Eddy current analysis in copper and various coins

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Eddy currents are induced currents in conductors due to a time varying magnetic field. As such, they are useful as a pedagogical tool to teach undergraduate students about Faraday's law. In industrial settings eddy currents are often used in areas such as non-destructive testing and inductive heating. This report explores techniques of material characterization of Canadian coins and non-destructive testing in copper disks with varying degrees of damage.

I. INTRODUCTION

A. History of eddy currents

Eddy currents, also known as Foucault currents [1], are loops of electrical current induced by conductors inside of a changing magnetic field using Faraday's law [2]-[4]. The first written accord of the effects of eddy currents were in 1824 by the French physicist, and 25th Prime Minister of France, François Arango who wrote about the magnetization of conductive bodies. His research was then completed by Michael Faraday. Not 10 years later in 1834 Heinrich Lenz published his discovery of Lenz's law in his landmark paper which stated that the direction of induced current flow will be opposite that of the direction of the changing magnetic field. Finally, in 1855 French physicist Léon Foucault is credited with the discovery of eddy currents when he discovered that the force required to rotate a copper disk was greater when the rim was between two magnets [2].

B. Practicality and mitigation of unwanted effects

Depending on the situation eddy currents can be seen as desirable, and necessary for function. This can be seen in MRI scanning coils where they are used as generators of high magnetic fields, while in other cases they can be seen as undesirable due to their energy loss effects which need to be minimized [2] [4]. In MRI technology eddy currents can cause blurry images, and the force exerted on the conductors can cause a reduction in expected lifetime of the apparatus. Often-times the way to control eddy currents in MRI's is by active shielding, applying pre-emphasis currents, and cutting slits in the conductors. Although eddy currents are a source of energy loss in AC machinery, they are highly useful in the fields of medical physics, non-destructive testing, as well as induction heating furnaces [2].

This paper discusses the effects of cutting slits in copper pieces and studying the effects of damaging conductors on eddy currents and how this is applied in MRI technology. Other relevant effects studied and discussed will include topics such as the effect of frequency on eddy currents, how eddy currents behave in imperfect conductors, as well as its use in non-destructive testing.

II. THEORY

A. Faraday's law of induction

Faraday's law states that when a conductive object is in the presence of time-varying magnetic field, an electromotive force (EMF) is induced in the material. This induced EMF causes the free electrons flowing through the conductor to travel in circular paths perpendicularly to the field lines. This effect is caused by Faraday's law which can be defined as

$$\mathcal{E} = -\frac{d\Phi_b}{dt}\,, \tag{1}$$

where $\mathcal{E}$ is the EMF, and Φ_b is the magnetic flux. The direction of the induced current will rotate in such a way that the induced magnetic field will oppose the primary static magnetic field. This induced magnetic field is caused by Ampere's law which states that the magnetic field created by a current-carrying conductor is directly proportional to the magnitude of the current.

B. Lenz's law

The direction of the induced current is determined by Lenz's law. The eddy currents will circulate in such a way to oppose the change in the applied magnetic field. More simply, Lenz's law can be described by the piecewise function

$$\frac{d\Phi_b}{dt} = \begin{cases} > 0 & \implies \mathcal{E} < 0 \\ = 0 & \implies \mathcal{E} = 0 \\ < 0 & \implies \mathcal{E} > 0 \end{cases} \tag{2}$$

which shows that the induced EMF $\mathcal{E}$ will drive currents that oppose the changing applied magnetic field $\frac{d\Phi_b}{dt}$. These resulting induced currents are known as eddy currents.

III. METHOD

There are three types of metals that are placed inside of the apparatus seen in Figure 1. The three metals tested were copper, Canadian dimes, and pennies. The measured coins were produced in various years while the copper was damaged in various places.

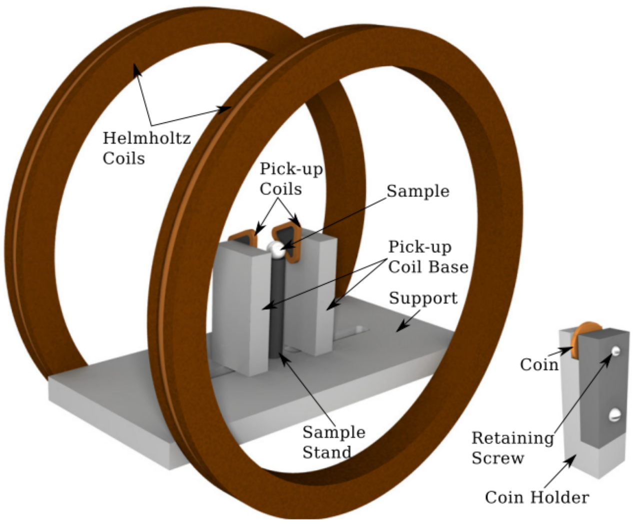

FIG. 1: The experimental apparatus depicting the Helmholtz coils, pick-up coils, and the sample stand. Sourced from Ref [6].

