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An Eddy Current Scanning Method for the Detection of Corrosion Under Fasteners in Thick Skin Aircraft Structures

B.A. Lepine * R.T. Holt **

ABSTRACT

An eddy current NDT scanning method is presented for inspecting simulated thick skin wing joints for second layer corrosion using a calibration specimen. It was found that single frequency methods are adequate for such configurations when it is known that first layer corrosion, varying air gaps, or fasteners are not present. Frequency mixing is essential, however, for detecting second layer corrosion under installed fasteners in such thick structures. With the appropriate frequency selections, corrosion under the fasteners is observable by minimizing the strong signals from the fasteners. In this case, the smallest detectable corrosion site had a diameter of 12.7 mm (0.5 inch) and a depth of 0.15 mm (6 mils) located in the second layer under a fastener with a 9.53 mm (0.375 inch) diameter head. The specimens, in which varying amounts of exfoliation corrosion were developed, were found to be useful for calibrating eddy current scanning inspection set-ups to detect corrosion above a set threshold. This could be useful for inspection of in-service aircraft components of the same material and structural configurations.

RÉSUMÉ

En se servant d'un appareil explorateur pour une inspection non-destructive et en utilisant des spécimens de calibrage, une méthode de courants de Foucault est présentée pour détecter la corrosion résidante dans la deuxième couche d'un assemblage simulant une aile d'avion. On a trouvé que les méthodes de fréquences simples sont adéquates pour de telles configurations quand il est connu que la corrosion de la première couche, les écarts d'air variés ou les rivets ne sont pas présent. Le mixage de fréquences multiples est essentiel, cependant, pour détecter la corrosion dans la deuxième couche sous des rivets installés dans des structures aussi épaisses. Avec les sélections appropriées de fréquences, la corrosion sous les rivets est observable en minimisant les signaux intenses de ces rivets. Dans ce cas, le plus petit site détectable de corrosion a un diamètre de 12.7 mm (0.5 pouce) et une profondeur de 0.15 mm (6 mils) situé dans la deuxième couche sous un rivet avec une tête de 9.53 mm (0.375 pouce) de diamètre. Les spécimens, dans

*Air Vehicle Research Section
National Defence Headquarters
Ottawa, ON, K1A 0K2
**National Research Council of Canada
Institute for Aerospace Research
1500 Montreal Road, Ottawa, ON, K1A 0R6

INTRODUCTION

Automated eddy current scanning of military or civilian aircraft for corrosion detection is rarely performed in the field. Usually manual tests are performed by simply placing or sliding a probe across the interrogated surface, using an eddy current instrument's impedance plane to observe flaw responses. This technique was used in an early study by Hagemaier to detect first layer corrosion around fasteners in thick wing skins using single frequency methods[1]. More recently, Thompson modified these basic techniques by introducing dual frequency methods to detect second layer corrosion in fuselage skin lap splices[2]. This was soon followed by another Hagemaier study that combined the multi-frequency mixing methods with automated scanning to detect corrosion thinning on the back side of the second layer of a fuselage lap splice[3]. During this evolution, advances in scanning and imaging technologies have sparked considerable interest and investigations in the feasibility of using automated eddy current nondestructive testing (NDT) methods in the aircraft community. Automated imaging techniques offer several advantages over conventional methods, including better reproducibility, reportability and detectability. Recent strides in these areas have dealt mostly with the detection of corrosion in thin skin structures between the fasteners, as evidenced by pillowing in fuselage lap splices. Wing structures, however, typically consist of much thicker material, where sub-surface corrosion in overlapping joints can occur under the fasteners. Although variable air gaps in thick skin structures are typically not as pronounced as in fuselage lap splices, the complications introduced by the larger material depths and fastener interference makes corrosion detection under fasteners a much more difficult one for eddy current scanning methods.

