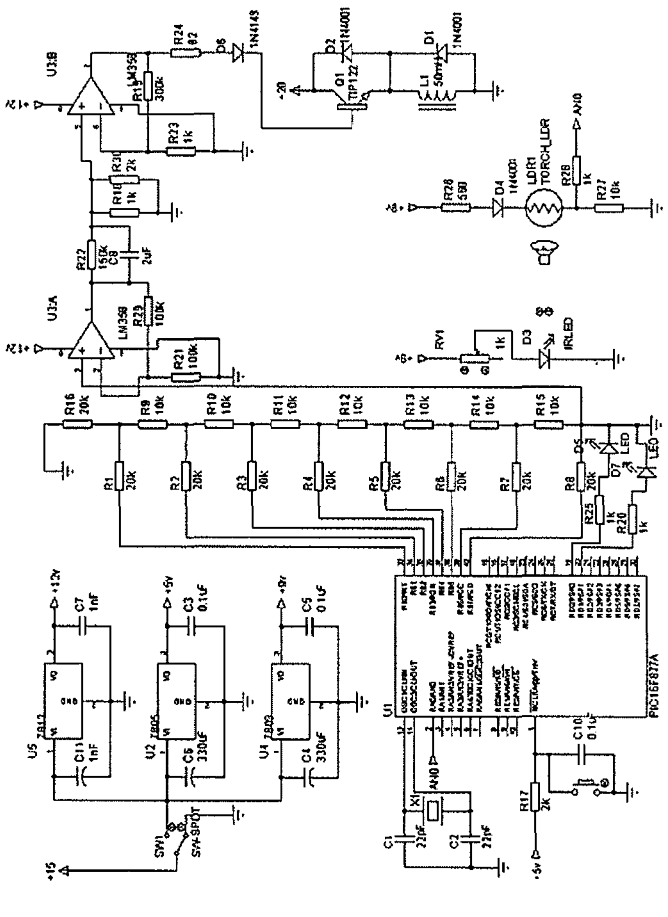

Figure 4. The electromagnetic levitation circuit

C. Chasis Design

The electromagnet and both sensors are attached on a chassis as in Fig. 5. The electromagnet is attached at the middle between the two sensors. The sensors' alignment is in a straight line parallel to the top frame and it through the middle of the bolt head. The gap distance between bolt head and the sensors should be in 5 mm around. Less than it the object will levitate too close to the coil and more than it a lot the coil is unable to levitate heavier objects such as bolt. Both of the sensors must be attached steady to avoid any movement that could vary the radiation and receiver angle. Consequently that will affect the output voltage of detector is differ with desired value and directly affect the PIC operating.

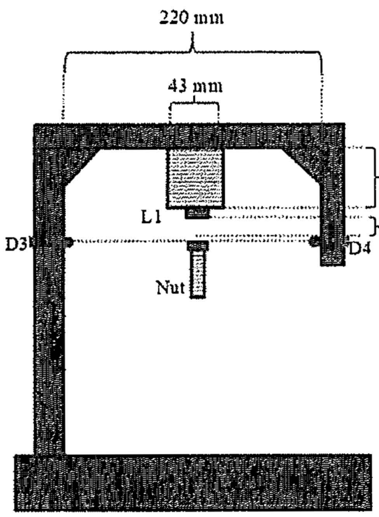

Figure 5. The levitation chassis

III. RESULTS AND DISCUSSIONS

A. SENSORS

The material used in infrared LED is AlGaAs, the radiant intensity is minimum $20 mW/sr$ and maximum forward current is $100 mA$. In the circuit of Fig. 4, the potential meter limits the forward current to the infrared LED to $15 mA$. Because of the LED is always on all the time, thus the current limit is purposed on protect the LED from burning.

From the prototype, the maximum output voltage of the infrared detector is $4.80 V$. Thus the operating range of voltage to turn on the transistor Q1 is set at between $0.70 V$ and $4.50 V$. The output signal of the infrared detector is analysed by using an oscilloscope. The probe is set to 10x and also the channel 1 coupling to AC mode. When the circuit is on and there is nothing presents between the infrared sensors, the output voltage is like in the Fig.6. The signal is flat due to the output signal is maintained at one point. But when there is an object is levitating, the infrared radiation is being partially blocking, this will affect the output voltage of the detector. The Fig. 7 is the output signal during levitation process. The signal is oscillating because of it is proportional to the position of the object [4].

