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DESIGN, DEVELOPMENT AND TESTING OF AN ELECTROMAGNET FOR MAGNETIC SUSPENSION SYSTEM

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ABSTRACT

This paper presents design and development of an electromagnet for use in magnetic suspension control system experiment. The method is purely based on analytical approach. Some materials are found to be good when used as a former for electromagnet. Cast steel is found to be one of such materials because of its high permeability and fairly good coercivity. Electromagnet is not very common in our market therefore this paper gives a method of designing, constructing, testing and getting the parameters of the magnet. The genesis for the design is based on the phenomenon of lifting power of a magnet. Thus cast steel is used as a former and the design is implemented using locally available component; the developed electromagnet is able to lift various weights from distances below the pole of magnet, by varying the current through the winding of the magnet. In the final analysis, the designed electromagnet is built with a cost saving of about 70% of its market value. The force constant of the magnet was determined.

INTRODUCTION

An electromagnet is a type of magnet in which the magnetic field is produced by the flow of an electric current. The magnetic field disappears when the current ceases. Electromagnet uses electricity to produce magnet force [1]. The main advantage of an electromagnet over a permanent magnet is that the magnetic field can be rapidly manipulated over a wide range by controlling the

amount of electric current. However, a continuous supply of electrical energy is required to maintain the field.[1]

The lifting power of an electromagnet is the ability of the magnet to lift a ferromagnetic material from a given distance. Different magnets have different magnetic strength. [2]

Computing the force on ferromagnetic materials is, in general, quite complex.

This is due to fringing field lines and complex geometries. It can be simulated using finite element analysis. However, it is possible to estimate the maximum force under specific conditions such as magnetic field being confined within a high permeability material, such as certain steel alloys.

Industrial lifting electromagnets are designed with both poles face at one side (the bottom). This confines the field lines to maximize the magnetic field. It's like a cylinder within a cylinder. Many loudspeaker magnets use a similar geometry, although the field lines are radial from the inner cylinder rather than perpendicular to the face.[1]

An electromagnet has many applications in industries. The principle of operation of electromagnet forms the basis on which relays and contactors are designed. In transportation industries, the present's magnetic levitated electric train uses an electromagnet to suspend the whole train [1] in some industries an advert is suspended on air by the use of electromagnet [6]. In laboratories electromagnet is used in the levitation control experiment [8].

Electromagnet is not very common in electrical/electronic shops in our country. Electromagnet can have different specification such as lifting power, maximum current it can passed and soon. Therefore this paper gives a method of designing, constructing, testing and even how the parameters of the magnet are obtained. The rest of the report is organized as follows section 2 gives the designed feature of the electromagnet. Section 3 highlighted the mathematical model of the electromagnet, section 4

gives some experimental results obtained and finally a conclusion is drawn in section 5.

MATERIALS AND METHODS

2.0 DESIGN FEATURES

The main consideration in the design of an electromagnet is its lifting power of the magnet [1]. Cast steel is selected for this design because it has a narrow loop area which gives it a high permeability and fairly good coercivity, hence making it suitable for core of electromagnet [1]. The core of the electromagnet is first specified, the core area (shape) , diameter, and the required length of the winding are then selected by estimating or calculating amount of current expected to pass through when lifting the required load. The estimated maximum force under specific conditions when magnetic field is confined within a high permeability material is given by [1], [2].

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$$(1)$$

Where:

