# Losses of Eddy current and material efficiency optimization

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**Abstract.** The usage of eddy current is significant in society, where being applied to transportation and entertainment like high-speed trains and rollercoasters. Many articles about eddy current mentioned its function and usage, but barely have focused on how to improve its efficiency. Therefore, this article will focus on the comparison of the efficiency between three different metals (copper, aluminum, and silver) by calculating its eddy current loss and filtrate the most efficient material. To compare the eddy current loss of each object, the calculation is necessary. The conductivity of each object will be compared, and the density will too. By using the equation and relationships, the eddy current loss will be shown and the result will be clear. In the findings of eddy current loss, aluminum has the highest eddy current loss whereas silver has the lowest. This means that silver has the highest efficiency of transferring energy and will create the highest eddy current when a magnetic flux is acting on it. For the application, due to that, there will be a stronger opposing force in a stronger eddy current, silver can be used in making the breaks of the maglev trains for stopping. However, there are still tradeoffs because of the cost of the quantity of silver. So, copper is recommended for making the track of the maglev trains.

**Keywords:** Eddy current, Conductor, Conductivity, Magnetic flu.

## 1. Introduction

In electrical engineering and materials science, one of the biggest challenges today is improving energy efficiency in devices that use magnets and electricity, like motors, transformers, and power grids. This is especially important as the world shifts to renewable energy (like wind and solar) and smarter technologies. A major problem in these systems is something called eddy currents. These are loops of electric current that form inside metal parts when they are exposed to changing magnetic fields—kind of like invisible whirlpools of electricity. While eddy currents can be useful in things like induction stoves, magnetic brakes (used in rollercoasters or trains), and even wireless chargers, they also cause a lot of wasted energy [1]. For example, in a transformer, eddy currents make the metal core heat up, which wastes electricity and can even damage the device over time. Scientists and engineers are trying to figure out how to reduce these energy losses while still keeping the useful parts of eddy currents.

The key to solving this problem lies in the materials used to build these devices. For instance, metals like iron or copper are great at conducting electricity, but that also means they are good at creating eddy currents. To fix this, researchers are experimenting with new materials or modifying existing ones. One idea is to use materials that do not conduct electricity as easily, which would slow down eddy currents and reduce energy loss. Another approach is to design materials with tiny structures (like layers or particles) that disrupt how eddy currents flow. Think of it like putting speed bumps in a parking lot to slow down cars—except here, the “speed bumps” are microscopic.

This research is not just about textbooks—it has real-world impacts. By improving materials, we could make electric car motors more efficient, help wind turbines generate more power, or even extend the lifespan of your phone’s wireless charger. Plus, using less energy means cutting down on pollution and fighting climate change. For example, if factories can use motors that waste less energy, they would burn fewer fossil fuels. This study also helps engineers understand why certain materials work better than others. For instance, if a metal is too dense or conducts electricity too well, it might create more eddy currents. By testing different materials in labs or using computer simulations, scientists can create guidelines for building better devices.

In addition, the goal is to design materials that are "smart"—ones that balance the good and bad sides of eddy currents. This could mean inventing new alloys (metal mixtures), using coatings to block unwanted currents, or even 3D-printing parts with shapes that control how electricity flows. As we rely more on clean energy and high-tech gadgets, solving the eddy current puzzle will be a huge step toward a greener, more efficient future.

## 2. Basic theory of eddy currents

### 2.1. Eddy current loss

Beginning with a question, what is eddy current? First off, an induced electromagnetic force is produced in a coil when there is a change in magnetic field that has some bond with that coil. This means that when there is a change in the magnetic field that is linked with a conductor, there will form an induced current that is perpendicular towards the magnetic field shown in figure 1. That current produced due to Faraday's Law of induction is called eddy current since the current has a shape like an eddy. (*note that Faraday's Law of induction states that a changing magnetic field induces a voltage in a circuit) [2].