BACKGROUND

Depending on the location of a corroded area (first layer, second layer, etc.) variations of the eddy current test parameters are implemented for optimum detectability, with excitation frequency being the most important controllable parameter. For single layer structures, single frequency eddy current inspection is sufficient to detect corrosion, with the frequency chosen as a function of the material's thickness. Single frequency eddy current inspections can also be used in multi-layered structures if only first layer corrosion detection is suspected. In such cases, the frequency should be high enough to concentrate the induced eddy currents in the first layer. This minimizes indications due to a possible changing air gap between the layers or interference from sub-structural members.

In second layer corrosion detection, a varying gap size due to plate separation produces a very similar impedance plane

lesquels des sommes variantes d'exfoliation de corrosion étaient développées, sont utiles pour calibrer un assemblage d'inspection pour détecter la corrosion excédant un niveau prédéterminé. Cela pourrait être utile pour inspecter des parties actuelles d'avion de mêmes configurations structurales et matérielles.

response to that from material loss due to corrosion. This is especially important in thin skin structures, such as fuselage lap-splices since corrosion products force the skins apart between the fasteners. This problem has been addressed in the past with the use of dual frequency mixing methods.[2,3]

This paper will present eddy current C-scan results of simulated wing joint specimens with second layer corrosion both away from and under installed fasteners. In all cases, the air gaps are kept constant. With these specimen configurations, the scanning method will attempt to overcome three significant obstacles. Firstly, the total thickness of these wing planks is high (8.89 mm or 0.350 inch). There is a concern regarding the reduction in sensitivity caused by the increased attenuation of the electromagnetic fields (hence, eddy currents) with material depth. Secondly, the spatial resolution and sensitivity to small areas of corrosion are reduced since deeper eddy current penetration is achieved with lower frequencies and larger diameter coils. Thirdly, the extremely high levels of signal interference from installed fasteners present the greatest problem. A modified frequency mixing approach is presented as a solution when inspecting for corrosion under fasteners.

EXPERIMENTAL PROCEDURE

Specimen Preparation

Aluminum alloy plates of the same thickness as found in the wing plank joints for the upper wing skin of the Canadair CL-601 (Challenger) were selected as test subjects for this study. The actual wing planks are machined from plate to a thickness of 4.45 mm (0.175 inch), shot peened, coated, drilled, countersunk and attached with nonferrous Hi-Lok fasteners. The upper wing skin material, aluminum alloy 7475-T7351, is generally considered to have good corrosion resistance for a high strength structural alloy, much better, for example, than 7075-T6xxx. However, the development of sub-surface corrosion at fastener holes is always a major concern, even with corrosion-resistant materials.

For the present study, specimens of 7075-T6 and 7475-T73 sheet, approximately 250x150x4.45 mm (10x6x0.175 inch) have been prepared with simulated corrosion sites in the form of flat-bottomed holes, as shown in **Figure 1**. The diameters of the holes in mm (and inches), from left to right are 25.4 (1.00), 22.2 (0.875), 15.9 (0.625), 15.9 (0.625), 12.7 (0.50), 9.53 (0.375) and 7.95 (0.313). The depth of the holes in the top row of **Figure 1** is 0.00 mm, in the second row 0.51 mm (20 mils) and in the bottom row 1.52 mm (60 mils). The remaining surface was then painted, after which the specimens were exposed to a standard corrosion solution (as per the EXCO exfoliation test in ASTM G34) for 28 hours, followed by rinsing, cleaning, and metallographic examination. The average depths of the unprotected, "naturally corroded" holes in each row were then measured at 0.15, 0.71 and 1.83 mm (6, 28 and 72 mils) respectively. [Later in the paper it will be shown that this corrosion damage can be used to calibrate eddy current testing methods to detect sub-surface exfoliation damage in wing plank splices, after which fasteners will be installed and the process repeated.]

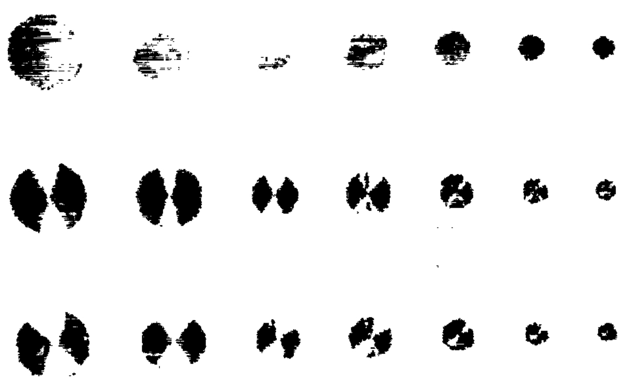

Figure 1.
Uncorroded, painted sheet specimen.

