EDDY-CURRENT MEASUREMENTS OF CORROSION-RELATED THINNING IN ALUMINIUM LAP SPLICES

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INTRODUCTION

The aging commercial aviation fleet requires new methods for detecting and characterizing corrosion. In particular, the need exists for a rapid and reliable method of nondestructively detecting and characterizing corrosion in layered aircraft skins. Aircraft skin consists of thin aluminum sheet. There are many joints at which these sheets are overlapped and attached to the airframe by fasteners that extend through the sheets and into the substructure. The overlapping aluminum sheets are generally separated by a thin gap, which may be filled with a sealant. Because of the overlapping nature of such joints, the second sheet and the substructure are not directly accessible from the surface.

Many methods are available for the detection and characterization of material loss due to corrosion in the outer (first) layer. Possible methods include x-rays, ultrasound, thermal waves and eddy currents. The present practice in commercial aviation is to use single-frequency eddy-current measurements to gauge the thickness of the first layer. Eddy-current inspections are relatively rapid and have the advantage of being non contacting. However, single-frequency measurements cannot be used to infer the dimensions of the second layer; they simply do not contain enough information. Another problem that arises in single-frequency measurements is discriminating between actual metal loss and separation of the two layers.

In this paper we describe a new eddy-current technique for determining the thickness and separation of two overlapping plates of aluminum alloy. The new method is adapted from an eddy-current method developed for determining thickness and conductivity of layered metal plates [1,2]. These methods are based on a kind of impedance spectroscopy: quantitative measurements of probe impedance over a wide range of frequencies. In the present case, the operating frequency of the probe was varied from 1 kHz to 200 kHz. We tested the new technique with measurements on a series of 2024 aluminum plates 1 mm thick with 38 mm square areas milled to various depths to simulate metal thinning caused by corrosion. We also used samples corroded electrochemically in an NaCl solution. Experimental results are compared to theoretical predictions based on the analytical solution of Cheng, Dodd and Deeds for the impedance of an air-core coil over a layered half-space [3]. Finally, we suggest how conventional eddy-current instruments could be used to determine the location and severity of corrosion-induced metal thinning.

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THEORY

The numerical method used to calculate the impedance of a right cylindrical, air-cored eddy-current coil placed over a layered half-space is based on the analytical solution given by Cheng, Dodd and Deeds [3]. Figure 1 shows the geometry of the system under study, consisting of a four-layer structure where layer 1 represents the supporting structure (or air, in the absence of any support), layer 2 is the inner (second) layer of the aircraft skin, layer 3 is the air gap between layers, and layer 4 is the outer (first) layer of the aircraft skin. The impedance of the coil is given by

$$Z = K \int_0^{\infty} d\alpha \frac{I^2(\alpha)}{\alpha^5} \left\{ 2L + \frac{1}{\alpha} \left[2e^{-\alpha L} - 2 + \left(e^{-\alpha h_1} - e^{-\alpha h_2} \right)^2 \phi(\alpha) \right] \right\}, \tag{1}$$

where L is the length of the coil ($= h_2 - h_1$),

$$K = \frac{\pi n^2 j \omega \mu_0}{L^2 (r_2 - r_1)^2}, \tag{2}$$

$$I(\alpha) = \int_{\alpha r_1}^{\alpha r_2} dx\, x J_1(x), \tag{3}$$

n is the number of turns, and other geometrical parameters are shown in Fig. 1. $\phi(\alpha)$ is a complicated function involving the material properties of each layer (conductivity and permeability), as described in reference [2]. Equation (1) can be adapted to model either the impedance of the coil over a corroded region or over an uncorroded region of the specimen. In practice, we measure the difference between the coil impedance over an uncorroded part of the sample and over the corroded area ($\Delta Z = Z_{ref} - Z_{corr}$). Therefore, in the calculations we report here, we have modeled ΔZ in the same fashion. The reason for modeling and measuring the *impedance change* rather than the total impedance is that the subtraction reduces errors caused by imperfect modeling of the coil and facilitates comparison of theory and experiment.

