

## NEW EDDY CURRENT PROBE FOR THICKNESS GAUGING OF CONDUCTIVE MATERIALS

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### INTRODUCTION

The accurate measure of material thickness is important for many non-destructive evaluation applications. Factors such as corrosion damage can jeopardize structural integrity through material thinning and process control considerations often mandate strict limits on material dimensions. Access to the material under test can be limited to a single side and large areas may need to be examined in a small time period. In an effort to enhance the effectiveness of material thickness measurements a flux focusing eddy current probe has been developed at NASA Langley Research Center [1]. The probe provides an accurate measure of the thickness of conducting materials from a single sided measurement. It is straight forward to use and can be easily automated for production line testing. The probe also requires only minimal instrumentation and power so that extremely portable units can be manufactured at a low cost.

This new eddy current probe has been used to accurately measure the thickness of aluminum alloy plates with a resolution of greater than 0.001" (25  $\mu\text{m}$ ). Simulated corrosion damage has also been detected on both single layer and multi-layer samples. The present work will explain the output voltage dependence of the device as a function of material thickness and present experimental results for thickness gauging and corrosion detection.

### FLUX FOCUSING PROBE DESIGN

The Flux Focusing Eddy Current Probe incorporates the use of a ferromagnetic material between a drive and pickup coil in order to focus the magnetic flux of the probe. Only magnetic field lines that pass around the ferrous lens will be sensed by the pickup coil. When a sample is placed under the probe these field lines are forced to pass through the

sample. The attenuation of the magnetic field caused by the eddy current flow in the sample results in a lower field level at the pickup coil location. Thicker samples cause a greater attenuation as the fields must pass through more material before reaching the pickup coil.

Fig. 1 displays a schematic diagram of the components of the Flux Focusing Eddy Current Probe. The magnetizing coil is used to generate a time-dependent magnetic field in the space surrounding the probe. A concentrically located ferromagnetic lens is used to focus the generated magnetic field into a cylinder surrounding the concentric pickup coil. The flow of the magnetic field about the probe is illustrated in Fig. 2 which displays both a conceptualized drawing and finite element modeling results. The field lines are shown to be concentrated within the flux focusing lens with a small but significant field circling around the bottom of the lens into the interior section of the probe where the pickup coil is located.

The behavior of the probe when in contact with a conducting sample is illustrated in Fig. 3. The figure displays finite element results for the eddy current density in the sample and lens wall at a drive frequency of 7 kHz. A high eddy current density is seen to exist at the outer edge of the flux focusing lens that rapidly decays to background levels at the inner wall. This shields the pickup coil from direct mutual inductance with the drive coil. A strong eddy current field is also seen directly under the coil windings and extending beyond the

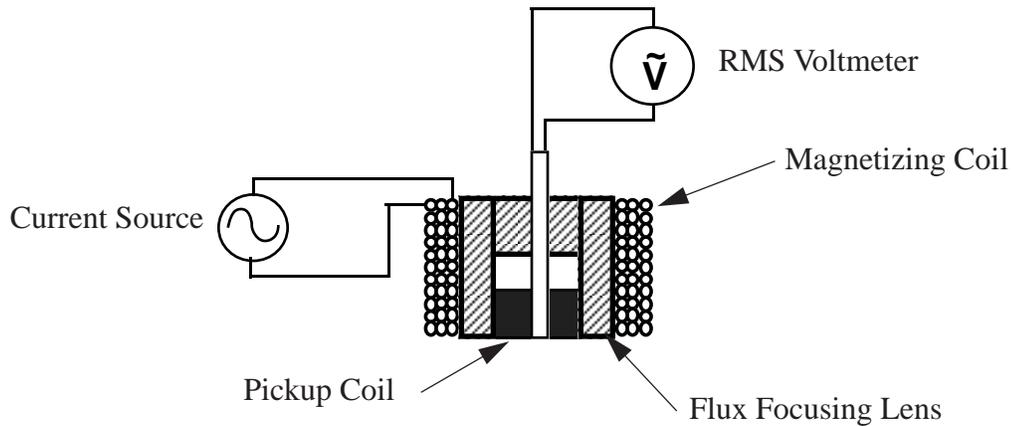


Fig. 1. Schematic diagram of Flux Focusing Eddy Current Probe.

