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FUSION OF MICROWAVE AND EDDY CURRENT DATA FOR A MULTI-MODAL APPROACH IN EVALUATING CORROSION UNDER PAINT AND IN LAP JOINTS

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ABSTRACT. Critical aircraft structures are susceptible to hidden corrosion. Find-it and fix-it approaches are inefficient as it relates to managing the problems associated with corrosion. More comprehensive corrosion information may be obtained using data fusion from several detection and evaluation methods. To this end, microwave, conventional and pulsed eddy current data from a multi-layer corroded panel, representing an aircraft lap joint, are fused and used as inputs to a structural analysis model to obtain a comprehensive snapshot of the corroded environment. This paper presents the data fusion algorithm and the structural analysis model along with a discussion of the results.

Keywords: Corrosion, Data Fusion, Eddy Current, Microwaves, Nondestructive Evaluation, Structural Analysis.
PACS: 81.70.–q

INTRODUCTION

Corrosion is a major maintenance issue, especially for aging commercial and military aircraft. The Air Force recently estimated that corrosion maintenance costs exceed $800M per year. Given this, it is desirable to reduce the amount of "find-it and fix-it" corrosion maintenance activities. One method is to introduce a damage tolerance approach for corrosion detection. In order for this to become a reality, a comprehensive snapshot of corrosion present must be generated. Not only does this include the material thinning phenomenon, but also surface characteristics and pitting. This investigation combines results generated using conventional and pulsed eddy current and microwave nondestructive evaluation (NDE) methods used for detecting and evaluating corrosion in lap joints and under paint, respectively. Fusion of the data generated using these methods is expected to provide a complete picture of the damage present and will improve the accuracy of structural analysis and prediction tools.

Microwave NDE methods offer several important advantages for detection and evaluation of corrosion under paint [1-8]. Microwave signals can penetrate inside low-loss dielectric materials and interact with their inner structure. They are also sensitive to changes associated with dielectric property variations and boundary interfaces, which makes them very attractive for detecting the presence of undesired layers such as

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corrosion under paint. Microwave techniques are non-contact, one-sided (reflection), fast, simple, while microwave measurement systems are small and easily adaptable to commercially available scanning/imaging mechanisms. They are portable, robust, battery-operated and handheld. Near-field microwave NDE techniques, utilizing open-ended rectangular waveguide probes, have been successfully used to detect the presence of corrosion product under paint and primer in both steel and aluminum substrates [2-6]. Recently these techniques have been successful in detecting and evaluating corrosion precursor pitting under paint due to their high spatial resolution [7-8]. However, microwaves do not penetrate highly conducting materials such as metals. Therefore, when considering a lap joint made of several aluminum panels, other methods must be employed to detect corrosion in between the various layers of the lap joints. Eddy current (EC) techniques can detect through metals and are also sensitive to corrosion severity. Eddy current method is a standard, well-established and well-developed NDE method [9]. Eddy current inspection systems are portable, inexpensive, and small and they provide for on-line and real-time measurement capabilities. Conventional EC methods are capable of providing effective metal loss information while pulsed EC methods provide information about the depth at which a layer of corrosion may exist in a multi-layered structure such as a lap joint.

Consequently, combining data obtained from these three methods (i.e., data fusion) has the potential to give a comprehensive snapshot of the corrosion environment in such structures. To accomplish this, first anomaly detection algorithms are used to highlight the presence of corrosion at different layers obtained from the microwave and EC images. Anomaly detection algorithms exploit the statistical relationships between gray levels in an image to highlight discontinuities. Subsequently, a simple data fusion approach is used to fuse the output of the anomaly detectors in order to achieve more reliable detection and obtain complementary information from the three NDE modalities involved. Moreover, in this study corrosion thickness was estimated for the under paint case from the microwave data and the acquired information was used to carry out structural analysis using the finite element modeling package ANSYS®. The detailed description of the method is provided in the next section.

METHODOLOGY

Microwave and eddy current images are generated from respective scans performed on the same panel, and the images are registered using linear translations and rotations. Data registration is necessary to ensure that corrosion detector outputs computed for the microwave and eddy current images can be compared on a pixel-by-pixel basis. In this investigation, corrosion detection was performed using two anomaly detectors, the RX algorithm and a fuzzy logic-based algorithm [10-11]. Anomaly detectors exploit the statistical relationship between gray levels in an NDE image to highlight discontinuities that may be unobservable to the human eye.

