Formation of Maximum Eddy Current Force by Non Ferrous Materials

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Abstract. This project is concerned with the study of eddy current effects on various materials such as aluminum, copper and magnesium. Two types of magnets used in this study; magnetic ferrite (ZnFe+2O4) and magnetic neodymium (NdFeBN42). Eddy current force will be exerted to these materials due to current flows along the magnet. This force depends on the type of magnet, type of material and the gap between the magnet and the material or between the two magnets. The results show that at constant magnet to material gap, the eddy current force decreases as the magnet to magnet gap increases. Similarly, at constant magnet to magnet gap, the eddy current force decreases as the magnet to material gap increases. The minimum force was achieved when the gap of magnet to material is maximum, similarly to the gap of magnet to magnet. The weakest force was between Copper and Neodymium at a magnet to material gap of 20 mm and magnet to magnet gap of 40 mm; the eddy current force was 0.00048 N. The strongest force (maximum) was between Magnesium and Ferrite and 0.42273 N at a magnet to material gap of 3 mm and magnet to magnet gap of 5 mm.

1. Introduction
This project focused on the fundamental study and application of eddy current technique as a separator in separating non-ferrous waste. Conceptually, a variety of metal scrape waste are passed through a separating station on a conveyor system. In the station, the waste can be recognized, differentiated and separated between ferrous and non-ferrous materials, where the non-ferrous waste will be thrown away a bit far automatically from the conveyor, due to internal force created by the eddy current. Thus the research is focusing on the fundamental of eddy current on the non-ferrous materials and the relationship with the gap between magnets and materials to produce eddy current force.

This research consists of studying eddy current forces exerted by magnets (ferrite and neodymium) to aluminium, copper and magnesium at various gaps between magnet and material, and between magnet and magnet. The research is conducted through simulation using ANSYS.
2. Eddy Current Technique

Changing magnetic field in a conductor will induce electric currents within the conductors: the induced currents are called eddy currents or also known by another name as Foucault currents. Since these circulating eddy currents have inductance, they will induce magnetic fields [1].

Figure 1 shows a rectangular-shaped conductor with an AC flux $\phi$. According to Faraday’s law, an AC voltage $E_1$ is induced across its terminals. If the conductor is short-circuited, a substantial alternating current $I_1$ will flow. If more conductor is placed inside the first one as in Figure 2, a smaller voltage will be induced because it links a smaller flux [2]. There are a number of factors, apart from flaws, which will affect the eddy current response from a probe [3] and material conductivity, permeability, frequency, geometry and proximity/lift T off [4].

![Figure 1. Conductor with an ac flux $\phi$ [2].](image1)

![Figure 2. More conductors carry AC currents [2].](image2)

2.1 Force acting on particles due to eddy current

In order to calculate the forces acting on particles due to eddy current, a dipole model was developed. It was assumed that the magnetic field induces Eddy-currents within a particle, which in turn generates a magnetic moment in that particle. The interaction between the magnetic moment and the external magnetic field results in Eddy-current forces. The force can then be expressed as:

$$F_{LP} = \mu_M \nabla B$$  \hspace{1cm} (1)

Since,

$$\mu_M = M_p V_p$$  \hspace{1cm} (2)

Thus, the torque on the particle is given by:

$$T = V_p M_p B_0$$  \hspace{1cm} (3)

Where,

$V_p$ – Volume of the particle

$M_p$ – Magnetization of the particle

$\mu_M$ – Effective magnetic dipole moment of the particle

$B_0$ – External magnetic induction

In order to determine the force acting on a particle, given by eq. (3), a magnetic field generated by the magnetic system must be calculated. Shown that the components of the magnetic induction in the cylindrical coordinate system $(r, \phi, z)$ relative to the drum axis can be written:

$$B_r = \sum_{n=0}^{\infty} b_n \left( \frac{r}{R_{drum}} \right)^{-2(n+1)k-1} \times \sin[(2n+1)k(\phi - \omega_{drum}t)]$$ \hspace{1cm} (4)

$$B_r = \sum_{n=0}^{\infty} -b_n \left( \frac{r}{R_{drum}} \right)^{-2(n+1)k-1} \times \cos[(2n+1)k(\phi - \omega_{drum}t)]$$ \hspace{1cm} (5)

Where $b_n$ are the Fourier coefficients, $R_{drum}$ the radius of the drum, $k$ the number of pairs of the magnets used in the drum and $\omega_{drum}$ the angular velocity of the drum. The Fourier coefficients can be determined by measuring the magnetic field strength as a function of distance from the magnetic pole surface.
Based on equation (4) and (5), obtained the following expressions for the tangential and radial eddy-current forces acting on the particle:

\[
F_{L\theta} = C_1 \frac{C_2}{1 + C_2^2} B^2 \tag{6}
\]

\[
F_{Lr} = C_1 \frac{C_2^2}{1 + C_2^2} B^2 \tag{7}
\]