$F = \frac{\mu_0 B^2 A^2}{4\pi}$ F is the force in newtons

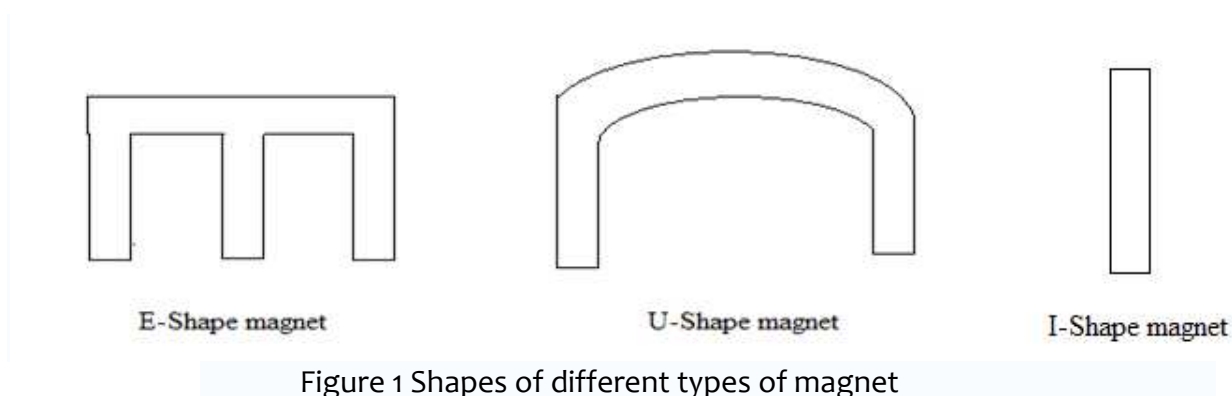
$B = \frac{\mu_0 I N}{l}$ B is the magnetic field in teslas

$A = \frac{\pi d^2}{4}$ A is the area of the pole faces in square meters

$\mu_0 = 4\pi \times 10^{-7} \text{ T}\cdot\text{m/A}$ μ_0 is the permeability of free space

In the case of free space (air), μ_0 **Error! Reference source not found.**

When the pole area of the magnet to be used, in lifting an object is not one, then the total force is divided by the no of poles used [1]. Some of the magnetic shapes with different number of poles are shown in figure 1. U-shape has two poles while E-shape has 3-poles [1].



3.0 MATHEMATICAL MODEL OF ELECTROMAGNET

Computing the magnetic field and force exerted by ferromagnetic materials is difficult, because the magnetic field and force are non-linear function of the current, depending on the nonlinear relation between magnetic field (B) and electrical field (H) for the particular core material used [7]. However, in designing DC electromagnet, in which the current is either on or off, the relations, can be simplified [7]. The main feature of ferromagnetic materials is that the B field saturated at a certain value, which is around 1.6T for most high permeability core steels. The B field increases quickly with increasing current up to that value, but above that value the field levels off, regardless of how much current is sent through the windings [7]. So it is not possible to obtain a much stronger magnetic field from electromagnet than 1.6T. The maximum force (holding force) exerted by an electromagnet is given by equation (1). So saturation set a limit on the maximum force per unit core area, or pressure, an electromagnet can exert [7]. Given core geometry, the B field needed for a given force can be calculated from equation (1); if it comes out to much more

than 1.6T, a larger core must be used [7]. Once the B field needed is known, the magneto-motive force, the current and the number of turns in the winding can be calculated [7]. The lifting power of an electromagnet is the ability of the magnet to lift a ferromagnetic material from a given distance [2]. Equation (1) is the lifting power or force for I-shape core of the electromagnet. For U-shape the force formula is divided by two, while for E-shape it's divided by three, this is because the U-shape has 2 poles and E-shape has 3 poles which will participate in lifting of the load.

In this design, a bolt and nuts that form an I-shape which is made from steel rod with the following dimension when measured is used. The following specification are chosen in this design; 10mm diameter of the bolt, 85mm pitch (length of the winding area or former) and 15mm pole diameter (diameter of the nut used as a pole). In this design also it is assumed that; the magnet is to lift a load of 100g from 25mm below the pole of the electromagnet (air-gap). This is one of the specification in the design, many specification are possible. The set up is showing in Figure 2