Eddy Current Testing of Unfastened Plates

The corroded plates were temporarily fastened to their respective uncorroded plates with double-sided adhesive tape. The paint was left on the second plate to represent the non-conductive anti-corrosion sealant that exists in real wing-skin lap joints. This provided two wing-skin representations (7075-T6 and 7475-T73) that exhibited corrosion in the top of the second layer. A schematic of this set-up is shown on the left side of **Figure 2.**

Single Frequency Analysis

Several single frequency eddy current tests were performed on both samples prior to Hi-Lok fastening. This was useful in determining the sensitivity of the scanning procedure with respect to the corroded sites alone, without the interference of the

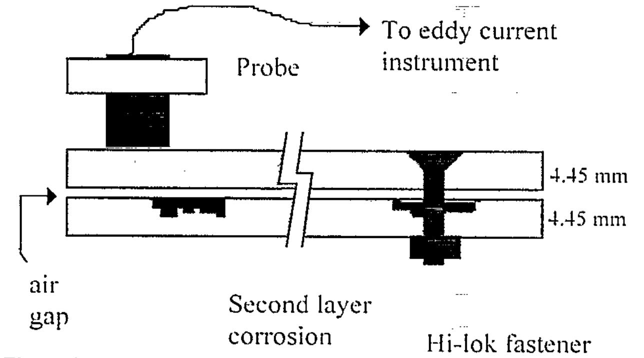

Figure 2.
Schematic of wing-skin representation prior to (left) and after installation of fasteners (right).

fasteners. The eddy current set-up consisted of a 16 mm (0.625 inch) diameter reflection probe, with a range of 100 Hz to 10 kHz, connected to a Zetec MIZ-40 Eddy Current Instrument capable of performing up to four different frequency measurements simultaneously. Each plate was scanned using an automated 2-axis table scanner controlled by Winspect™ data acquisition and motor control software with a 16 channel digitizer, of which only eight were connected to the eddy current instrument. It is important to differentiate this multi- frequency set-up from an actual multi-frequency eddy current technique. In this case, the actual scans were analyzed one frequency at a time, making it a single frequency method. The implementation of this multi-frequency set-up simply reduced the number of required scans.

The impedance plane responses in magnitude and phase are digitized into a 0 to 255 intensity scale, while the sample is scanned in a raster pattern. The 250x150 mm (10x6 inch) plates typically require up to 15 minutes to scan with a 1mm resolution. The software displays the data from the 2-D scan by mapping the intensity scale onto an arbitrary colour scale (or, alternatively, a grayscale), resulting in a 256 colour (or, shades of gray) C-scan image for each test and frequency. Since the instrument's phase is selected to maximize the corrosion responses in the vertical, or 90 degree, direction, only the vertical amplitude data will be imaged. In addition, only a portion, or a "window", of the image's 256 wide scale is related to the varying levels of material loss since its signal may not occupy the entire range, as is shown in the palette of **Figure 3**.

Results and Observations

The scan results are shown in **Figures 3** and **4**. A palette shows the magnitude of the vertical signal from low to high, with red depicting the highest levels of corrosion. Note that these palettes are used to control the range of the vertical signal to be displayed in each image, thus allowing one to remove background noise and to view a larger dynamic range of colours for the corrosion indications. The image data can alternatively be presented in a gray scale, using the varying shades of gray from white to black to indicate increasing levels of corrosion.

The images in **Figures 3** and **4** show that single frequency eddy current imaging can successfully be used to detect a large range of second layer corrosion in thick components. To obtain similar depths of penetration, different frequencies were used to compensate for the different specimen conductivities. Hence, one can immediately see that the more corrosion susceptible 7075-T6 (32 % IACS) exhibits more corrosion than the 7475-T73 (40 % IACS) in the top row. The top row indications in **Figure 3** are from the unmachined sites that exhibited pure exfoliation to a depth of 0.15 mm (6 mils) in the second plate; since both plates have a thickness of 4.45 mm (175 mils), this metal loss corresponds to 3.4% thinning. Note, however, that the surfaces of the plates were pristine, greatly minimizing common noise sources.