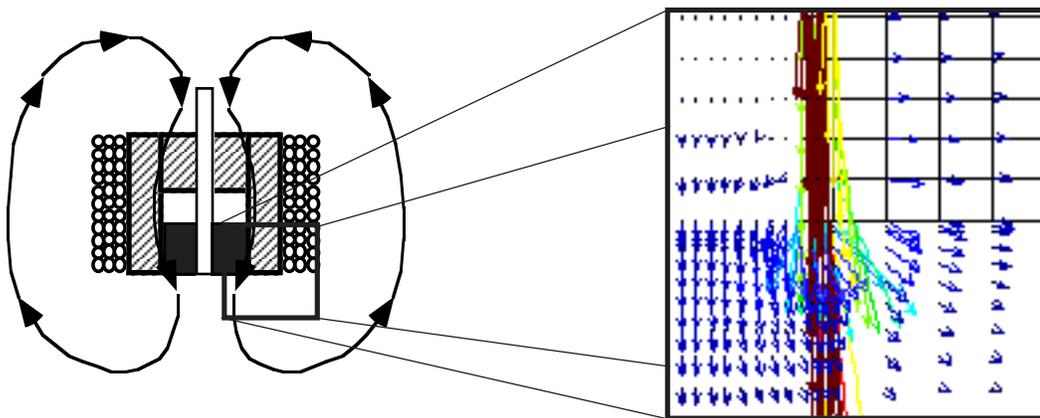


Fig. 2. Magnetic field flow about Flux Focusing Eddy Current Probe.

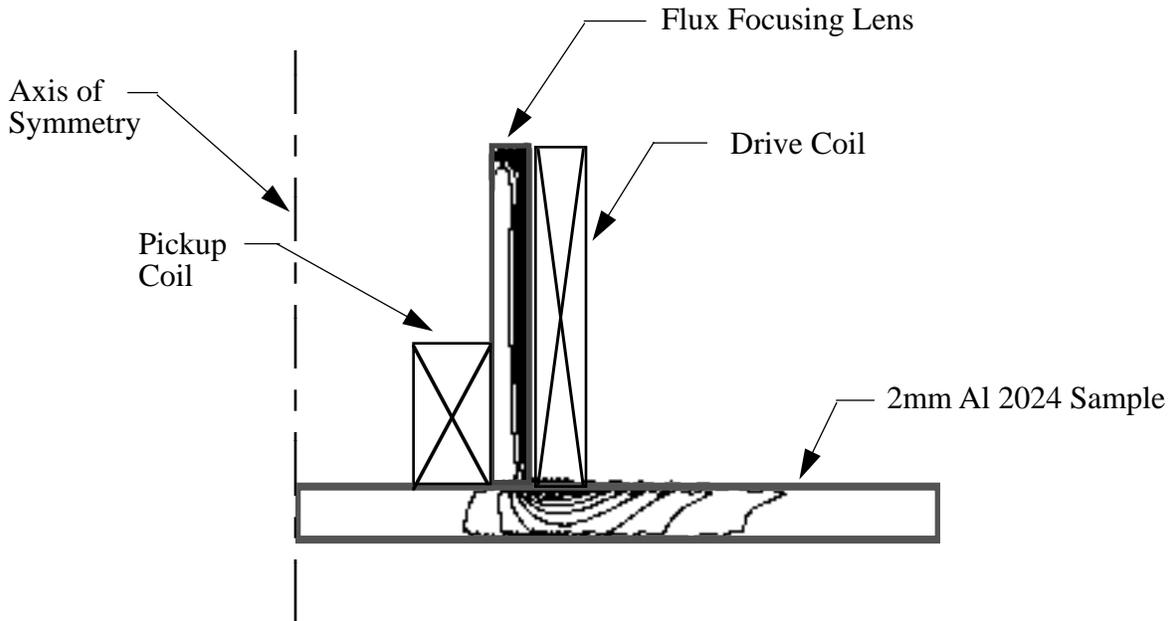


Fig. 3. Plot of eddy current density in sample and flux focusing lens for a 7 kHz drive. The contour lines which reach the pickup coil travel deep into the sample and therefore carry information on the thickness of the sample.

inner diameter of the lens wall. Further details of the properties of the flux focusing lens are discussed in a companion paper [2].