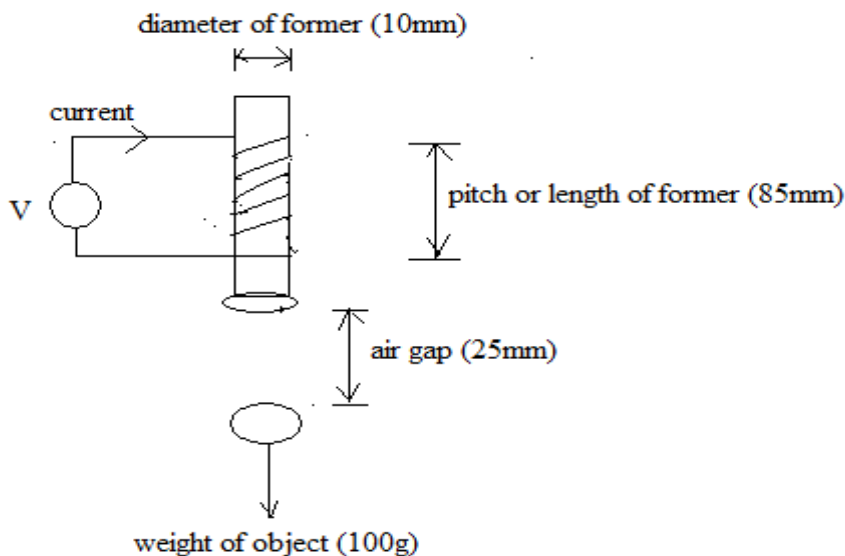


Figure 2 Dimensions of the I-shape electromagnet

When the magnet energizes, it will tend to lift the ferromagnetic material around its pole(s) [5]. It can only lift this load (object) when the magnetic force is greater than the gravitational force of the load [6]. The gravitational force is given by:-

$$F = mg$$

(2)

Where m is the mass of the load and g is the acceleration due to gravity (9.81m/s^2) at equilibrium the two forces are equal. $F_{\text{magnet}} = F_{\text{gravity}}$. From the above specification the load is 100g

In this case-study the maximum mass of the object to be lifted is 100g (0.1Kg). Therefore, the gravitational force is $100\text{g} (0.1\text{kg}) \times 9.81\text{m/s}^2 = 0.981\text{N}$.

The lifting force has to be greater than 0.981N before it can raise the object. The pole area is given by $A = \pi d^2 / 4$, where d is the pole diameter which is 15mm

$$A = \pi (15 \times 10^{-3})^2 / 4 = 1.767 \times 10^{-4} \text{m}^2 \quad (3)$$

$\mu_0 = 4\pi \times 10^{-7}$, $m = 100\text{g}$, and $g = 9.81\text{m/s}^2$ substituting this into equation (1) we have:-

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(4)

From which B is calculated as 0.1193wb/m^2 This is the flux density in the air gap and is the same as the flux density in the core for a very small air-gap; the total flux in the core is [2]

$$\Phi = B \times A$$

(5)

Where A is the core area, since the magnet acts like a closed cylinder; the area is given by [3]

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(6)

Where r is the half diameter of the core and l is the length of the former, Since $r = 5\text{mm}$ and $l = 85\text{mm}$.

The area is computed to be $A=0.00283\text{m}^2$
Hence the total flux from equation (5) is obtained to be $\Phi = 3.373 \times 10^{-4}\text{Wb}$.

This total flux in the core is the same as the flux in the air-gap [3]. The magnetizing force (H) in the air-gap is given by $H = B/\mu_0$

(7)

Therefore **Error! Reference source not found.** = **Error! Reference source not found.** = $94,936\text{AT/m}$

For the air-gap of 25mm the magneto-motive force (mmf) is given by

$$AT = H \times L = 94936 \times 25 \times 10^{-3} = 2373.4\text{AT}$$

(8)

L is the length of air-gap specified as 25mm

This magneto-motive force is the product of the current that will go round the magnet and the number of turns of the wire that make up the magnet. If one of the variable is chosen the other variable can be calculated, thus if the number of turns is chosen to be 1320, then the current in the electromagnet is given by;

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(9)

Therefore the current is computed to be 1.789A.

Finally the lifting power or force of the magnet is computed using equation (1) as

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(10)

The maximum operating voltage and the current are determined by the wire used to create the magnetic field.