Further observation reveals that the signal strength varies with both the amount of thinning and the size of the affected surface areas, i.e., the volume of the flaw. This is a direct result of the eddy current's characteristic sensitivity to volumetric flaws in a material. As a result, the signal amplitudes will be proportional to the flaw's volume as opposed to only its thickness, although only up to a certain flaw area dictated by the probe size. The lower row clearly illustrates this effect. The larger spot sizes will produce larger signals, in red, for the same amount of thinning also present in all the smaller spot sizes. This result is also amplified by the probe diameter, or "footprint". In thick structures such as these, larger probes are needed for deeper penetration; hence, this effect must be carefully taken into consideration when calibrating a set-up for percent wall loss detection.

Eddy Current Testing of Plates With Fasteners

The above specimens were fastened with nonferrous Ti Hi-Lok fasteners to simulate exfoliation corrosion under installed fasteners, as shown on the right side of **Figure 2**, along with two uncorroded reference fasteners. Both samples were scanned as before, but only the results of the 7075-T6 sample are presented since the outcome was similar in both cases.

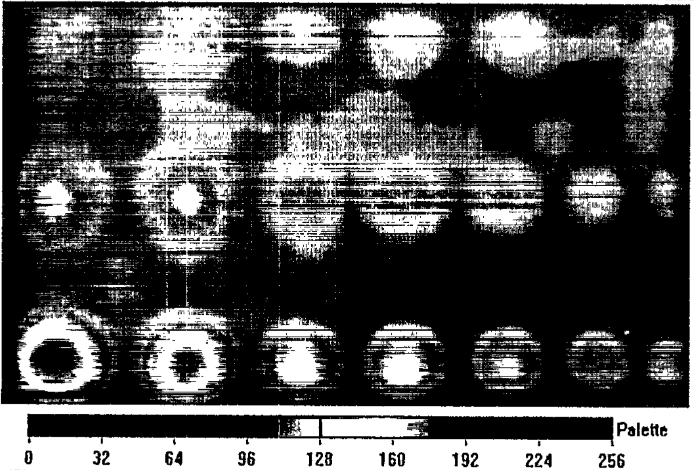

Figure 3.
900 Hz scan of 7075-T6 with 2nd layer corrosion (EXCO 28 hrs, no fasteners).

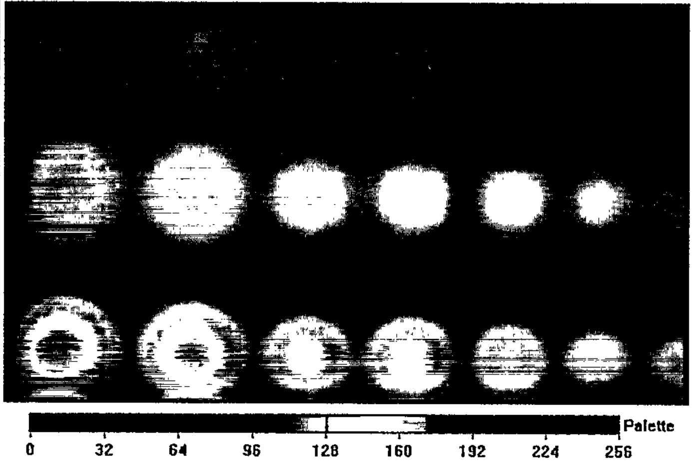

Figure 4.
600 Hz scan of 7475-T73 with 2nd layer corrosion (EXCO 28 hrs, no fasteners).

Single Frequency Method and Results

A typical single frequency scan is shown in **Figure 5**. The fasteners, including the two reference fasteners situated at non-corroded sites between the rows, have the effect of producing large impedance plane responses that are in-phase, or close to in-phase, with corrosion signals. Hence, most of the corrosion indications become masked in the impedance plane, as well as in the amplitude C-scan image. Consequently, it becomes very difficult to separate the fastener signal from the corrosion signal when the latter originates directly beneath the fastener head.