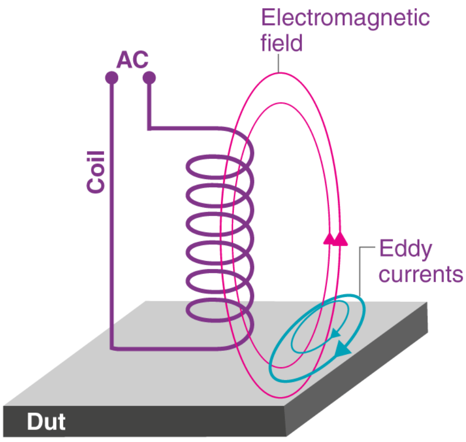


**Figure 1.** Diagram of the formation of eddy current

Before knowing what is Eddy's current loss, knowing what causes the loss is significant. Since different materials have different conductivities, it influences the electric current flows inside them. This means that the electric energy cannot be fully transferred, causing some energy of the circulating currents to become in the form of heat. This waste of power due to the inherent resistance of the conductor is known as the eddy current loss. Going further, the magnitude of the induced current and resulting loss depends on the strength and rate of change in flux, resistivity of the material, and its geometry [3,4]. The strength and rate of change in flux, basically depend on the magnetic force of the magnetic field, meaning that the larger the magnetic force, the larger the magnetic field will be acting on the conductor, which leads to a stronger eddy current. The second factor is the resistivity of the material. The resistivity of the material depends on the type of conductor a magnetic force acting on. Since there is no ideal conductor that has zero resistance, there will always be an eddy current loss. For the conductor, their conductivity depends on several factors, like the number of valence electrons, types of bonding, and more. These factors influence the conductivity and eventually influence the magnitude of the induced eddy current generated. Lastly, for the geometry, there are also several factors inside. For instance, the area, length, and shape all have influences. For the area and length, it can be defined for calculating the resistance using Ohm's law, whereas for shape, it is different. For the shapes that are linear and straight, the electrons can easily pass through the shape without collisions, and their speed will not be transferred into thermal energy causing heat. Now, to calculate the eddy current loss, there will be a mathematical formula containing all the factors below [3]:

### 2.2. Calculations

$$P_e = K_e B_m^2 t^2 f^2 V \tag{1}$$

Where:

$P_e$ is the eddy current loss (Watts)

$K_e$ is the eddy current coefficient that depends on the conductivity ($\partial$) and resistivity (ρ) of the material

$B_m^2$ is the magnetic flux density (T)

$t^2$ thickness of the conductor (m)

$f^2$ frequency of the alternating magnetic field (Hz)

V volume of the conductor (m3)

Since the topic is focusing on the conductors, the main element that will be changing is the $K_e$.

The eddy current coefficient equation is defined as [5]:

$$K_e \propto \frac{\sigma}{\rho} \tag{2}$$

Where:

σ is the electrical conductivity of the material

ρ is the density of the material

This means that $P_e \propto \sigma$. So, if the material conductivity is high, then the eddy current loss will be high too.

Conductivity is the measure ease of electrical charge can pass through a material, where metals are the most conductive. In this case, finding out the conductivity of each material provides the ability to compare the eddy current loss because of the proportion. Table 1 shows the conductivity of different metals.

**Table 1.** Table of metal conductivity at 20°C [6]

| Metal conductivity at 20°C | |
|---|---|
| Metal | Conductivity ($\sigma$) |
| Silver | $6.30 \times 10^7$ |
| Copper | $5.96 \times 10^7$ |
| Aluminum | $3.5 \times 10^7$ |

From table 1 above it is clearly shown that silver has the best conductivity, and aluminum has the least. However, from the equation above, there is still a factor influencing the $K_e$, which is the density of the material. Each material has its density, if the thickness and volume are assumed constant, the density will not be constant in the equation, so just finding the conductivity is not enough. Table 2 shows the density of metals at a temperature of 20°C.

**Table 2.** Table of metal density at 20°C [7]

| Metal density | |
|---|---|
| Metal | Density (g/cm$^3$) |
| Silver | 10.49 |
| Copper | 8.93 |
| Aluminum | 2.7 |

Since the conductivity is directly proportional to eddy current loss and density is inversely proportional, their eddy current loss can be compared by conductivity over density. Table 3 above presents the eddy current loss of the three objects. The relationship is Al > Cu > Ag.