Where,

\[C_1 = \frac{2sV_p}{\eta_\theta \omega}\] (8)

\[C_2 = (k\omega_{drum} + \Omega) \tau\] (9)

\(\omega\) – Width of one pair of magnet

\(s\) – Shape factor of the particle

\(\Omega\) – Angular velocity of particle rotation

\(\tau\) – Characteristic time with induced magnetic field decays in the particle

\[\tau = \frac{\mu_0 \sigma_p S B^2}{\mu_0}\] (10)

Where,

B – Particle radius

The torque on the particle was found to be:

\[T = \frac{sV_p}{\mu_0} \frac{C_2}{1 + C_2^2} B^2\] (11)

It can be seen that the eddy-current forces and the torque depend on the square of the magnetic field strength. By replacing ceramic ferrite permanent magnets by rare-earth magnets, a considerable increase in the separating force can be, therefore, achieved [5].

A non-ferrous metal is any metal either pure or alloy that does not contain iron in appreciable amounts. Non-ferrous metals are generally more expensive than ferrous metals. They are used because of their desirable properties such as low weight (e.g., aluminium), higher conductivity (e.g., copper), non-magnetic property or resistance to corrosion (e.g., zinc) [6].

Material selection mainly depends on how easily the can be shaped. Although the same operations are used with ferrous as well as nonferrous metals and alloys, the reaction of nonferrous metals to these forming processes is often more severe. Consequently, properties may differ considerably between the cast and wrought forms of the same metal or alloy [7].

2.1.1 Ferrite magnet.

A ferrite is a chemical compound of ceramic materials with iron (III) oxide (Fe2O3) as its main component. Yogoro Kato and Takeshi Takei of the Tokyo Institute of Technology invented magnet from ferrite in 1930 [5][6]. The density of ferrite magnets is about 5 g/cm³ [8][9].

2.1.2 Neodymium magnet.

A neodymium magnet (also known as NdFeB or Neo magnet) is the most widely used type of rare-earth magnet. It is a permanent magnet made from an alloy of neodymium, iron and boron to form the Nd2Fe14B tetragonal crystalline structure. Developed in 1982 by General Motors and Sumitomo Special Metals, neodymium magnets are the strongest type of permanent magnet commercially available [14]. The greater force exerted by rare-earth magnets creates hazards that are not found in other types of magnet. Neodymium magnets larger than a few cubic centimetres are strong enough to cause injuries
to body parts pinched between two magnets, or a magnet and a metal surface, even causing broken bones [11]. The greater strength of neodymium magnets has inspired new applications in areas where magnets were not used before. Neodymium magnets are used in the surgically placed Linx anti-reflux system [12].

2.2 Analysis of eddy current
This research consists of studying eddy current forces exerted by magnets (ferrite and neodymium) to aluminium, copper and magnesium at various gaps between magnet and material, and between magnet and magnet. The research is conducted through simulation using ANSYS. The ANSYS program uses Maxwell's equations as the basis for electromagnetic field analysis. Electromagnetic analysis may be coupled to circuit, heat transfer, mechanical, or fluid dynamics analysis [12, 14]. The type of formulation suitable for an analysis is determined by the way the current is introduced into the model [13].

3. Methods and Materials

3.1 Eddy current proximity sensors.
Alternating current and alternating magnetic field is produced if a coil passes a current. If there is a metal object in close proximity to this alternating magnetic field, then eddy currents are induced in it. The eddy currents themselves produce a magnetic field.

This distorts the magnetic field responsible for their production, which changes the impedance of the coil and the amplitude of the alternating current. At some pre-set level, these changes can be used to trigger a switch. The changes can be utilized to make a sensor which is used for the detection of non-magnetic but conductive materials; See Figure 3, the sensors have the advantages of being relatively inexpensive, small in size, with high reliability and can have high sensitivity to small displacements [14].

3.2 Simulation of the magnetized material.
The arrangement of the magnet and the material to be investigated is shown in Figure 4. The red rectangular is the magnet (either ferrite or neodymium) while the blue circle is the material (aluminium, copper or magnesium). When a current flows in the magnet, it will exert eddy current force to the material [14]. The force will depend on the gap between the magnet and the material, the amount of the current, the material and the type of the magnet. The gap is 3 mm, 5 mm, 10 mm, 15 mm and 20 mm.