3.1 WIRE SELECTION

The choice of the wire gauges for a given current density is conveniently made in terms of circular mils per ampere [2]. A circular mil is the area of a circle whose diameter is 1 mil (0.001 inch), and it is usually abbreviated as cir mil. To compute the circular mils for any wire, the current and current density need to be known before computing and then selecting the wire.

Circular mils = working current density x current

(11)

The standard working current density (j) are;- 700, 1000, 1500, 2000 etc .

A standard working current density of 1000 is selected. This is because the current of this category can lift a medium weight. Using equation (2.9) with a computed current of 1.798 the circular mils is 1798.

Hence from the standard Annealed copper wire, solid American wire gage (B&S) English unit the following were extracted [2].

Cir mil for gage number 17 is 2050

Cir mil for gage number 18 is 1620

Cir mil for gage number 19 is 1290

Again from another table of AWG [2] the following were extracted

At a working current of square inch density of 1000 the 17 AWG can withstand 2.463A.

At a working current of square inch density of 1000 the 18 AWG can withstand 1.810A.

At a working current of square inch density of 1000 the 19 AWG can withstand 1.257A.

The diameter of the above 3 different wire gages were;-

17 AWG has a diameter of 0.056 inch

18 AWG has a diameter of 0.048 inch

19 AWG has a diameter of 0.040 inch

Considering the above 3 different comparison gage 18 wire was selected for this design because it gives the approximate values to our computed/selected values. The diameter of gage 18 is 0.048 inch which equivalent to 1.2192mm.

3.2 DETERMINATION OF THE LENGTH OF THE WIRE NEEDED

The wire is to be wound on the former of the electromagnet. At this point, the following parameters are known; the diameter of the former is 10mm, the length of the pitch or former is 85mm and the diameter of the wire to be wound is 1.2192mm.

The maximum number of winding in the first layer will be $85\text{mm} / 1.2192\text{mm} = 69.72$ turns,

Chosen a stacking factor of 0.9, the maximum number of turns on the first layer will then be $69.72 \times 0.9 = 63$ turns. If each layer is to have this maximum number of turns then, the total number of layers required to give the total number of turns will be;-

Total no of layers = **Error! Reference source not found.** $= 1320 / 63 = 21$ layers

When rewinding the wire the perimeter of each subsequent layer will be increased by $2d$, where d is the diameter of the wire i.e. (1.2192mm)

First layer perimeter (length) will be $\pi D \times 63 = \pi \times 10\text{mm} \times 63 \text{ turns} = 31.42\text{mm} \times 63 \text{ turns}$

Hence the length of one turn on first layer is 31.42mm

The length of one turn on second layer is $31.42\text{mm} + 2d$, $= 31.42 \text{ mm} + 2 \times (1.2192\text{mm})$

The length of one turn on third layer = second layer perimeter + $2d$

The length of one turn on fourth layer = third layer perimeter + $2d$

The length of one turn on fifth layer = fourth layer perimeter + $2d$ etc this form an Arithmetic Progressive (AP) [3]. The AP formed has the following parameters;-

First term (a) = 31.42mm, common difference $d = 2d = (2.4384\text{mm})$, number of terms $n = 21$

The length of the wire can be computed using sum of AP [3]

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$$(12)$$

Substituting above in to equation (12) we have sum = 1,172,094mm

Hence the total length required is the sum multiply by the total number of turns.

The total length is $1,172,094 \times 63 = 73,841,922\text{mm}$ or 73.841922m which is the same as 80.755 yards or 242.264 ft.

3.3 RESISTANCE AND INDUCTANCE OF THE WIRE

The resistance of the wire is computed from the table of resistance, for 18 AWG, the 18 gage has a resistance of 6.51Ω per 1000ft or 34.4Ω per miles at 25°C and 7.51Ω per 1000ft at 65°C [4]. Since the length of the wire is 242.264ft therefore at 25°C the resistance will be $6.51 \times 242.3 / 1000 = 1.5773\Omega$ and at 65°C the resistance is 1.819Ω .

