COMPLEX-RELUCTANCE PLANE BEHAVIOR OF ALUMINUM SAMPLES

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INTRODUCTION

Coil eddy-current (CEC) technology generates real and complex reactances of the search coil. These reactances are frequently plotted in a complex-impedance (C-I) plane with inductive reactance as the ordinate and resistance as the abscissa. This plane is a useful tool in nondestructive evaluation (NDE), and it is known to virtually all NDE technicians using electromagnetic fields. The complex-impedance plane is generally used to establish the operating conditions for particular eddy-current coils and for particular NDE problems. It can also be used to establish the effect of lift off and to identify flaws.

Magnetic circuit eddy-current (MCEC) technology generates real and imaginary reluctances from the sample and from which a complex-reluctance (C-R) plane can be constructed. The C-R plane has uses in NDE which are similar to the uses of the C-I plane. The C-R planes are introduced through an examination of aluminum samples of various thicknesses.

The purpose here is to compare C-I plane analysis of CEC with C-R plane analysis of MCEC and to demonstrate several simplicities which result from the use of MCEC for NDE.

MAGNETIC-CIRCUIT EDDY CURRENT

Real reluctance is a concept familiar to most readers. The concept of imaginary reluctance may be new to some. Real reluctance is the constant of proportionality between the driving magnetomotive force and the total magnetic flux. This quantity is introduced in almost all elementary college-physics and electrical-engineering texts. The concept of imaginary reluctance was introduced by Zinke and Schmidt [1] for linear ac magnetic-flux

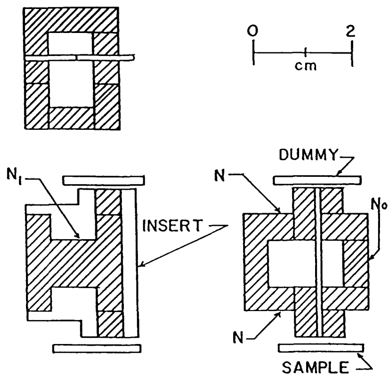

Figure 1. Typical bridge construction. The hatched area is ferrite. The insert is of copper. The input coil is at position N_i, the output coil is at N_o. The coils required to null the bridge are at N.

circuits (which achieve linearity only in approximation). A more complete discussion of its use with ac magnetic bridges is contained in an article by Schmidt and Zinke [2]. While real reluctance is primarily related to energy storage in ac magnetic circuits, imaginary reluctance is primarily related to energy dissipation. Thus, the ac magnetic-flux energy convention is the reverse of the ac electrical-circuit convention. When the ac magnetic-circuit conventions are used for devices such as the core of a transformer, the imaginary reluctances transform obediently into the real reactances of the ac electrical circuit.

The AC magnetic bridges used in MCEC are nothing more than Wheatstone bridges where magnetic-flux conductors (such as ferrite) are substituted for electrical conductors. In order to shape the magnetic field, electrical conductors are inserted between the gaps (which form impedance equivalents which can be easily manipulated in magnetic circuits). In ac magnetic-flux circuits, good electrical conductors are, paradoxically, insulators. To take this reasoning to its extreme, super conductors would be the best possible ac magnetic-flux insulators.

A drawing of the actual construction of a bridge is shown in Figure 1. The drawing shows two H-shaped ferrite cores rotated at 90 degrees with respect to each other and separated by a piece of copper called here a "gap-insert". In Figure 1, the ferrite is represented by hatching. The positions of the input and output coils are indicated by N_i and N_o respectively. The position of the coils used to manipulate the flux in the bridge arms is indicated by N. The orientation of the sample with respect to one gap is shown as is the position of a dummy sample which is occasionally placed at another gap to balance the bridge. This same geometry has been used in a frequency range from 10 hz to 150 khz.

The purpose of the copper in the gap is to force (through superposition of the induced and inducing fields) the net magnetic field out of the gap and into a region in which a sample can be conveniently placed [3]. Figure 2 shows the face which a gap in the bridge presents to the sample. The quantity D is the gap-insert width. Samples are placed with respect to the gap as shown in Figure 1 and schematized in Figure 3. In Figure 3, the lift-off space is indicated, and two flux paths are shown. One path (A) is completely in the lift off space. The other path (B) intersects the sample. The consequences of Lenz's Law on currents