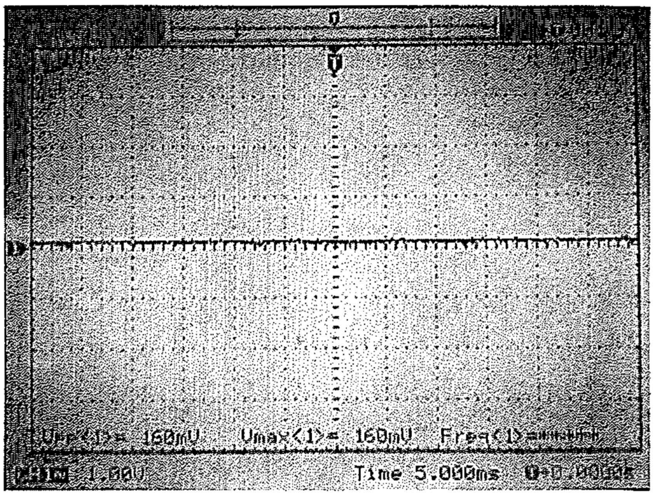

Figure 6. The output signal of the infrared detector when there is nothing blocking the infrared radiation

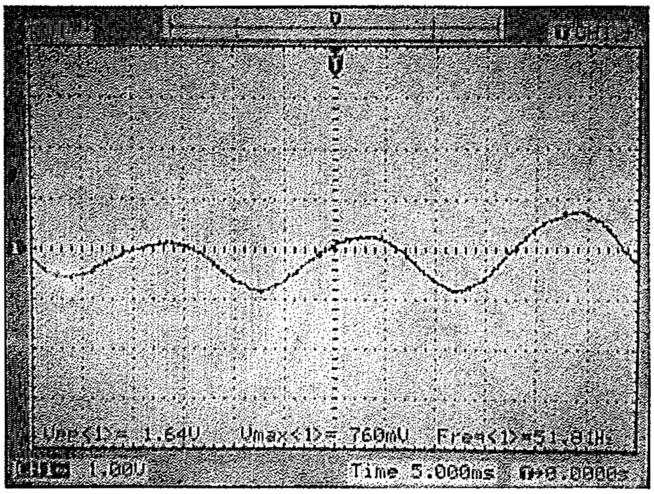

Figure 7. The output signal of the infrared detector when an object is blocking the infrared radiation

B. PIC

The PIC reads the signal from the detector and only produces digital output in the operating range. The PIC consists of analog to digital converter (ADC) which converts the analog signal to digital number. The Successive Approximation Method can be used to encode the analog signal [5]. The 8-bits registers with a full-scale range of $5V$ are used in the conversion.

E.g. The PIC reads the output voltage of the detector is $3V$. The binary value is 10011001_2. After the processing of the PIC, it will output 8-bits digital signal. The signal is converted to analog voltage by R-2R ladder DAC. The output voltage of the DAC is:

$$V_{out} = V_{ref}\,[b_1 2^{-1} + b_2 2^{-2} + \ldots + b_N 2^{-N}] \qquad (1)$$

E.g. take the 10011001_2 binary values, the output voltage is

$$V_{out} = 5V[(1)2^{-1} + (0)2^{-2} + (0)2^{-3} + (1)2^{-4} + (1)2^{-5} + (0)2^{-6} + (0)2^{-7} + (1)2^{-8}]$$
$$= 2.988V$$

This output voltage of $2.988V$ is less than the input voltage of $3V$. This is due to there is not always be linearity between a digital input and analog output.