The flow of the magnetic field through space will be along equi- $\bar{A}$  contours [3]. For a sinusoidal drive the eddy current density is given by,

$$\bar{J}_e = \sigma \bar{E} = \sigma \left( -\frac{d\bar{A}}{dt} \right) = -j\omega\sigma\bar{A} \quad (1)$$

where  $J_e$  is defined to be the eddy current density and  $\sigma$  is the conductivity of the test sample. The magnetic field flow through the sample will therefore be along equi-eddy current density lines. Fig. 3 can then be viewed as a plot of the magnetic field flow in the sample. From this viewpoint it is clear that the field lines which link the pickup coil when the probe is placed on a conducting sample travel deep into the material under test. The only contour line reaching the interior of the probe makes contact with the back surface of the sample. Since the only information reaching the pickup coil travels deep into the sample, a more accurate thickness measurement can be made than by conventional eddy current techniques for which the greatest amount of information is obtained from the surface of the sample, decaying exponentially with depth.

The output voltage of the pickup coil is related to the magnetic field passing through the area of the coil by Faraday's law of electromagnetic induction [4]. In CGS units Faraday's law states

$$\varepsilon = -\frac{1}{c} \frac{dF}{dt} \quad (2)$$

where  $\varepsilon$  is the induced electromagnetic force (emf) around a coil loop and  $F$  is the magnetic flux linking the loop, defined by

$$F = \int_s (\bar{B} \cdot \bar{n} da) \quad (3)$$

where  $\bar{B}$  is the magnetic field in the neighborhood of the probe and  $\bar{n}$  is the normal to the

pickup coil loop. The output voltage of the pickup coil is simply the sum of the induced emf for each turn of the coil. An N turn coil would then have an output voltage of

$$\epsilon = -\frac{1}{c} \sum_N \left( \int_s \left( \frac{d\bar{B}}{dt} \cdot \bar{n} da \right) \right) \quad (4)$$

or, assuming a sinusoidal drive frequency of  $\omega$ ,

$$\epsilon = -\frac{\omega}{c} \sum_N \left( \int_s (\bar{B} \cdot \bar{n} da) \right) \quad (5).$$

The high turn pickup coil of the probe is located at the bottom the probe where the flux linkage around the ferrous wall is greatest. A large output voltage is therefore generated when the probe is operated in-air. When the probe is placed above a conducting sample the flux that had circled around the lens is forced to travel through the sample. An emf will be generated in the sample by the same mechanism given above for the pickup coil. The induced emf will cause eddy currents to flow according to ohm's law,  $I = \epsilon/\rho$ , where  $\rho$  is the resistivity of the sample and  $I$  is the current amplitude. These eddy currents will attenuate the primary magnetic field as it passes through the material. As the sample thickness increases the primary flux must propagate through a greater depth of material so that the flux linking the pickup coil will be reduced. This reduction in flux linkage corresponds to a decrease in output voltage of the probe, as detailed above. The probe output voltage can then be directly correlated with the thickness of the material under test.