A flowchart summarizing the data fusion processes investigated here is shown in Figure 1. From Figure 1, three types of data fusion were explored. First, the RX and fuzzy anomaly detector outputs were generated independently and fused from the registered eddy current and microwave images, respectively. Second, the RX detector outputs were produced separately from the registered images and combined to yield an RX detector fused image. A fuzzy detector fused image was obtained using a similar process. Finally, the RX detector and fuzzy detector fused images were combined to produce a multimodal decision level fusion image. Further details of the data fusion steps are provided in the Results and Discussions sections.

RX Anomaly Detector

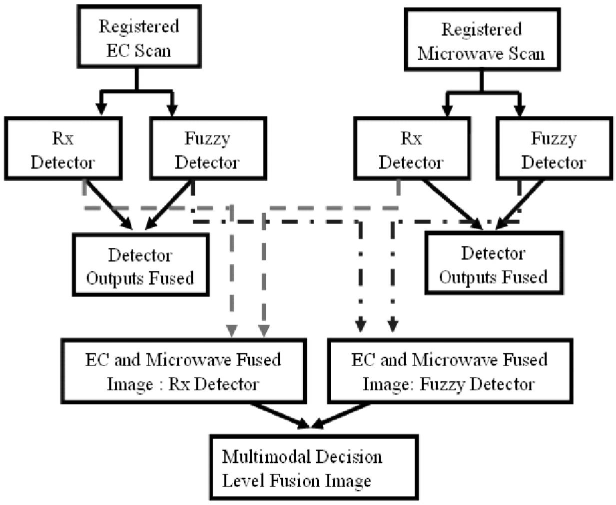


FIGURE 1. Data fusion algorithm flowchart.

The RX detector provides a rotation invariant approach to anomaly detection [10]. This attribute of the detector is particularly important as it is desired that detection sensitivity is not affected with varying orientation of corrosion patches. The RX statistic is defined as:

$$\gamma(x,y) = \bar{b}_s^T M_c \bar{b}_s \quad (1)$$

where, $\bar{b}_s$ represents the typical signature of a corrosion patch and M_c represents the unknown background covariance matrix which is computed from the corresponding zero mean image $Z(i, j)$. The expressions for determining $Z(i,j)$, $\bar{b}_s$ and M_c are:

$$Z(i,j) = I(i,j) - \frac{\sum_{(i,j)\in J_M} I(i,j)}{|J_m|} \quad (2)$$

$$\bar{b}_s = \frac{\sum_{(i,j)\in N_S} Z(i,j)}{\left(|N_S|\right)^{0.5}} \quad (3)$$

$$M_C = \frac{\sum_{(i,j)\in J_m} Z(i,j)Z(i,j)^T}{|J_m|} \quad (4)$$

where J_m represents a circular demeaning mask with diameter J_m and cardinality $|J_m|$, N_S represents a circular corrosion patch (target mask) with diameter d_s and cardinality $|N_S|$ and I represents the digital image of the scanned test specimen. The demeaning mask and the target mask are concentric circles with $J_m > d_s$. The confidence value for corrosion detection is given by the RX statistic $\gamma(x,y)$, which has a value between 0 and 1 and is computed at each image pixel. Higher confidence values represent stronger 'hits'.

Fuzzy Logic Based Anomaly Detector

A fuzzy set theory-based anomaly detector was developed for this investigation [11]. Let B denote the fuzzy set representative of the gray levels associated with the non-corrosion areas or the background in the EC and microwave images. The associated membership function μ_B can be represented mathematically as follows:

$$\mu_B(x) = \begin{cases} \left(\frac{x}{F}\right)^{0.5}, \text{ for } 0 \le x < F \\ 1 \quad , \text{ for } x \ge F \end{cases} \tag{5}$$

Based on previous research, F was determined to be 95% of area under the secondary histogram of the image [11]. The secondary histogram plots the histogram bin hits (n) on the x-axis versus the number of histogram bins with (n) hits per bin on the y-axis. If $|\alpha_B|$ is the number of eight connected neighbors of a particular pixel, $I_{(x,y)}$, such that $\mu_B(I_{(x,y)}) \ge \alpha$ and $|S(B)|$ is the number of eight connected neighbors such that $\mu_B(I_{(x,y)}) \ge 0$ then, a fuzzy clustering confidence measure at the pixel location (x, y) is defined as $R(\alpha) = \frac{|\alpha_B|}{|S_B|}$. This measure has a value between 0 and 1 for a specified value of α and provides the degree of association of each pixel in an image to the fuzzy set B representative of the non-corroded areas in that image.