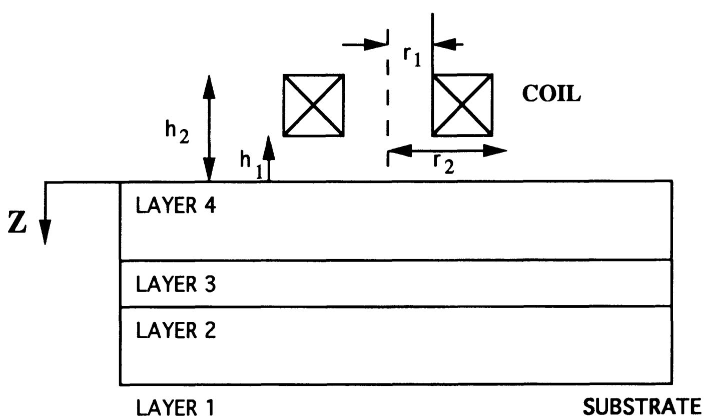

Fig. 1. Diagram of eddy-current coil geometry and structure of lap joint.

EXPERIMENT

A schematic diagram of the experimental set-up is shown in Figure 2. All of the measurements were made using an impedance analyzer (Hewlett-Packard Model 4194A), which is capable of measuring complex impedances at frequencies between 100 Hz and 40 MHz. For the measurements reported here we typically made measurements at 399 points spaced evenly between 1 kHz and 200 kHz. The coil used for the measurements was a precision wound air-core eddy-current coil with a mean diameter of 9.4 mm and 505 turns. An air-core coil was used to facilitate comparison with theoretical predictions, but ferrite-cored probes could be used as well. The impedance of the coil over two layers of aluminium without any thinning was measured first. The impedance difference ΔZ was formed by subtracting the coil impedance measured over an area containing the thinned metal from the first measurement. Data were taken repetitively to assure reproducibility; the averaged results of at least five measurements are reported in this paper for each case.

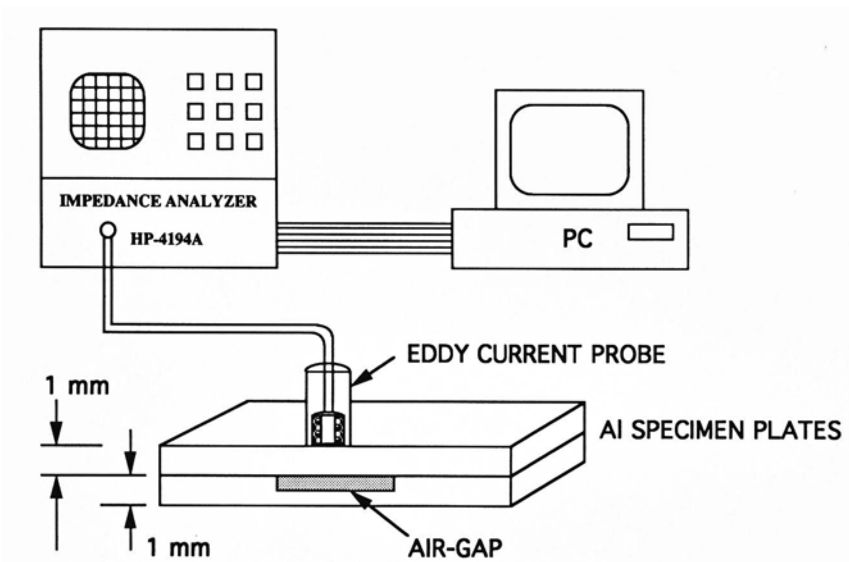

Fig. 2. Experimental apparatus used to measure impedance of eddy-current coil over simulated lap joint.

For the preliminary experiments we prepared a series of samples by milling flat holes of varying depths (ranging from 0.05 mm (2 mils) to 0.5 mm (20 mils) in 1 mm thick plates of 2024 aluminium. These plates were approximately 75 x 125 mm in size and are representative of those typically used in the manufacture of aircraft skins. Pairs of plates were mounted in an acrylic test fixture specifically designed to hold the test panels flat, enabling reproducible measurements to be made. Small amounts of tilt or liftoff introduced during the two measurements of impedance can result in errors in ΔZ. Four different orientations of the samples were studied with the missing metal at different locations: at the bottom of the first (outer) layer, at the top of the second layer, at both these locations at the same time, and at the bottom of the second layer (an area where corrosion can occur but no existing techniques can be applied).

For the next phase of this study we prepared laboratory corroded samples by a simple electrochemical procedure. Plates of 2024 aluminium were masked with several layers of tape such that a 38 x 38 mm window was left exposed on one side of the plate and the backside was completely covered. The plate was placed in a 0.5-mole solution of sodium chloride and positioned 0.5 cm from a platinum electrode. A 4.5 V dc voltage was applied across the platinum anode and the aluminium cathode to initiate the electrolytic process. Each plate was corroded for a specific time (varying from 4 to 20 hours.) A set of four samples with varying degrees of corrosion were prepared in this fashion.