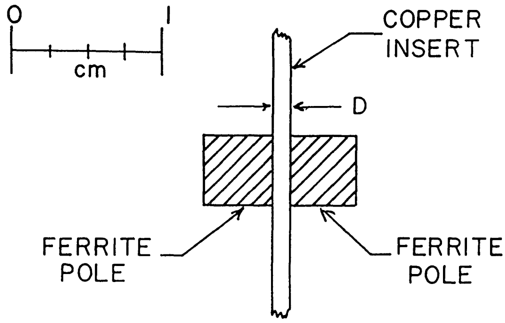

Figure 2. Pole face presented to the sample. The value D indicates the thickness of the copper insert.

induced in the sample, force flux into the lift-off space as a consequence of the conduction of the sample and/or the frequency of the electromagnetic field. The real reluctance results primarily from the net flux in the lift-off region. Thus, changes in the conductance of the sample affect the real reluctance. However, since the imaginary conductance depends on energy dissipation in the sample, it should be almost exclusively a function of path B in Figure 3. Schmidt and Zinke have modeled this gap quasistatically [4] and conducted some tests on the model [5].

CONSTRUCTION OF A COMPLEX-RELUCTANCE PLANE

In order to compare CEC and MCEC, a brief review of the C-I plane is necessary. The C-I plane diagrams shown here as Figure 4 were taken from an eddy-current training manual for NDE [6]. On the C-I diagram for a single frequency in Figure 4, the numbers 1, 2, 3, etc., represent variations of inductive reactance and resistance of the eddy-current coil

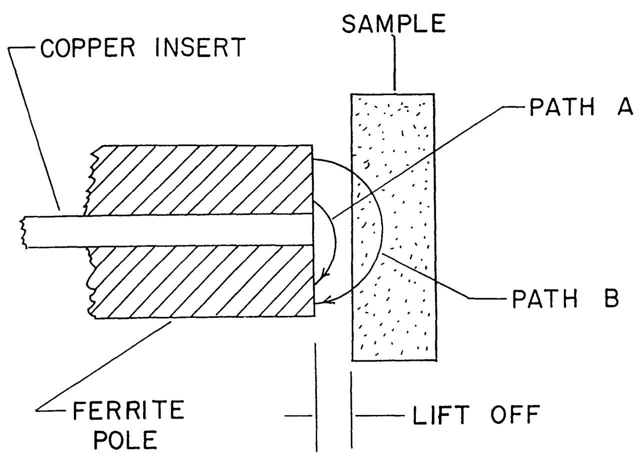

Figure 3. A cross section of the pole face and sample showing sample and lift-off space and flux paths A and B.

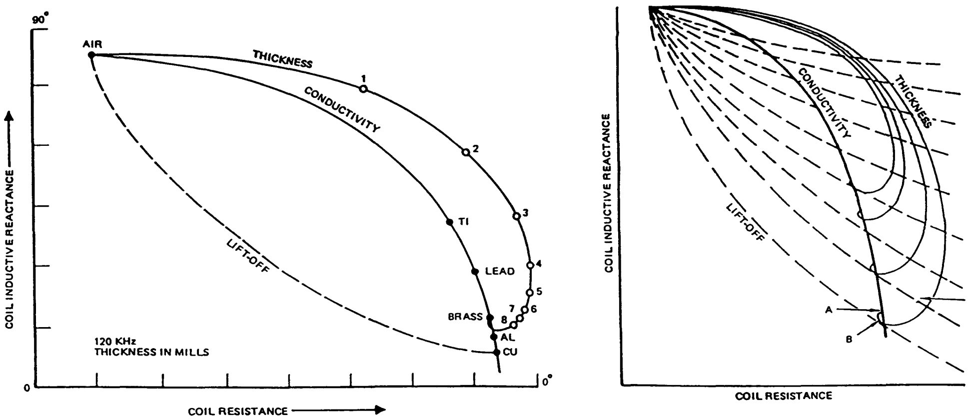

Figure 4. Complex impedance-planes for a single frequency and for a series of frequencies showing lift-off corrections.

with progressively thicker samples of the representative metal. At infinite thickness, the thickness curve for the particular frequency ends on the conductivity curve except that the reading has to be corrected for lift off at any point on the thickness curve in a manner indicated by the dashed line. The conductivity curve represents samples of infinite thickness (much thicker than the skin depth) for samples of various conductivities.

Variations with frequency for a representative metal are also shown in Figure 4 as a series of solid lines, one corresponding to each frequency. The point a on this figure is the intersection of the thickness line with the conductivity curve. The point b is used where lift-off variations are a problem because the thickness curve is parallel to the lift-off curve. The point c is used for sample thickness because the thickness curve is perpendicular to the lift-off curve for the particular frequency. It is apparent that lift off is a primary consideration in making eddy-current measurements.