Dual Frequency Mixing

One common method of minimizing noise responses involves using the instrument's built-in dual frequency mixing capability. Since defects and other material characteristics each produce signal responses that vary differently with frequency, the instrument mixes the properly selected dual frequency signal responses in a way (usually by vector subtraction) that enhances the hidden corrosion signal while minimizing the noise. The discriminating features between the noise and the corrosion signals that are brought out of this operation are based on the slight phase shifts and amplitude changes between the two frequency responses. This method has been demonstrated in the past to reduce the effects of air gap variations between plates.[2,3] A similar procedure was employed here to reduce the effects of fasteners.

Two frequencies were selected such that the low, or primary, frequency was low enough to penetrate to the second layer, and the high frequency was within 2 to 4 times the primary. The instrument was then nulled with the probe located away from any corrosion and fasteners. With the probe positioned near a reference fastener, a linear scan was performed across, but slightly off-center to that fastener to keep the resulting noise signals at both frequencies within the boundaries of the instrument's screen. Scanning over the center of a fastener results in a large saturated signal that cannot be mixed effectively. **Figure 6** illustrates this offset as D_{offset}. These signals were mixed using the instrument's on-board mixing functions. The probe then was scanned in a line off-center, as before, to a fastener under which it was known to have a significant amount of corrosion. The procedure was repeated with various combinations of frequencies, gains, and D_{offset} distances until the mixed signal exhibited minimal fastener signal with maximum corrosion signal and phase separation. Note that the resulting mixed signal can be phase rotated to maximize the corrosion signal in the vertical direction. Ideally, the residual fastener signal should be in phase with the lift-off signal with both signals being perpendicular to the corrosion response. However, it was very difficult to find the parameters that achieved the best phase separations. A set-up was deemed acceptable if it could generate a corrosion signal that was over 45 degrees to the lift-off signal. [This constraint could have limitations in practice where there are significant variations in paint thickness and surface roughness.] Finally, the entire plate was scanned in a raster pattern, as before, with the above dual frequency set-up.

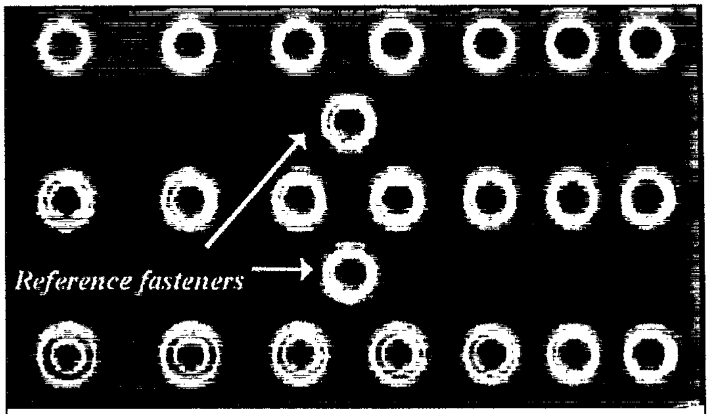

Figure 5.
900 Hz scan of 7075-T6 sample with fasteners.

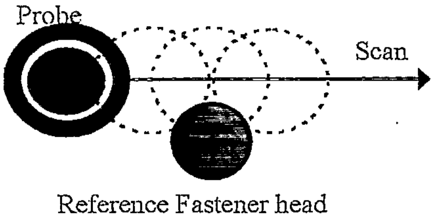

Figure 6.
Off-set fastener scan.