False Alarm Mitigation Scheme

A false alarm mitigation scheme was implemented in order to reduce the number of instances in which an image pixel was falsely labeled by the RX and fuzzy logic detectors as representing corrosion. A technique suggested by Goldman and Cohen [12] was used to accomplish this. The technique utilizes the local statistics of an image, eliminating the need to know the exact statistical characteristics of the background and the targets (areas of corrosion). The images were then iteratively partitioned into two mutually exclusive subsets; namely, background B_k and anomaly A_k, where, k denotes the iteration number. At each successive iteration, the pixels that were classified as corrosion in the previous iteration were further partitioned into two subsets as mentioned above. Hence, with each iteration, the number of false hits was reduced. This process continued until a pre-defined criterion was reached. The resulting mask was ANDED with the RX or the fuzzy detector outputs in order to eliminate regions of false alarm.

Data Fusion

A number of different data fusion algorithms exist in literature and most have been used extensively in a variety of different applications [13-14]. For this investigation, an extension of a maximum likelihood approach to data fusion was employed to fuse data obtained from the different anomaly detectors. Accordingly, the fusion of data obtained from multiple sensors was accomplished using a weighted sum of the raw data points obtained from the individual sensors (i.e., images). The weights were made to be inversely proportional to the variance of the confidence values over the image from the RX and fuzzy logic detectors, respectively. A large variance of confidence values over an image for a detector implies that the detector is less reliable, and this translates into a lower weight for the detector in the weighted sum [14].

CORROSION DATA

Plates and the Panel Under Test

Three aluminum plates, each measuring 12" x 12" x 0.04" were corroded in a salt fog chamber with varying exposure times from one day to five days resulting in varying corrosion levels. The plates were masked with tape to produce square corrosion patches with dimensions ranging from 1" to 0.125" as shown in Figure 2b [7]. A lap joint like structure was mimicked by stacking three aluminum panels one on top of the other as shown in Figure 2. The top panel was painted subsequent to having been corroded. This composite layered structure hereon is referred to as the test panel.

Microwave Measurements

In this investigation near-field microwave reflectometers with open-ended rectangular waveguide probes were used at V-band (50 - 75 GHz) and W-band (75 - 110 GHz). The DC output voltage of the reflectometer is proportional to the changing (as the probe is scanned over a sample under test) phase and/or magnitude of the reflected signal. The resulting matrix of DC voltages is normalized (with respect to its range) and plotted as a grayscale image. The open-ended rectangular waveguide probe produces images with relatively fine spatial resolution and is sensitive to the presence of corrosion under paint. A relatively simple signal processing procedure can be used to remove unwanted influences (e.g., influence of standoff distance variation which is referred to distance between the aperture of the probe and the surface of the plate) [1-7]. Figure 3a shows the processed microwave image of plate 1 (top most layer of the test panel) obtained at V-band after removal of influence of standoff distance variation. Figure 3a shows that indications of the corrosion areas, as shown in Figure 2b, with sharp boundaries are clearly visible and their dimensions are very close to the actual dimensions.

Eddy Current Measurements

Eddy current testing was carried out using the Boeing MAUS™ (Mobile Automated Scanner). Images were obtained at frequencies of 2 kHz and 20 kHz. The image 20 kHz-image was able to detect corrosion under paint quite well but failed to reveal hidden corrosion in deeper layers of the test panel. Therefore, the image obtained at the lower scan frequency of 2 kHz was used for this investigation. Figure 4a shows the eddy current image obtained at 2 kHz.

RESULTS AND DISCUSSIONS

Anomaly detection and data fusion results for the microwave and eddy current images of the test panel are presented in Figures 3-5. It can be seen that the fuzzy logic based and the RX anomaly detectors are able to highlight the areas of corrosion with a reasonably high degree of accuracy and acceptable false alarm levels.

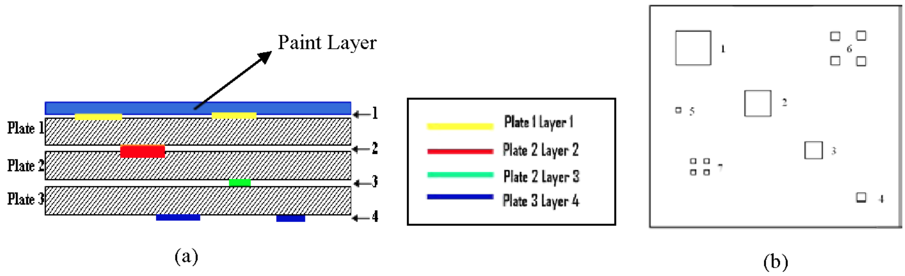


FIGURE 2. Schematic of stacked plates mimicking a lap joint like structure (a) side view, (b) top view.