RESULTS

Figure 3 displays the results of typical measurements made with the milled area located on the bottom of the first layer. Results are shown as plots of ΔR vs. frequency for three different amounts of metal loss, ranging from 7.5% to 30% of the layer thickness. Theoretical predictions for each case are shown in Fig. 3 as well. The agreement between theoretical and experimental results is good. Similar curves of ΔR are obtained when the thinning occurs at the top (faying surface) of the second layer, at the base of the second layer, or symmetrically at the interface of the two plates. The frequency dependence of the real part of the ΔZ is observed to start from zero at low frequencies and then decrease to a minimum as the frequency increases, followed by a maximum at higher frequency. Detailed discussion of this trend and its theoretical interpretation have been presented elsewhere [1].

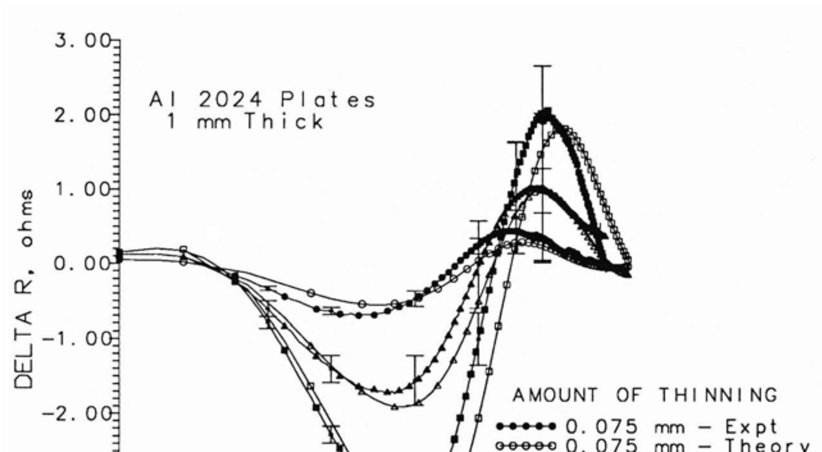

Fig. 3. Change in the real part of eddy-current probe impedance as a function of frequency for simulated corrosion at the bottom of the first layer of lap joint for 7.5, 20, and 30% metal loss. Open symbols are theoretical predictions; solid symbols represent mean of five independent measurements.

We observe that the strength of the extrema in ΔR increases as the depth of the milled region increases, and this trend is also followed when the metal loss occurs in other locations. To obtain a series of calibration curves that can be used to infer the amount of metal loss from measurements, we plot the depth of the minimum in ΔR against the depth of the milled area in the test panel. These data are shown in Fig. 4 for all four orientations of the test panels studied. Several trends can be seen in this graph. When the missing metal is at the bottom of the first layer the calibration curve is quadratic. When the milled region is at the top of the second layer or at the base of this layer a linear response is obtained. In the second case the scatter in the experimental data is somewhat higher than in all of the other cases due to the much smaller signal strengths for this situation. As expected, when there is thinning in both the base of the first layer and the top of the second layer, the curves obtained are a combination of those obtained for the two individual cases and the resulting calibration curve is a much weaker quadratic.

An interesting feature in the curves of ΔR vs. frequency is the position of the minima. The frequency at which the minimum occurs for a particular depth shifts to lower frequency as the eddy currents probe deeper into the material. For illustrative purposes, in Fig. 5a we plot characteristic curves of ΔR vs. frequency for the specimen milled to a depth of 0.2 mm (8 mils) for orientations in which the thinning is in the first layer, the faying surface of the second layer, and the base of the second layer. The shift in the minimum in ΔR to lower frequency as we probe deeper into the material is clear and this behaviour is typical for all the specimens, although the shift gets smaller as we look at smaller amounts of thinning. This characteristic frequency shift can be used as a tool to evaluate where corrosion has occurred in the material. Once the location of corrosion has been determined, the appropriate calibration curve can be used estimate the amount of thinning present.