Results and Observations

The advantages of frequency mixing are evident in the images of the 7075-T6 sample shown in **Figures 5** and 7. Whereas the single frequency scan in **Figure 5** is cluttered and dominated by the fastener signals, the mixed frequency scan of **Figure 7** amplifies the corrosion signal and reduces those from the fasteners. This is further emphasized in **Figure 8** where the fastener signals are clipped out by choosing a signal range in

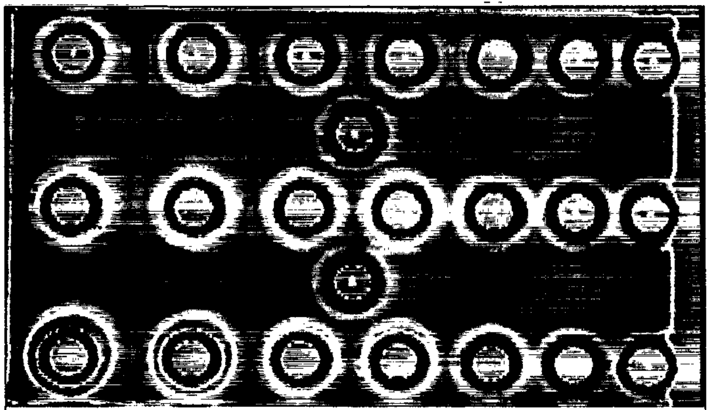

Figure 7.
2.3 kHz -900 Hz mixed scan of 7075-T6 sample with fasteners.

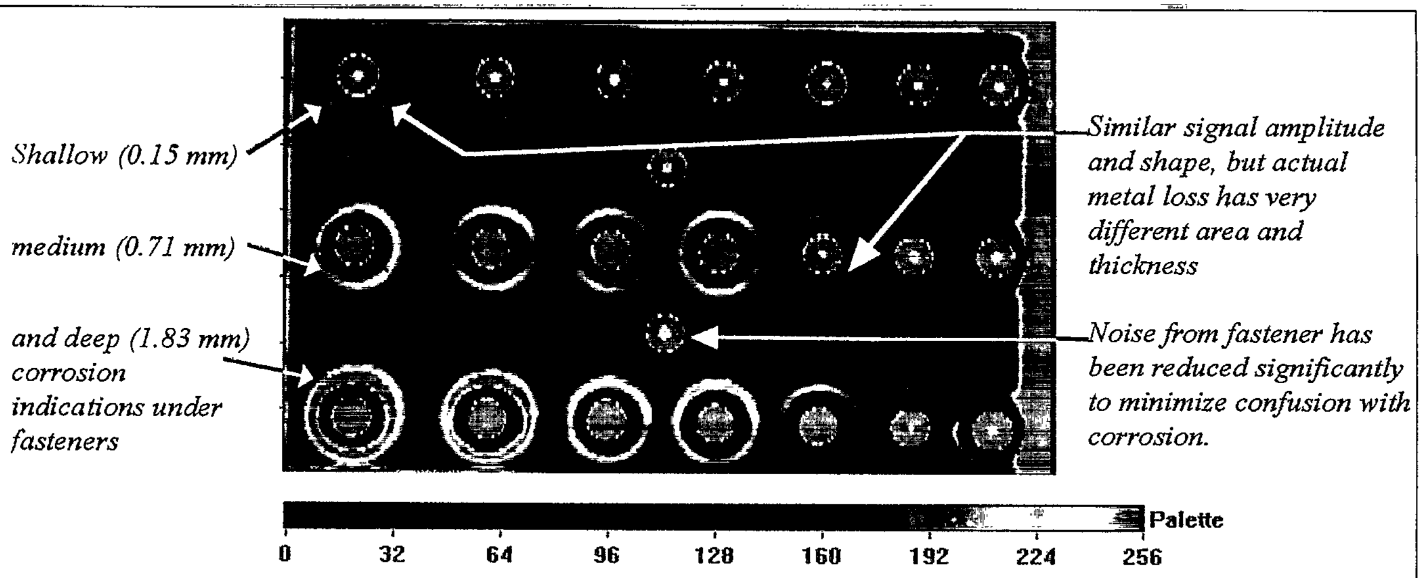

Figure 8.
2.3 kHz-900 Hz mixed scan of 7075-T6 sample (as in Figure 7 , after clipping out the reference fastener).

the colour palette that only contains the corrosion indications. Note that the fasteners cannot be completely clipped out since their signals are too large to allow a D_{offset} of zero during the mixing procedure.