## THICKNESS GAUGING

The Flux Focusing Eddy Current Probe has been used to accurately measure the thickness of aluminum alloy sheets as a means toward improving the non-destructive evaluation of commercial airframes. Fig. 4 displays the output voltage of the device as a function of frequency for sample thickness varying from 0.030" (750  $\mu\text{m}$ ) to 0.035" (875  $\mu\text{m}$ ) in 0.001" (25  $\mu\text{m}$ ) increments. After an initial increase in amplitude all the curves show a decreasing

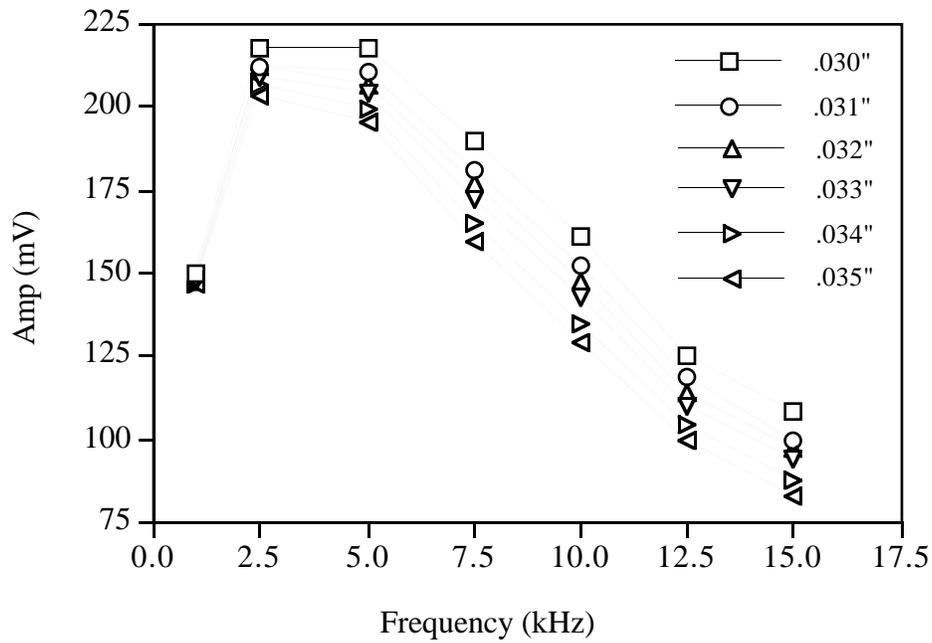


Fig. 4. Swept frequency measurements on aluminum 2024 show a clear separation as a function of thickness with a resolution greater than 0.001".

trend as the frequency is increased. Thicker samples show a lower output voltage across the frequency bandwidth, with a maximum separation of the curves occurring at approximately 10 kHz.

A more physical understanding of the data in Fig. 4 can be achieved by backing out the magnetic field at the location of the pickup coil. The pickup coil voltage is proportional to  $\omega\bar{B}$  so that dividing out the frequency of the excitation current will provide a quantity proportional to the magnetic field across the frequency range. In addition, skin depth considerations predict an exponential decay of the magnetic field into the sample as

$$B_z = B_0 e^{-z/\delta} \quad (6)$$

where the skin depth is given by

$$\delta = \frac{c}{\sqrt{2\pi\mu\omega\sigma}} \quad (7) [3].$$

An exponential decay of the magnetic field for a given thickness  $z$  is therefore expected with the square root of the frequency. Fig. 5 displays a plot of the output amplitude of the pickup coil divided by the drive frequency versus the square root of the drive frequency for the 0.035" (875  $\mu\text{m}$ ) thick aluminum alloy sample. The data points have been fit to an exponential curve, showing the clear decay characteristics of the field level in the interior of the probe.

The exact thickness of a test sample can theoretically be calculated, through equations 6 and 7, from the coefficients of the exponential fit to data processed as in Fig. 5. The complex nature in which the magnetic fields are traveling about the ferromagnetic flux focusing lens, however, makes this direct calculation difficult. The skin depth equation assumes a uniform field in the plane of the sample which diffuses into the sample in the direction normal the surface. The field configuration about the Flux Focusing Eddy Current Probe does not meet these assumptions. The fields are diffusing through the sample in a elliptical path around the lens as well as directly through the lens wall. The field in the interior of the probe is a combination of these two effects, which are frequency dependent and difficult to sepa-