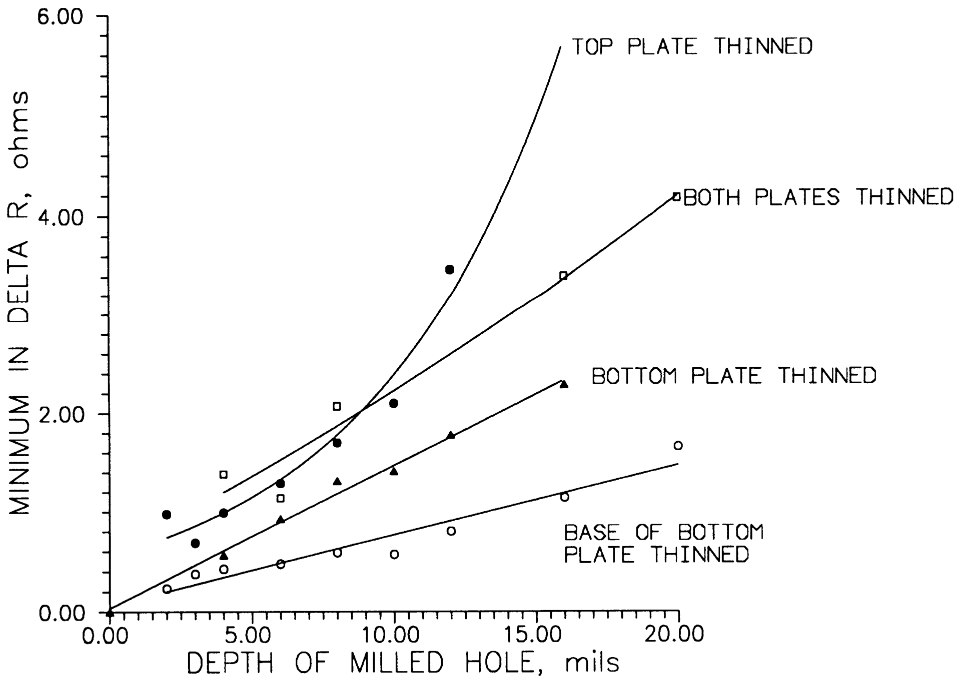

Fig. 4. Calibration curves showing strength of the minimum in the ΔR vs. frequency curve plotted against depth of the milled region for each of the four sample orientations studied.

To determine the feasibility of this approach, we proceeded to further analyze the experimental measurements in the following way. First, we observe from Fig. 3 that the average frequency of the minima in ΔR when metal loss occurs on the base of the first layer is about 20 kHz. From similar curves generated for thinning on the top of the second layer and the base of this layer, we note that the average frequencies where minima occur are approximately 12 kHz and 6.5 kHz, respectively. Figure 5b shows the value of ΔR for the 0.2-mm specimen plotted for these three frequencies when the metal loss occurs in the first layer, second layer, and at the bottom of the second layer. The shape of the curves is strikingly dependent on the location of thinning. We observe that when metal loss occurs in the first layer, ΔR tends towards larger negative values as the frequency increases. The trend is just the opposite with thinning at the base of the second layer; in this case the slope of the curve is opposite in sign. For the case where thinning is on top of the second layer, the slope of the curve changes sign at 12 kHz. Thus, measuring ΔR at just three frequencies can determine the location at which corrosion is likely to have occurred. The frequency at which the largest negative value of ΔR is obtained will give information regarding the location of corrosion.

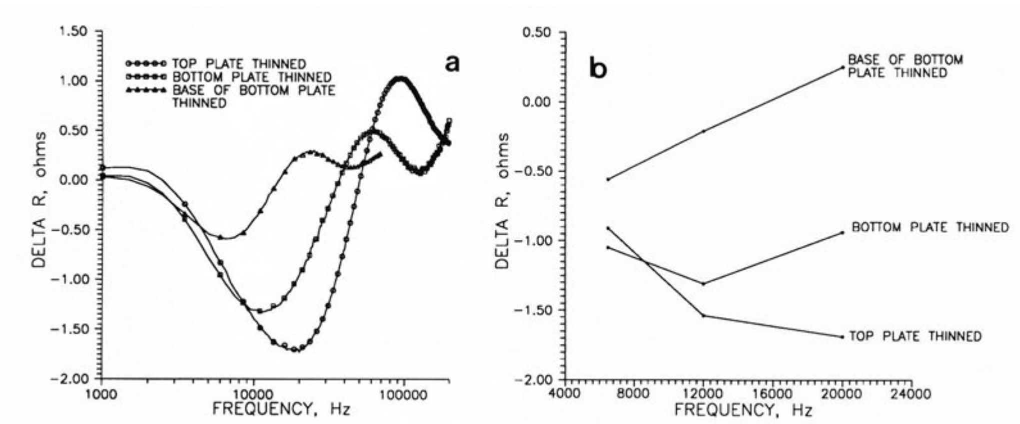

Fig. 5. Change in the real part of eddy-current probe impedance as a function of frequency for specimen milled to a depth of 0.2 mm with simulated metal loss located at different positions in lap joint. Complete impedance spectra (left) and value of ΔR at three selected frequencies (right).