To construct a C-R plane, MCEC measurements had to be made at a series of frequencies and lift-off values on a series of samples of differing thicknesses. Therefore, samples of various thicknesses were cut from a 2024 aluminum bar of 2.54-cm diameter. Measurements of real and imaginary reluctance were taken in the center of each sample. The measurements were compared to measurements of the empty x gap. The measurements were made over a range of values of lift off and frequency with the insensitivity of the measured reluctances previously reported [2]. There was almost no variation of the measured reluctances with lift off throughout the lift-off range from 0.1 mm to 0.38 mm in the frequency range from 200 hz to 2000 hz.

A C-R plane calculated from the reluctances measured in the 2024 aluminum samples at 200 hz is shown as the single curve in Figure 5. This curve compares to the single curve in the C-I plane shown in Figure 4. There are no dashed lines representing lift off because no lift-off variations occur. The numbers along the curve from 1 to 8 represent sample thicknesses from 0.41 mm to 6.35 mm. At 200 hz, the curve shows no sign of approaching a point similar to the conductivity curve in Figure 4.

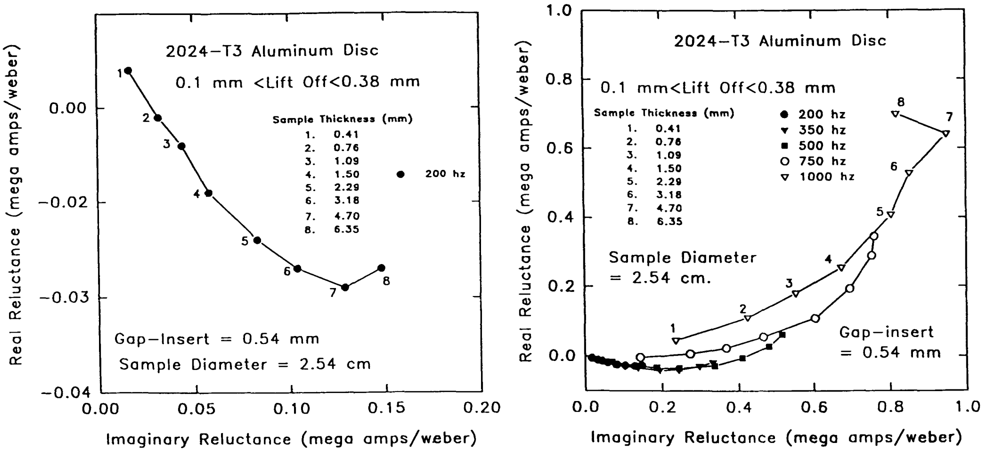

Figure 5. Complex reluctance-planes for a single frequency and for a series of frequencies.

The family of curves on Figure 5 represent reluctances calculated at 200, 350, 500, 750 and 1000 hz. Instead of the family of curves seen in the C-I plane on Figure 4, the C-R plane seems to generate a single composite curve where each curve extends toward values of higher reluctances as the thickness of the sample increases. The reluctance results for 750 and 1000 hz are somewhat offset from the composite curve of the lower frequencies. These results would be particularly useful for the instruction of and the use by NDE technicians if they formed a single composite curve at all frequencies. Under such circumstances, the series of curves seen in Figure 4 would reduce to a single curve simply extending to higher values of reluctances as the frequency increased. It is quite possible that this is the case, i.e. that a single curve is formed. Again, lift off is not represented because it is not a factor in the measurements. With a single curve representation, the choice of an operating point for a particular NDE measurement of sample thickness would hinge on nothing more than selecting a frequency where the sample thicknesses were appropriately spread out along the curve. Nonferritic metals other than 2024 aluminum should form similar curves in the reluctance-plane.

If MCEC is used to measure sample thicknesses, Figure 4 indicates that sensitivity to changes in sample thicknesses is not particularly sensitive to frequency. In fact, in some thicknesses ranges, the operator has a choice of using a lower frequency to obtain changes in imaginary reluctances or higher frequencies to obtain changes in real reluctances with no substantial loss of sensitivity.