To test the eddy currents the coins and copper pieces, which will henceforth be referred to as metal pieces, were tested for their surface conductivity. This form of testing allowed us to probe the material of the coin without the use of destructive testing methods. They were placed inside of a plastic coin-holder and fastened into place using a screw. It's important to note that aside from the Helmholtz and pick-up coils, the rest of the apparatus was 3D printed so as to not be magnetically conductive.

A computer controlled function generator was used to logarithmically increase the $\vec{B}$ field of the Helmholtz coils so as to measure the conductivity of the surface of the metal pieces. A computer controlled oscilloscope was used to automatically adjust the height of the oscilloscope sensitivity so as to keep the peak-to-peak voltages between half and full-scale to ensure accurate results.

Prior to initial testing of the metal pieces, a normalization run was taken by angling the pick-up coils outwards which can be seen in Figure 2.

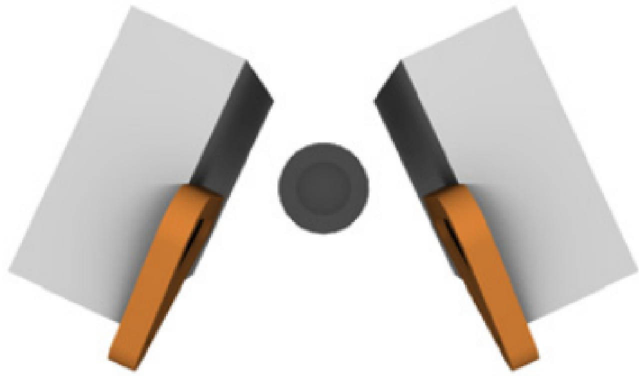

FIG. 2: A top-down view of the pick-up coils in Figure 1. This is a visual depiction of the normalization run with out-turned pick-up coils and no metal pieces, Sourced from Ref [6].

The oscilloscope was programmed to take 50 steps between 10^3 and 2×10^5 Hz and measure the phase difference between the eddy currents as well as to take the voltage amplitude of the signal. To analyze the data, the measured phase values were taken as the phase difference between the sample field and the drive field, while the measured voltage amplitudes were divided by the normalization data. The real part was determined by taking the cosine of the phase difference θ between the sample field and drive field, while the imaginary part was determined by the sine of θ.

$$Real = Mcos(\theta) \tag{3}$$
$$Imaginary = Msin(\theta) \tag{4}$$

where M is the normalized voltage magnitude, and θ is the corrected phase difference.

Various copper pieces were modified to simulate damage. This allowed for analysis on the effectiveness of eddy current generation in damaged metal. To test the eddy current generation capabilities of the modified copper pieces they were shielded with plastic for random testing. The shielded copper pieces were compared visually to their analyzed data to see what form of modification fails to generate eddy currents the most.

IV. RESULTS AND DISCUSSION

Figures 3-5 display eddy current responses for the varying metal pieces where the applied magnetic field was exerted orthogonally to the face. The normalized induced EMF in the pick-up coils were plotted as a function of frequency caused by the time rate of change of the eddy currents in the sample.

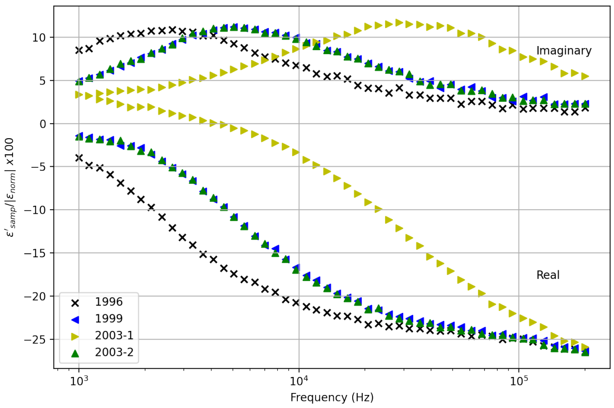

FIG. 3: Eddy current response of 1-cent coins where the magnetic field was applied orthogonally to the face. The year of minting of the different coins is given in the legend.

The data collected from the 1-cent coins were found to closely replicate the results from Honke & Bidinosti, 2018 between the frequency bounds posed in the paper. Due to the similar results it is a fair assumption to make that the real and imaginary components of the 1996, 1999, and 2003-2 coins approach zero as frequency decreases. Since the real component of the 2003-1 coin crosses the induced EMF zero-line and approaches a direct current (DC) value, it can be reasoned that the coin has magnetic features which match with the nickle-plated description of the coin found in Source [7]. There was overlap between the minting of 1-cent coins in 1999 and 2003, and this can be observed in the 2003-2 and 1999 coins due to their data overlap leading to the conclusion that they are minted out of the same material.