The inductance of the coil formed is computed as follows;-

$$L = N\Phi / I$$

$$(13)$$

Where L is the inductance of the coil
 $L = 1320 \times 3.373 \times 10^{-4} / 1.798 = 0.2476H$

3.4 WEIGHT OF THE WIRE

The wire is normally sold per kilogram; from the table gage 18 has a weight of 20.92 pounds per 1000 yards. As mentioned above, the length of the wire is 80.755yards, therefore the weight is calculated as follows:-

$$\frac{20.92 \text{ pounds}}{1000 \text{ yards}} \times 80.755 \text{ yards} \times \frac{0.4536 \text{ kg}}{1 \text{ pound}} = 0.766 \text{ kg}$$

The results obtained in section 3 are used to develop the electromagnet. It is used to lift various weights at different positions below the magnetic pole. The following results were obtain when lifting a known weight at a known distance the current, voltage, weight and the corresponding magnetic force constant are obtained;- Table 1 shows the current taking when lifting various weights. The weight and the current are showing in Figure 3, it can be seen how initially the relation is linear before saturation at weight above 500gms.

4.0 EXPERIMENTAL RESULTS

Table 1

| S/N | Current (A) | Weight (grms) |
|-----|-------------|---------------|
| 1 | 0.10 | 132.32 |
| 2 | 0.20 | 177.23 |
| 3 | 0.30 | 247.23 |
| 4 | 0.40 | 297.23 |
| 5 | 0.50 | 305.23 |
| 6 | 1.00 | 508.13 |
| | | 562.9 |
| 7 | 1.50 | 1 |
| | | 621.6 |
| 8 | 2.00 | 2 |
| | | 648.3 |
| 9 | 2.50 | 3 |

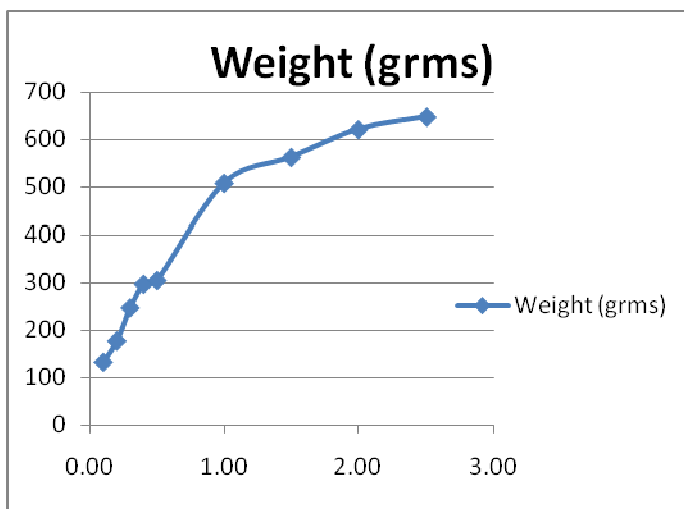


Fig 3 Weight and current relationship in Electromagnet

Table 2 shows the relationship between the current following in the magnet and the voltage across the magnet. Figure 4

shows how the current and voltage are linearly related before reaching 15V at reading 12.

Table 2 Voltage and Current readings

| S/N | volt (V) | Current (A) |
|-----|----------|-------------|
| 1 | 3 | 0.1 |
| 2 | 5 | 0.7 |
| 3 | 6 | 0.9 |
| 4 | 7 | 1.25 |
| 5 | 8 | 1.5 |
| 6 | 9 | 1.8 |
| 7 | 10 | 2.0 |
| 8 | 11 | 2.4 |
| 9 | 12 | 2.5 |
| 10 | 13 | 2.8 |
| 11 | 14 | 3.0 |
| 12 | 15 | 3.2 |
| 13 | 18 | 3.8 |
| 14 | 19 | 4.2 |
| 15 | 20 | 4.4 |