The displacement of the 750 and 1000 hz curves from the curves at all other frequencies observed in Figure 4 may result from edge effects. The samples used for this investigation were cylindrical with a diameter of 25.4 mm. The sensor was placed in the middle of the sample and was thus no more than 12.7 mm from the edge and the presence of the edge may have affected the results. In a separate experiment edge effects were examined on the 10-cm square, rolled 6061 aluminum samples. The reluctances measured in this experiment at 500, 750 and 1000 hz can be used to speculate on whether the displacement of the 750 and 1000-hz curves might result from edge effects. The plates were scanned from 30 mm to 5 mm from the edge along a line which bisected the samples into symmetric

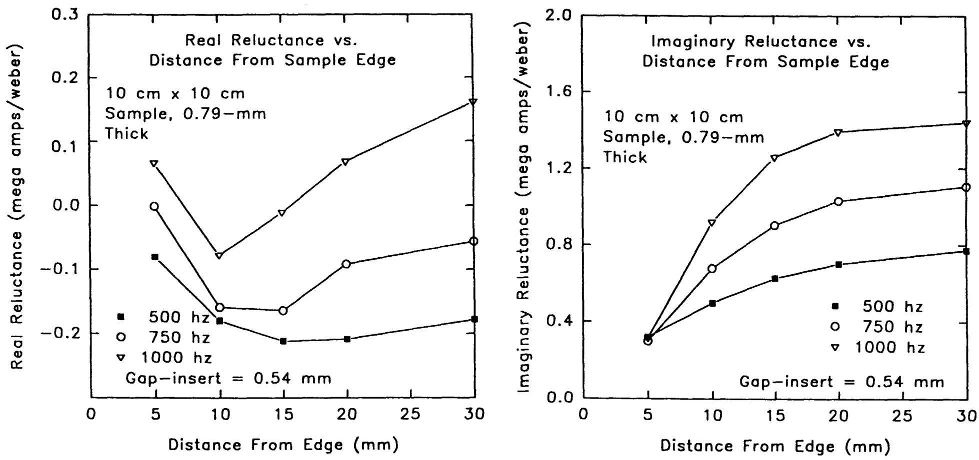

Figure 6. Variation of real reluctance and of complex reluctance from edge of an aluminum sample.

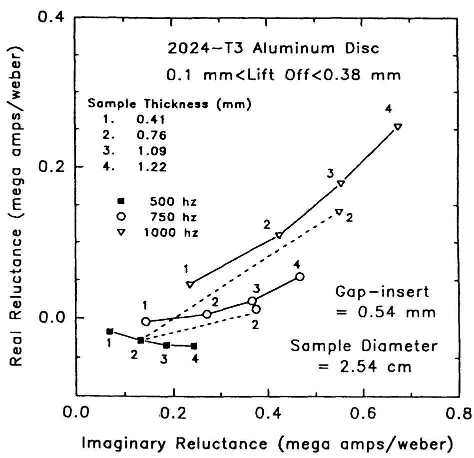

Figure 7. A series of curves in the complex-reluctance plane for frequencies 500, 750 and 1000 hz showing edge-effect correction to the 0.82 mm sample at 500 hz for 750 and 1000 hz.

rectangles. The long dimension of the gap-insert pictured in Figure 2 was parallel to the approaching edge of the sample in these scans. The real and imaginary reluctances as a function of distance to the edge are shown in Figure 6. The three curves in each figure represent frequencies of 500, 750 and 1000 hz. These reluctances were measured with respect to the reluctance of an empty gap. Therefore, the imaginary-reluctance results tend to zero as the edge is approached as expected. At 12.7 mm from the edge, the magnitude of the imaginary reluctances are about what is observed in Figure 5 given that there are two types of aluminum involved in radically different geometries. There is considerable slope in the imaginary reluctance at 12.7 cm which certainly indicates the presence of edge effects. If the differences between sample geometries and the two alloys of aluminum are ignored and the results from the edge-effect experiments are used to calculate the change from the 0.76-mm samples [2] in Figures 6 and 7 for the two frequencies 750 and 1000 hz, the dashed lines occurring on Figure 7 indicate the effect of edges on the reluctance readings. This calculation is only meant to indicate the direction and order of magnitude of the shift of the reluctance plane curve which can be expected from edge effects. Therefore with samples of larger area, the measurements at the various frequencies on Figure 5 could very well fall on a continuous curve.

CONCLUSIONS

Magnetic-circuit eddy-current offers simplicities in choosing operating points for certain kinds of electromagnetic inspection of nonferrous materials. Lift off does not have to be considered in choosing an operating point. If material thickness is to be measured, a wide variety of frequencies are available and the operator can choose whether the change to be measured is primarily real or imaginary reluctance.

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