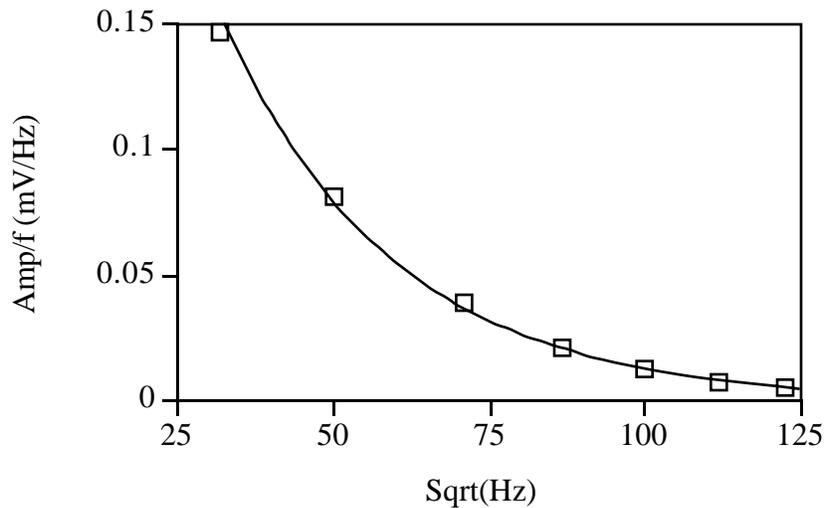


Fig. 5. Plot of amplitude of pickup coil output divided by frequency versus the square root of the frequency for 0.035" thick aluminum alloy sample. The data has been fit to an exponential curve, highlighting the decay characteristics of the field in the interior of the probe.

rate. Work is currently in progress to characterize the path of the flux around the lens and to determine the relative magnitudes of the field due to propagation through the lens wall as opposed to through the material under test. Future work will focus on analytically determining the thickness of a material from a swept frequency measurement although accurate thickness measurements can currently be made using reference standards and look-up tables.

## CORROSION DETECTION

Corrosion damage in a structure can be detected by the material thinning that occurs as the base metal is converted to corrosion by-products. The Flux Focusing Eddy Current Probe will register a higher output voltage over areas where corrosion damage is present as compared to measurements over unflawed metal. Fig. 6 displays the results of a single frequency scan over a 1 mm thick aluminum 2024 plate. Material was machined out from the back surface of the sample in order to simulate corrosion pitting occurring at the back surface of the metal. A frequency of 10 kHz was chosen for the scan in order to optimize the voltage changes associated with material loss from the base thickness. The figure shows that even the smallest flaw, 0.1 mm deep in the center and 3 mm diameter across the base, was detected using the flux focusing probe. The increase in the probe amplitude as the defects are crossed is clearly evident in the voltage contour plot. The concentration of contour lines along the borders of the figure is due to the edge effect.

The detection of simulated inter-layer corrosion was also performed with the new eddy current probe. Fig. 7 shows the results of a scan over a two plate panel in which material was milled from the back surface of the top plate. The two plates were then bonded together, sandwiching the flaw between the plates. The base thickness of the top aluminum plate was 1.6 mm, and up to 7% of the thickness of the top panel was removed. The thicker base material necessitated the use of a lower frequency than for the previous figure, and a