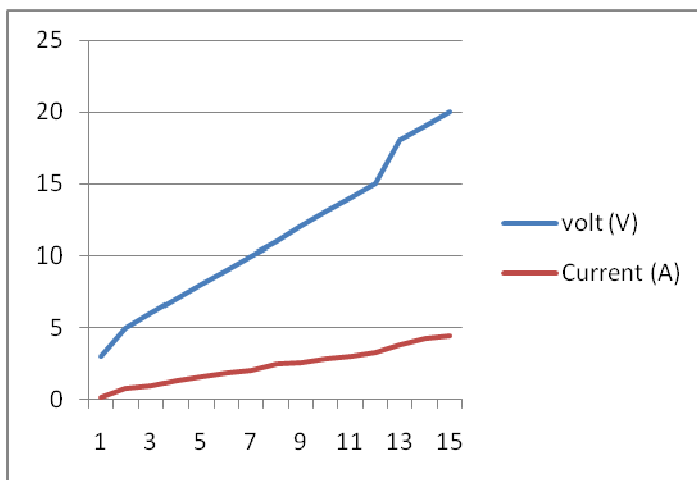


Fig 4 Current and Voltage relationship in Electromagnet

Figure 5 shows a relationship between the current and the voltage across the magnet the inverse of the slope gives the resistance of the magnet. The measured

resistance of the magnet is almost the same as the value obtained from the graph.

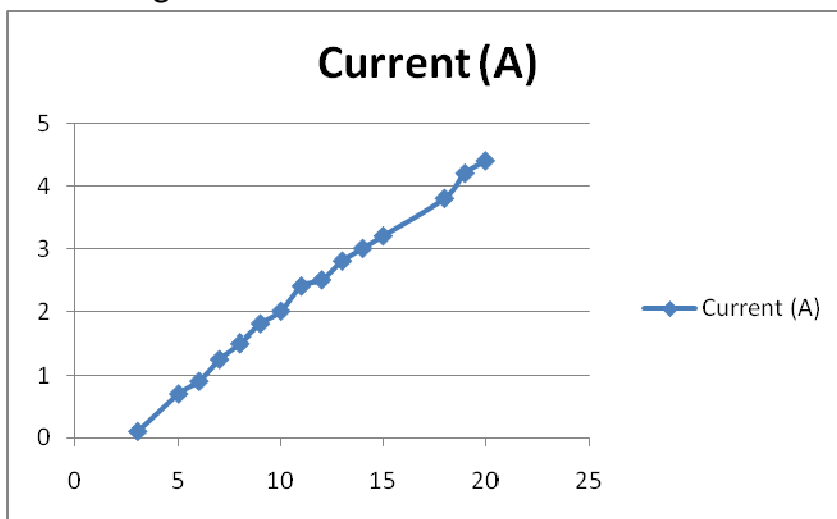


Figure 5 Resistance of the Magnetic coils

The magnet is then used to suspend a steel ball of various weights at different positions. A phase lead compensator is designed and implemented for the

suspension of the steel ball. The magnetic strength is computed using the formula [6]

$$C = (y/l)^2 * mg \tag{14}$$

Where y is the distance between the pole and the steel ball in meters, I is the current through the magnet when the steel ball is suspended and, m is the mass of the steel ball and g is acceleration due

to gravity ($9.8m/s^2$) Table 3 gives the computed values of constant of the Magnet or Strength of the magnet when used to suspend a ferromagnetic material.

Table 3 Relationship of some variables

| S/N | Weight (gm) | Current (A) | Distance (mm) | Force Constant (NM/A) |
|-----|-------------|-------------|---------------|-----------------------|
| 1 | 10 | 0.23 | 10 | 0.00280 |
| 2 | 8.7 | 0.21 | 13 | 0.003167 |
| 3 | 8.7 | 0.27 | 15 | 0.003654 |

Table 3 gives the values of some selected weights the current taken by the weight, the distance between the weight and the magnetic pole and the resultant force constant of the magnet. The force constant of the magnet is approximately the same irrespective of the weight and distance.

5. CONCLUSION

The electromagnet is designed and constructed and it was found out that it can fully suspend the steel ball at different

positions when the current through it was varied. The more the current through the electromagnet the smaller the distance between the pole and the steel ball of the same weight. The electromagnet can suspend any ferromagnetic material irrespective of its shape and size. The current through the magnetic coil limits the maximum load it can lift There is a cost saving when compared with modern electromagnet.

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