![Figure 3. Eddy current sensor [3].](image1)

![Figure 4. Arrangement of magnet and material.](image2)

3.3 Method of analysis of eddy current.
Analysis of eddy-current effect on aluminum material is done by ANSYS Software where Eddy force, magnetic flux density, magnetic field intensity and interaction force can be determine. The main reason
of this analysis is to determine the force acting on non-ferrous material (aluminum) produced by the Neodymium magnets (NbFeB42). The analysis manipulated data is the distance between magnet to magnet and the distance between magnets to material [14].

![Figure 5. Analysis on effect of Eddy-Current on aluminum](image)

Figure 5 shows the two distances between magnet to magnet and magnet to material. Here, \( m \) is representing magnet to magnet gap and \( n \) representing magnet to material gap. The gaps are measured in millimeter (mm).

3.4 Materials and gaps for the simulation.
In the simulation done, there are three materials to be chosen (aluminum, copper and magnesium). Those materials are chosen because in industry, there are over 60% of them which become waste. For the magnets, ferrite and neodymium magnets are used.

To analyze the eddy-current effects, two different kinds of gaps are used; they are magnet to magnet gap and magnet to material gap. Figure 6 shows the placement of magnet and material while Figure 7 shows Mesh of the analyzed parts.

![Figure 6. Placement of magnet and material.](image)
![Figure 7. Mesh of the analyzed parts.](image)

4. Results and Discussions
In the simulation done, it is decided to use smaller materials to reduce the force used to rotate the magnets. From the results of preliminary analysis, it can be seen that the critical or greater force is at the non-ferrous materials. This shows that the closer the gap between the magnet and the materials, the higher the eddy current force required to push the materials away from the magnet. The results described in the next part prove that the eddy current could be formed if there is a considerable gap established...
between magnet to magnet and magnet to materials. Total maximum Eddy force analysis is shown in Figure 8.

![Image of total maximum Eddy force analysis](image)

**Figure 8.** Total maximum Eddy force Analysis.

ANSYS software is used for analysis. Here, the simulation used the 5 mm Magnet to Magnet Gap and the 3mm Magnet to Material Gap. From the analysis for 5mm magnet to magnet gap and 3mm magnet to material gap, other result of analysis on different gap distance of magnet to magnet and magnet to material can be done. Figure 9 shows the respond of Ferrite Magnet to Magnesium, which results to the maximum eddy current force, while Figure 10 shows the respond of Neodymium Magnet to copper, which results to the minimum eddy current force.

The combination of overall result will show on the best result of maximum Eddy force acting on non-ferrous material. The highest maximum Eddy force acting on the material can be able to produce highest lift force to the material in the separation process of non-ferrous materials.
The pattern of eddy current force for other combination of magnet and materials is similar as has been explained for eddy current force for aluminum and ferrite [14]. The results of all the analysis are summarized in Table 1 and Table 2. From Table 1 and Table 2, it is seen that maximum eddy current force is achieved when the magnet is ferrite and the material is magnesium. Minimum eddy current force is achieved when the magnet is neodymium and the material is copper. X1=magnet to material (3 mm to 20 mm) and X2=magnet to magnet (5 mm to 40 mm)
| Table 1: Maximum and minimum eddy current for Ferrite and the three materials. |
|---------------------------------|---------------------------------|
| Max. eddy current at x1 = 3 mm and x2 = 5 mm | Min. eddy current at x1 = 20 mm and x2 = 40 mm |
| Magnesium-Ferrite | 0.42273 | 0.02023 |
| Aluminum-Ferrite | 0.258140 | 0.002832 |
| Copper-Ferrite | 0.003940 | 0.002037 |

| Table 2: Maximum and minimum eddy current for Neodymium and the three materials. |
|---------------------------------|---------------------------------|
| Max. eddy current at x1 = 3 mm and x2 = 5 mm | Min. eddy current at x1 = 20 mm and x2 = 40 mm |
| Aluminum-Neodymium | 0.096118 | 0.000926 |
| Magnesium-Neodymium | 0.02146 | 0.00114 |
| Copper-Neodymium | 0.001927 | 0.00048 |

5. Conclusion
From the simulation conducted, it is found that at constant magnet to material gap, the eddy current force decreases as the magnet to magnet gap increases. Similarly, at constant magnet to magnet gap, the eddy current force decreases as the magnet to material gap increases. It can be seen that the minimum force was achieved when the magnet to material gap is maximum and the magnet to magnet gap is also maximum.

The maximum force was achieved when the magnet to material gap is minimum and the magnet to magnet gap is also minimum. The results of the simulation are summarized in Tables 7 and 8. It is found that the weakest (minimum) force was between Copper and Neodymium at a magnet to material gap of 20 mm and magnet to magnet gap of 40 mm; the eddy current force was 0.00048 N. The strongest force (maximum) was between Magnesium and Ferrite and 0.42273 N at a magnet to material gap of 3 mm and magnet to magnet gap of 5 mm.

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