**Table 3.** Table of eddy current coefficient

| Comparison of eddy current coefficient | |
|---|---|
| Metal | Eddy current coefficient ($\sigma cm^3 g^{-1}$) |
| Silver | $6.01 \times 10^6$ |
| Copper | $6.67 \times 10^6$ |
| Aluminum | $1.30 \times 10^7$ |

### 2.2.1. Results

From the results shown in table 3, aluminum has the highest eddy current loss and silver has the lowest eddy current loss. This means that there is more energy being transferred into thermal energy, decreasing its efficiency. From this, it can be defined that the silver has the highest eddy current, so there will be a stronger opposing force acting when there is a magnetic flux.

### 2.2.2. Experiment

To increase the reliability of the calculations done above, creating an experiment is necessary. In a YouTube video called "Eddy Currents Tube" created by an organization named Educational Innovations, they created an experiment comparing the speed of a magnet falling straightly through two types of tube. The two different tubes (copper and aluminum) have been created in two different lengths. The aluminum tube is two times the copper tube, as shown in the image below:

**Figure 2.** Picture of the experiment of a magnet falling in copper and aluminum tube [8]

He created an aluminum tube that is two times the copper tube's length shown in figure 2, and the result shows that the magnet passes through both tubes at the same time. This means that the opposing force created from the eddy current in the aluminum tube is half the copper tube, so the eddy current loss is two times the copper tube. Moreover, this experiment has further proven the reliability of the eddy current loss calculated above in table 3, showing that aluminum has almost two times the eddy current loss than copper with the value of 1.3 x 107 and 6.67 x 106.

## 2.3. Applications of eddy current

As a conductor is influenced by a magnetic flux, eddy current generates loops inside the conductor. After that, this current generates a secondary magnetic field that opposes the original magnetic field. This opposing magnetic field creates a repelling force, which is very strong. Moreover, when a conductor moves through a magnetic field, eddy currents are induced. These currents produce a magnetic field opposite to the motion of the conductor, and it slows down the motion, acting like a brake.

### 2.3.1. Examples of applications

1. Electromagnetic breaking

Eddy current brakes use magnetic fields to create a drag force that slows or stops moving objects without physical contact, preventing mechanical wear. They are commonly found in roller coasters, where copper plates on the cars pass through strong magnets, generating resistance that slows the ride.

Similarly, railroad cars and power tools (like circular saws) use this braking method. When electromagnets are used instead of permanent magnets, the braking force can be adjusted by changing the magnetic field strength [9].

2. Identification of metals

Some coin-operated vending machines use eddy currents to detect counterfeit coins or slugs. As a coin rolls past a fixed magnet, eddy currents generate resistance, slowing it down. The amount of deceleration depends on the metal's conductivity—genuine coins and slugs slow at different rates, allowing the machine to sort out fakes and reject them.

3. Vibration and position sensing

Eddy currents are used in certain proximity sensors to monitor the vibration and position of rotating shafts within bearings. This technology was first developed in the 1930s by General Electric researchers using vacuum tube circuits. In the late 1950s, Donald E. Bently of Bently Nevada Corporation introduced solid-state versions. These sensors are highly sensitive to tiny displacements, making them ideal for detecting minute vibrations (as small as a few thousandths of an inch) in modern turbomachinery. A typical vibration-monitoring proximity sensor has a scale factor of 200 mV/mil. Their widespread use has led to industry standards such as API Standard 670 and ISO 7919, which define their application. Additionally, a Ferraris acceleration sensor (or Ferraris sensor) is a contactless device that utilizes eddy currents to measure relative acceleration [10].

## 3. Limitations

### 3.1. Material Costs

Though the experiment results shows that silver has the highest efficiency of the transfer of energy, the price should be considered when using silver as a material. Table 4 below shows the cost of the metals for each kilogram:

**Table 4.** Table of eddy current coefficient [11]

| Cost of metals per kilogram | |
|---|---|
| Metal | Dollars per kilogram ($/kg) |
| Silver | 1059.67 |
| Copper | 11.212 |
| Aluminum | 2.6228 |

In table 4 above, silver costs way much than copper and aluminum, so this will be a tradeoff for using the highest efficiency material. However, by looking at table 3, the difference in the eddy current loss of silver and copper is not much, so copper has a higher performance-cost ratio than silver. This depends on the quantity needed and the expectation of the quality. For instance, if there is a tiny machine that needs high eddy current, silver is recommended. Inversely, if there is a demand for a large quantity of materials, copper will be the superior choice for the material use. Additionally, copper is recommended for either the use of electromagnetic breaking or vibration and positioning due to the small difference in eddy current loss presented in the calculations in table 3.