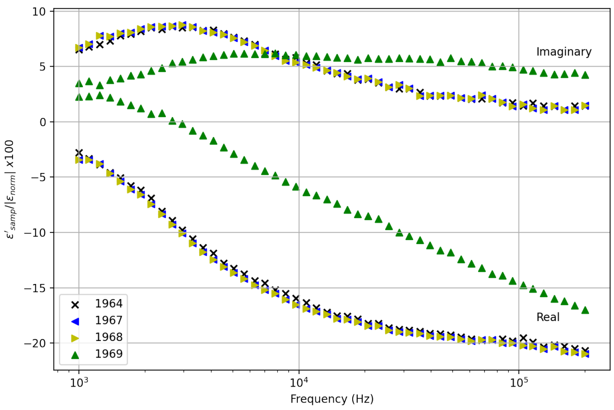

FIG. 4: Eddy current response of 10-cent coins where the magnetic field was applied orthogonally to the face. The year of minting of the different coins is given in the legend.

The data collected from the 10-cent coins were found to show an switch to the use of ferro-magnetic material in coins over time. The 1969 dime was minted with 99.9% nickel which is a good conductor of magnetic fields [8]. The 1964, 1967, 1968 10-cent coins were minted out of the same material using 80% silver and 20% copper which are less magnetically conductive than their 1969 nickel counterpart. The magnetic conductivity can be seen in the real component of the 1969 10-cent coin where it crosses the induced EMF zero-line and approaches a DC value.

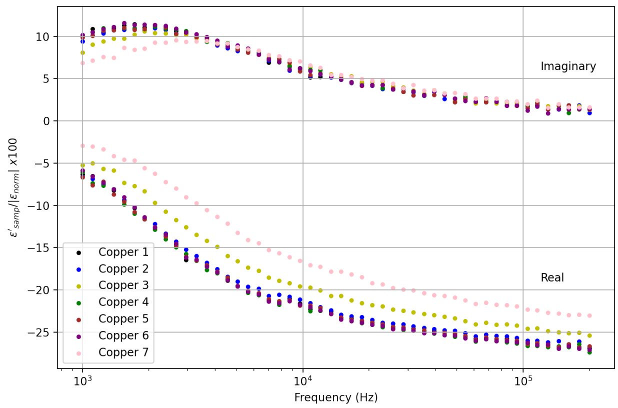

FIG. 5: Eddy current response of various modified copper pieces where the magnetic field was applied orthogonally to the face. The copper pieces are numbered in the legend.

Although it is known that the copper pieces are made out of the same metal, it was demonstrated in Figure 5 that it is so by virtue of the similar real and imaginary data trends between copper pieces 1-8. Copper piece 8 was not included in the plot as it created zero detectable eddy currents due to its modification.

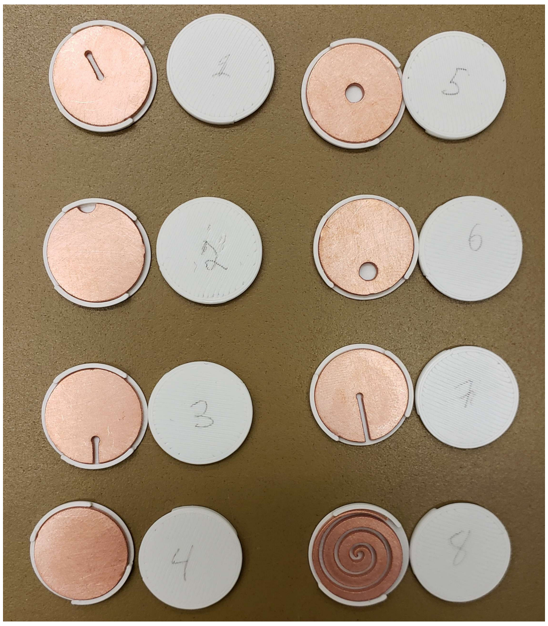

FIG. 6: A photograph of the pieces of copper used in the experiment showing the varying degrees of modification.

When the copper pieces were visually analyzed for their modifications and compared to the normalized induced EMF in the pick-up coils found in Figure 5 several conclusions could be drawn. It was found that straight slits cut into the edge of the copper created the greatest interference with the generation of eddy currents. Examples of this can be found in copper pieces 3 and 7. Copper piece 8 created the worst generation of eddy currents due to its inability to sustain circularly moving electric current. Copper pieces 1, 2, 4, 5, and 6 were found to generate similar levels of generated eddy currents despite their varying levels of damage.

V. CONCLUSION

The results found in Figure 3 were found to closely replicate the results found by Honke & Bidinosti, 2018. It was found that the 2003-1 penny was minted nickle-plated due to its magnetic conductivity. The 1964, 1967, and 1968 dimes were found to be minted out of the same material, while the 1969 dime was minted out of 99.9% nickle making it magnetically conductive. Copper piece 8 was measured to have the worst capacity to generate eddy currents due to its shape being unsustainable for promoting circularly moving current. Copper pieces with straight slits cut at the edge were also measured to have a bad ability to sustain eddy currents. The copper pieces with circular hole modifications, small straight slits that do not connect with the edge of the copper piece, and the copper piece with zero modification were found to have the same capacity for eddy current generation over a range of frequency of 10^3 to 2×10^5 Hz.

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[8] 10 cents — The Royal Canadian Mint. (n.d.). Retrieved from https://www.mint.ca/en/discover/canadian-circulation/10-cents