The Fig. 8 is the program of PIC. The program is started with convert the analog signal to digital signal. Then compare the digital signal to on or off the PIC output.

```
#include <16f877a.h>
#device adc=8
#fuses HS,NOWDT,NOPROTECT,NOLVP
#use delay (clock=20000000)
#byte PORTA=5
#byte PORTB=6
#byte PORTD=8
#use fast_io(A)
#use fast_io(B)

void main()
{
unsignedint input;

setup_adc( ADC_CLOCK_INTERNAL );
setup_adc_ports(RA0_ANALOG);
set_adc_channel( 0 );
set_tris_b(0x00);
set_tris_d(0xFE);

while (TRUE)
  {
input = read_adc(); //read analog input

if (0b00100011 <= input && input <= 0b11100101)
//set operating range
  {
output_b(input);
output_high(pin_d0);
    }
```

Figure 8. Program of PIC

C. Compensation Network

The compensation network is acts as a high pass filter to stabilize the control loop. The Fig. 9 and Fig. 10 show the signal before and after filtered and attenuated by the compensation network. There is a distinct smoother signal at the output of the network.

D. Electromagnet

The electromagnet generates magnetic field to attract the object. The force of attraction is equals to the weight to be levitated. This force is inversely proportional to the distance of separation between the coil and the object. This is proved by the (2), where the force of attraction, F_m is

$$F_m = \frac{\mu}{2}\left(\frac{NI}{g}\right)^2 \times Area \qquad (2)$$

Where μ= permeability of core and free space
NI = Ampere turns
g= gap length

The relationship between the force of attraction and gap length can be plotted as in Fig.11. The curve (a) is dc excitation while the (b) is ac excitation with series capacitor [6].

The magnetic field strength (H) is proportional to the number of turns (N) and current (I) of the electromagnet. For a solenoid, this proportional relationship is proved by (3) [7].