### 3.2. Thermal expansion

Thermal expansion is an important factor for the material density. It is the general increase in the volume of a material as its temperature increases [12]. In the beginning, the calculations have assumed that the temperature is at a constant 20°C, but as the temperature changes each material's volume changes. Due to this, the different temperatures can determine different material densities, thus different eddy current loss. The table 5 below shows the thermal expansion of different materials.

**Table 5.** Table of linear thermal expansion of metals

| Linear thermal expansion coefficients | |
|---|---|
| Metal | Thermal expansion ($10^{-6}$ in/°C) |
| Silver | 19.8 |
| Copper | 17.6 |
| Aluminum | 23.6 |

Thermal expansion is the ratio change in length per degree of temperature. Table 5 above, shows the increase in inches as each degree °C is increased, where aluminum is the highest and copper is the lowest. As thermal expansion increases, the volume increases, causing density to decrease. The decrease in density means a decrease in eddy current loss, so it can still influence the eddy current loss and the efficiency of the transfer of energy. In future calculations, these factors should be considered. For instance, an electrical brake is needed for a maglev train, people should be measuring the temperature and surroundings of the rail track after deciding factors like eddy current loss and cost. If the temperature is extremely high, copper will not present as well as silver because its density will not decrease as much as silver and aluminum, which may influence the final calculation of the eddy current loss.

## 4. Conclusion

The findings of this research underscore the critical role of material selection in systems involving eddy currents, particularly in optimizing energy efficiency and cost-effectiveness. Among the three metals analyzed—aluminum, copper, and silver—aluminum exhibited the highest eddy current loss, with a coefficient of $1.3 \times 10^7$, followed by copper ($6.67 \times 10^6$) and silver ($6.01 \times 10^6$). Since eddy current loss inversely correlates with energy transfer efficiency, silver emerged as the most efficient material due to its minimal loss, making it ideal for applications prioritizing maximal energy conservation. However, its exorbitant cost of $1059.67 per kilogram compared to copper's $11.212 per kilogram positions copper as the superior choice when balancing performance with economic feasibility. This highlights the importance of evaluating both technical and financial factors in material selection, particularly for large-scale or cost-sensitive projects.

The implications of this study extend beyond immediate applications. As global industries increasingly prioritize energy efficiency—such as in renewable energy systems, electric vehicle powertrains, and wireless charging technologies—the demand for materials that minimize eddy current losses will grow. Silver's exceptional efficiency could revolutionize high-performance sectors like aerospace or medical devices, where precision and energy conservation outweigh cost concerns. Conversely, copper's affordability and competitive efficiency make it indispensable for consumer electronics, power grids, and sustainable infrastructure projects, especially in developing economies where cost barriers hinder technological adoption.

Future work can consider a wider variety of materials, like metals, superconductors, or composites, that could provide better combined performance in terms of eddy current loss and cost. Including some more details like resistivity, thermal stability, material pureness, and even the environmental impact such as the carbon footprint or recyclability would help provide better conclusions. For example, if the cost of production becomes reasonable, graphene or carbon nanotubes could set new standards of efficiency due to their ultra-high conductivity and low eddy current production. In the same fashion, new nanostructured materials and magnetic shields might reduce losses in high-frequency applications.

The methodology developed here also holds promise for interdisciplinary innovation. By integrating machine learning or computational modeling, researchers could rapidly simulate material performance under diverse conditions, accelerating the design of optimized systems. Furthermore, collaborations between material scientists, economists, and policymakers could establish standardized guidelines for selecting materials based on regional resource availability, sustainability goals, and economic constraints. Such advancements would not only enhance energy efficiency but also drive the global transition to greener technologies, reducing waste and operational costs across industries.

In summary, this research provides a foundational framework for material selection in eddy-current-prone systems, emphasizing the trade-offs between efficiency and cost. By broadening the scope of analysis and embracing emerging technologies, future studies can unlock transformative solutions that align technical excellence with economic and environmental sustainability, ultimately fostering a more energy-efficient and resource-conscious world.

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