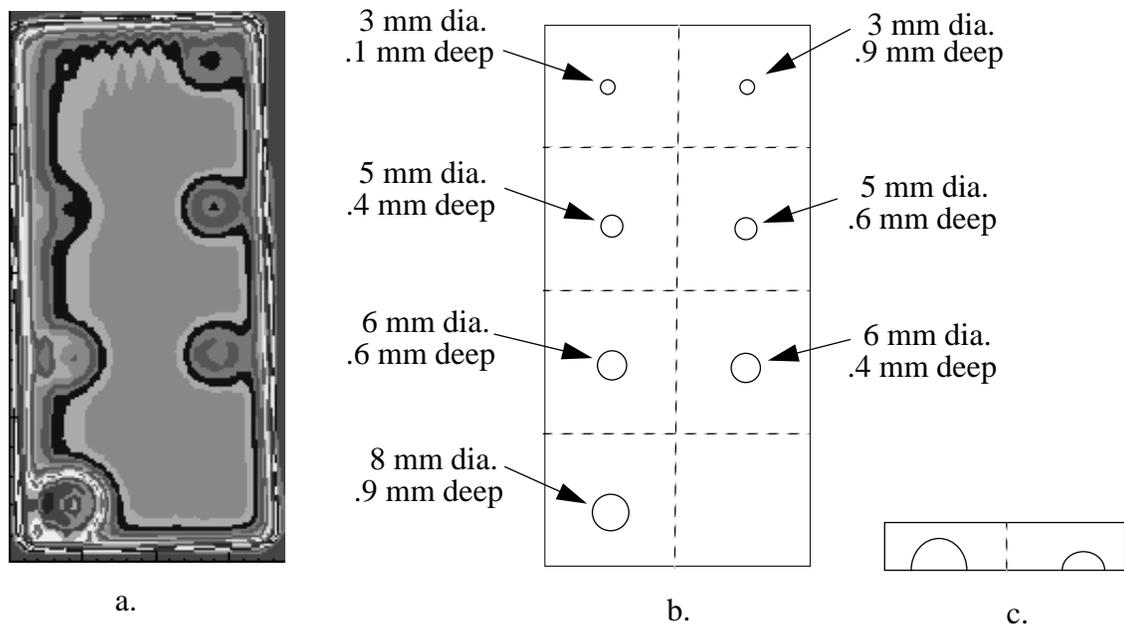


Fig. 6. Detection of simulated corrosion pitting with flux focusing probe. Voltage contours displayed in fig. a clearly delineate all defects in the sample, as detailed in fig. b. Corrosion pitting was simulated by drilling material away from the back surface of the sample in order to create defects as pictured in fig. c.

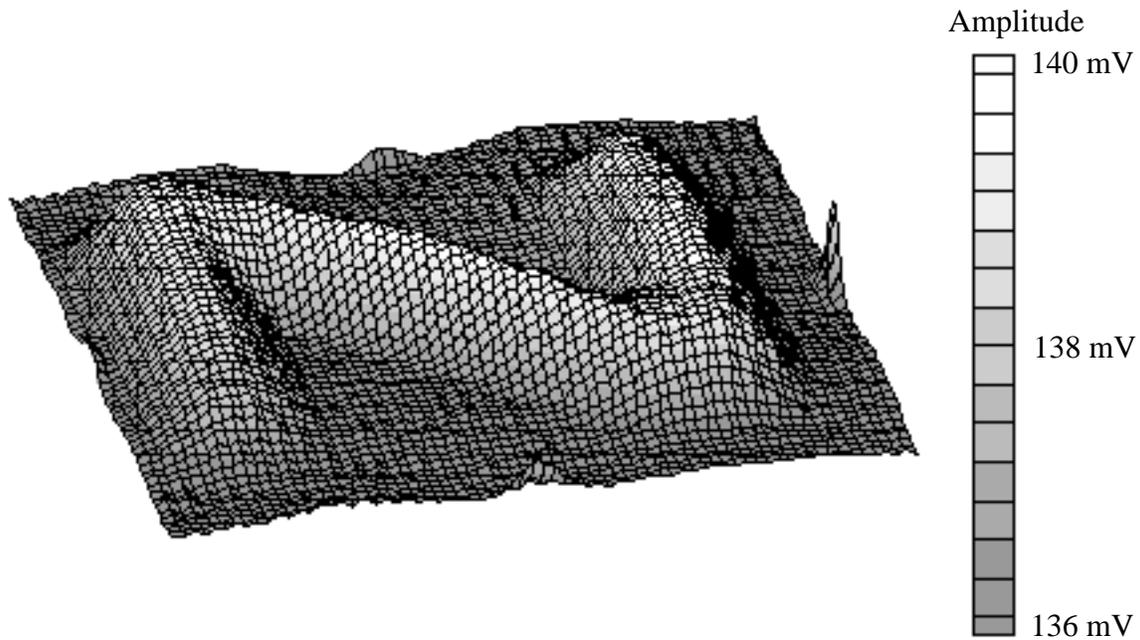


Fig. 7. Detection of simulated interlayer corrosion damage with flux focusing probe. Material losses of less than 7% from back surface of 1.6 mm top layer are easily detected.