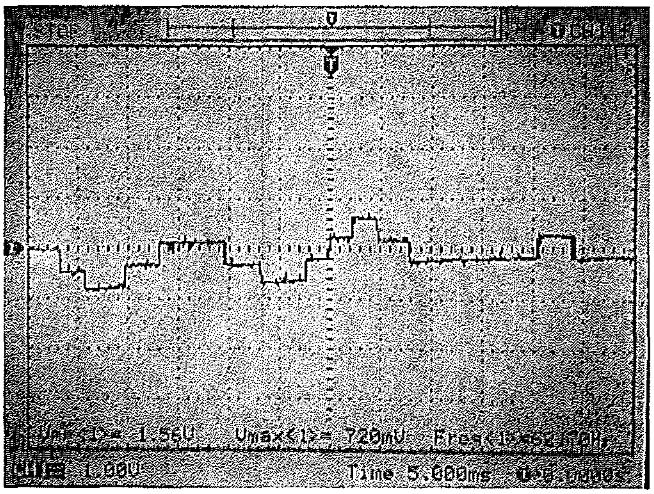

Figure 9. The signal before filtered and attenuated

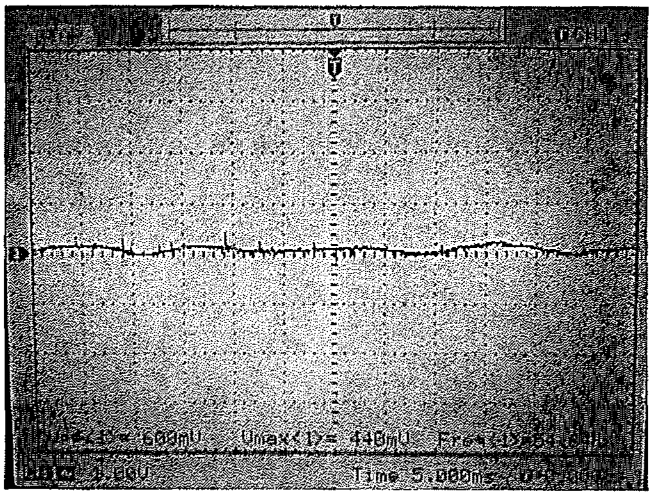

Figure 10. The signal after filtered and attenuated

$$H = \frac{IN}{l}, l = \text{length of flux path} \tag{3}$$

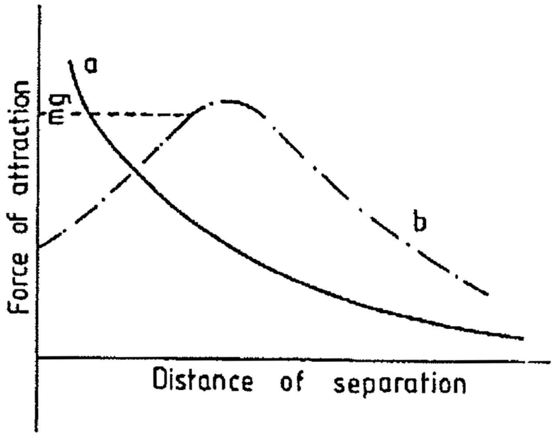

Figure 11. The force/ distance curve

In this project, the electromagnet is built by enamelled copper wire of AWG 18. The number of turns is 1500 turns. The coil's dimension is stated in Fig. 5.

E.g. If 1 ampere current is supplied to the coil.

$$H = \frac{1(1500)}{0.045} = 33.333 kA/m$$

The magnetic flux density is

$$B = \mu_0 \mu_r . H \tag{4}$$

Where the μ_0 is permeability of free space; μ_r is permeability of the bolt.

From the (3), since $H \propto IN$; and the N is fixed, so the current is regulated to generate proportional force to levitate object.

Since the electromagnet is a multilayer multi-row coil, the inductance can be calculated by (5) [8].

$$L = \frac{0.8\pi \mu_0 \mu_r r^2 N^2}{0.9r + l + d} \tag{5}$$

Where r= Radius of the inside of the coil in meters; N = total number of turns; d = depth of coil, and l = length of coil.

The parameters are: $r = 4.5mm$, $N = 1500$, $l = 43mm$, and $d = 17mm$. Hence the inductance of the electromagnet coil is $2.247\mu_r mH$ since the μ_r is the permeability of the bolt.

E. Air Friction

One of the main reasons of applying electromagnetic levitation technique on trains is the only friction working against it is between the trains and the air. This is proved by impart a bit of a spin to the levitated object and momentum will carry it for quite a long time. The Fig.12 shows a bolt is floating and spinning underneath the electromagnet while it is located in no moving air room. By apply a bit of force to spin it; the bolt takes 23 minutes to finish spinning. Of course, the time taken of the bolt to finish spinning is dependent of the surrounding conditions, the level of applied force, and the magnetic field strength. But this is proved that the air friction is very small.

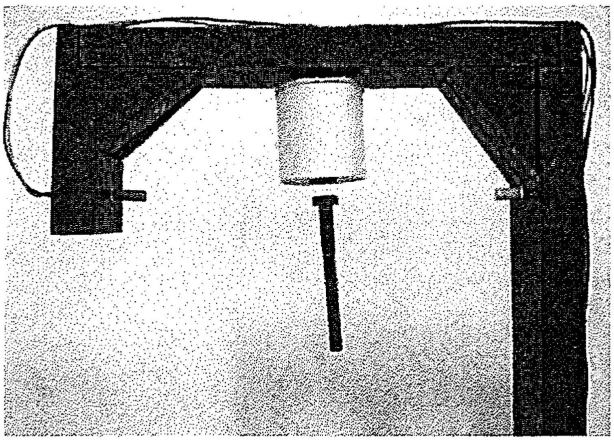

Figure 12. The bolt is keeps spinning for a long time after a force is applied to spin it

IV. Conclusion and Recommendation

The electromagnetic levitator project is finished perfectly by successfully achieves all the objectives of this project. To design the circuit, literature review plays an important role to determine the components used and the designing circuit. By a few lines of program, it gives instructions to the PIC to switching the current to avoid the electromagnet getting hot. For the compensation network, it is acts as a high pass filter to block slow voltage changes. Beside this, it is also functions in attenuates the slow voltage changes. These two assurances are maintaining the stability of the system. The signal of before and after filtered can be analysed by using oscilloscope, whereas the waveform is smooth or not as shown in Fig. 10 and Fig. 11. At the end of this project, the metallic object such as bolt, nut, or steel ball are able to levitate with stable underneath the electromagnet.

The technology of electromagnetic levitation currently is mainly applied to maglev train. This technology should be developed to other fields such as home appliances; this is a potential field that will utilize the technology and carry forward to upper level.

V. References

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