This technique could be more easily implemented in practical field applications, as a bulky (and expensive) impedance analyzer would not be necessary and a conventional eddy current instrument could be used instead. An additional benefit would be the increased speed of measurement compared to measurements with an impedance analyzer.

Results of measurements made on laboratory corroded specimens are shown in Fig. 6a,b for orientations representing thinning of metal at the base of the first layer and the top of the second layer, respectively. We note that the shape of the curves is consistent with those obtained for the milled samples. Again, we observe that the minima in ΔR occur at a lower frequency for metal loss deeper within the structure. We estimated the amount of corrosion for each case for both orientations by noting the value of the minimum in ΔR and using the calibration curves shown in Fig. 4. Results of this analysis are given in Table I. The amounts of metal loss inferred from the two independent calibration curves are consistent and demonstrate the robustness of this technique. These values are in good agreement with direct measurements of metal loss made on similar samples which were cut and studied by micrographic techniques.

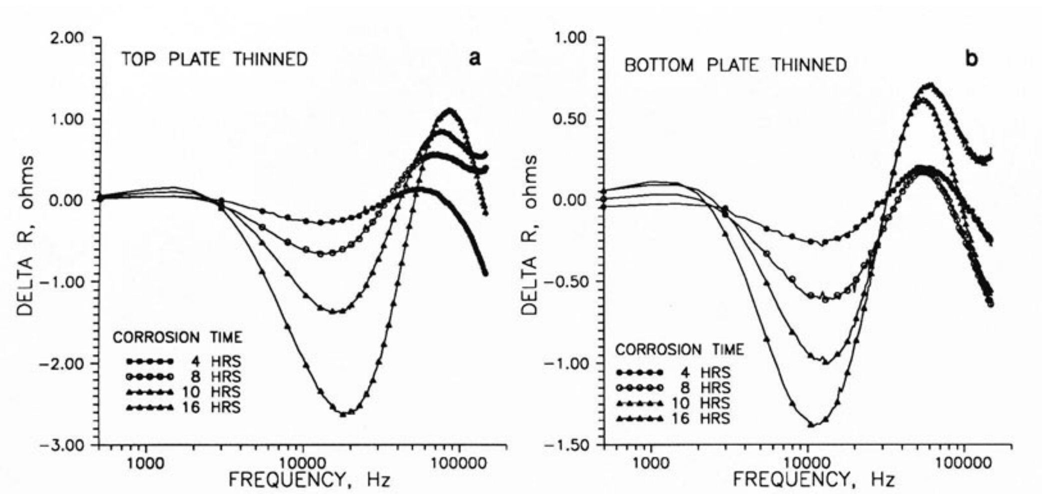

Fig. 6. Change in the real part of eddy-current probe impedance as a function of frequency for 2024 aluminum plates corroded electrochemically in NaCl solution for various times. Corroded region located at bottom of first layer (left) and at top of second layer (right).

CONCLUSIONS

We have presented a new eddy-current technique for measuring corrosion-related thinning in aluminium lap splices. The technique is able to detect and quantify corrosion in milled test panels as well as laboratory corroded specimens. Using a series of test panels representing metal loss of 5% to 50%, we generated characteristic calibration curves corresponding to the occurrence of corrosion at different locations in an aircraft lap joint. Furthermore, we observed a characteristic shift in the frequency of the extrema in the impedance spectrum as the location of the corroded region shifts to different depths in the structure. Based on this observation, a simple three-frequency technique has been developed to effectively predict the location and amount of metal loss. Following preliminary work with milled test panels, the technique was tested successfully on laboratory samples corroded by an electrochemical procedure. By using calibration curves generated with the milled specimens, we were able to successfully infer the amount of metal loss in the corroded samples.

Table I. Amount of metal loss in electrochemically corroded samples inferred from measurements of change in eddy-current probe impedance using calibration curves in Fig. 4.

Location of corrosion	Corrosion time (hours)	Minimum in ΔR (ohms)	Amount of metal loss (mm)	Inferred metal loss (mm)
Top Layer	4	-0.28	0.016	0.025
	8	-0.66	0.053	0.075
	12	-1.36	0.199	0.15
	16	-2.61	0.260	0.25
Bottom Layer	4	-0.25	0.016	0.025
	8	-0.61	0.053	0.1
	12	-0.97	0.199	0.15
	16	-1.38	0.260	0.225

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