Given the appropriate frequency mix and signal range, one can easily identify those fasteners which exhibit significant amounts of exfoliation corrosion, as shown in the lower two rows of **Figure 8**. Note the corrosion indications are apparent down to, and including, the 12.7 mm (0.5 inch) diameter sites. This implies that the technique will pick up corrosion in the second layer if it extends at least 1.59 mm (0.0625 inch) past the 9.53 mm (0.375 inch) diameter fastener head. In addition, Figure 8 points to the scan's inability to discriminate between a fastener that has a large area of corrosion but little thinning, and one with a small area of corrosion but large thinning. There are also false indications between the two fasteners on the right of each row. Despite these limitations, the scans indicate a capability to detect relatively low levels of corrosion under fasteners, as shown in the shallow sites in the top row of **Figure 8**.

It is worthwhile noting that the indicated areas of corrosion, and fastener head sizes, in the C-scans are larger than their actual size due to the large diameter of the probe. Better resolution can only be achieved from smaller probe diameters, but this usually results in weaker signals and less depth of penetration. Furthermore, since these eddy current images are only amplitude representations, they do not display information about the entire signal that can help interpret the effects of the fasteners, a variable air gap, and corrosion in multiple layers. The phase changes, for example, can provide complementary information when displayed alone, and enhanced images when properly combined with the amplitude data. In this study, however, this was not attempted since the phase images were very noisy due to the very low frequencies and subsequently low sensitivites.

Although first layer corrosion inspections were not performed in this study, it would be difficult to completely discriminate between first and second layer corrosion, and to infer the actual amount of material loss from a given signal, unless several frequencies are used in combination with more quantitative methods. For example, swept-frequency quantitative measurements of both the amplitude and phase are required to completely characterize multi-layer thinning due to corrosion[4]. For this reason, images cannot be quantitative; they are only useful when the inspection is set up and calibrated to detect a pre-determined range of defects, presented in terms of a meaningful colour or gray scale, in a constrained configuration. Therefore, the calibration scans could be used to determine a threshold intensity value above which any indications in future scans on similar inspectable components would signify corrosion beyond those acceptable limits.

CONCLUSIONS

Single frequency eddy current scanning methods are adequate for detecting second layer corrosion in thick, two-layer Al-alloy wing planks when it is known that first layer corrosion, varying air gaps, or fasteners are not present. This was demonstrated with an eddy current image scanner that detected a series of exfoliated areas in the second layer of an unfastened test wing joint panel, of which the smallest indicated flaw had a diameter of 7.95 mm (0.313 inch) and a depth of 0.15 mm (6 mils). Frequency mixing is essential, however, for detecting second layer corrosion under installed fasteners in thick structures. With the appropriate frequency selections, corrosion under the fasteners is observable from the scans by minimizing the strong signals from the fasteners. In this case, the smallest detectable corrosion site had a diameter of 12.7 mm (0.5 inch) and a depth of 0.15 mm (6 mils) located in the second layer under a fastener with a 9.53 mm (0.375 inch) diameter head. In the present study it was not possible to detect second level corrosion if it was confined to an area smaller than that of the fastener head.

The exfoliation corrosion specimens produced for these tests can be used to calibrate eddy current scanning inspection set-ups to detect corrosion above a set threshold in actual aircraft components of the same material and structural configurations. Hence, frequency mixing can be combined with eddy current image scanning methods to develop similar eddy current field inspections for today's aging aircraft.

FUTURE WORK

Future improvements to these multi-frequency scanning methods may include combining the eddy current images from each frequency to provide better signal to noise ratios. The technique can also be enhanced to extract more information from the entire signal, rather than just the vertical signal, such as phase changes that could be used to provide more flaw depth information. Swept frequency quantitative methods will be adapted to the scanning technique to accurately infer metal and air layer thicknesses, hence allowing one to discriminate between first and second layer thinning, and plate separation. Furthermore, the effects of measuring corroded areas smaller than the coil itself must be closely examined to develop a better understanding of their relationships for improved flaw characterization.

ACKNOWLEDGMENTS

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