2.5 kHz drive was found to give good results. The figure clearly shows the area of material loss, which was removed in the shape of an N. In Fig. 8 the actual values of material loss as measured with a caliper before the plates were bonded together is compared with the output voltage of the flux focusing probe. The curve in the figure is a plot of the material loss along the crest of the N as a function of distance along the material loss region. The normalized output voltage of the probe is seen to agree very well with the actual measured values of material loss, where sharp changes in the actual material loss of the sample are somewhat smoothed out because the probe is averaging material thickness information over a wider area.

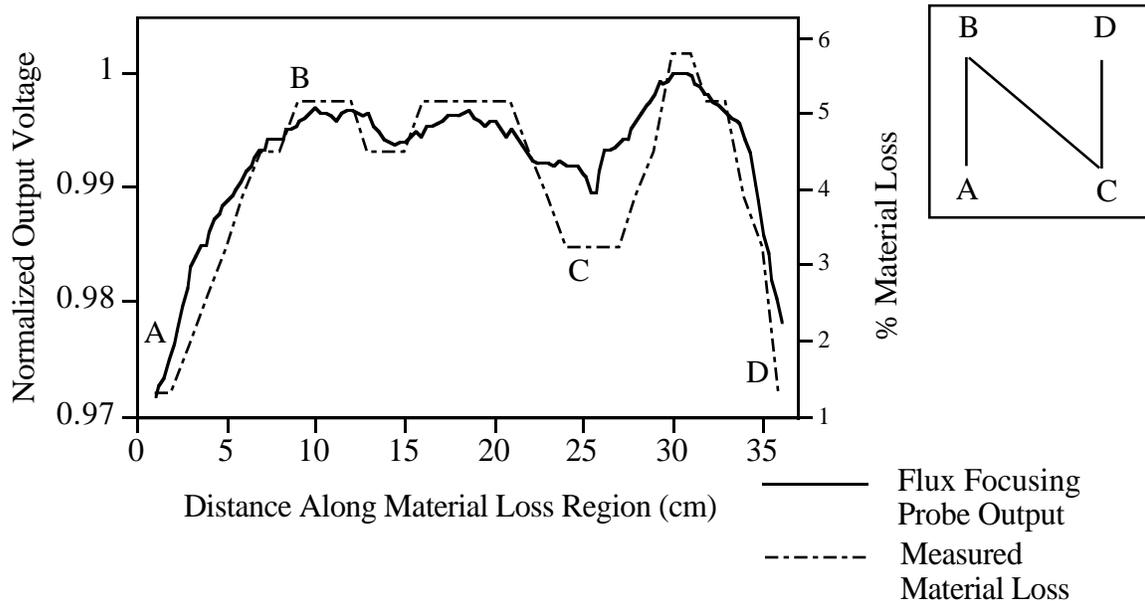


Fig.8. Comparison of normalized flux focusing probe output with measured values of material loss for interlayer corrosion damage sample.

## SUMMARY

The Flux Focusing Eddy Current Probe has been shown to be a useful tool for accurately measuring material thicknesses as well as detecting corrosion damage. The unique probe design forces the magnetic flux deep into the sample, so that an accurate measure of the thickness of the test part can be made. Swept frequency measurements are able to clearly separate material thickness changes of less than 25  $\mu\text{m}$ . Detection of corrosion damage has been performed with a single frequency scan, where the drive frequency is chosen based on the thickness of the base metal. Simulated corrosion pitting with a material loss volume of under 0.7  $\text{mm}^3$  and interlayer corrosion with material losses of 1.5 to 5.5% of the base metal thickness have been detected.

## ACKNOWLEDGEMENTS

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