From Figures 3d and 4d it can be inferred that the fusion of the anomaly detectors results in improved corrosion detection as compared to when the detectors are used independent of each other. Figure 5a shows the image obtained by fusing the images shown in Figure 3d and 4d. This composite image represents the fusion of results obtained from the anomaly detectors used on the eddy current and the microwave images. The schematic of the corroded panel, in Figure 5b, with the corrosion patches at different depths marked out, demonstrates that the fusion image from Figure 5a successfully captures the corrosion information under paint as well as at deeper layers of the test panel.

A model of plate 1 of the panel was created using ANSYS to assess the plate's structural integrity. The plate model generated in ANSYS was based on corrosion thickness under paint estimated from the microwave image of plate 1, as shown in Figure 3a. based on evaluating corrosion thickness under paint. Uniform pressure of 1 kips was assumed to be applied to the left and right edges of the plate and a contour plot of the Von-Mises stress distribution was obtained. An examination of the stress plot for the corroded plate given in Figure 6 reveals that there is greater stress concentration in areas that have greater corrosion thickness (of the order of 1.4 microns) as compared to lesser corroded areas, as expected. The stress distribution is uniform in the pristine areas of the plate.

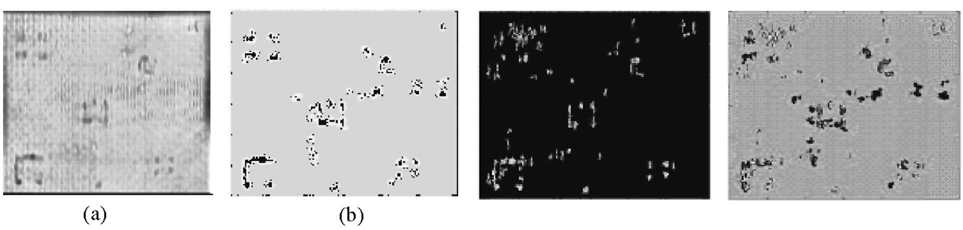


FIGURE 3. Anomaly detection results (a) V-band microwave image, (b) fuzzy anomaly detector, (c) RX anomaly detector, (d) fused fuzzy and RX detector outputs.

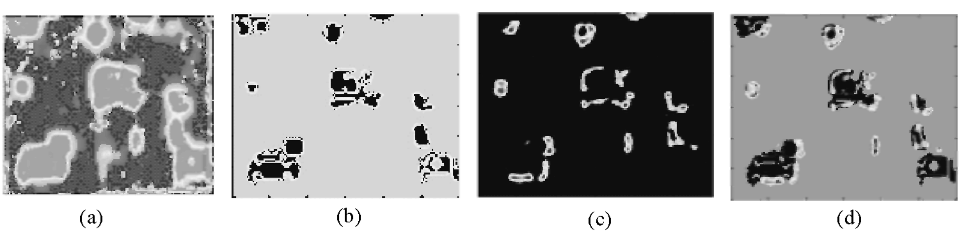
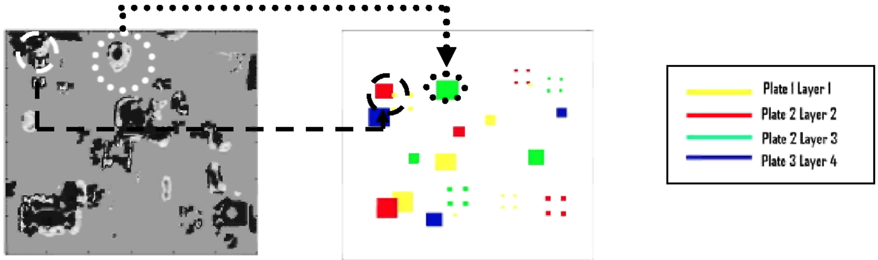


FIGURE 4. Anomaly detection results: (a) eddy current image at 2 kHz, (b) fuzzy Anomaly Detector, (c) RX anomaly detector, (d) fused fuzzy and RX detector outputs.



(a) (b)

FIGURE 5. Data fusion results (a) multimodal fusion Image, (b) schematic of the stack of corroded panels.

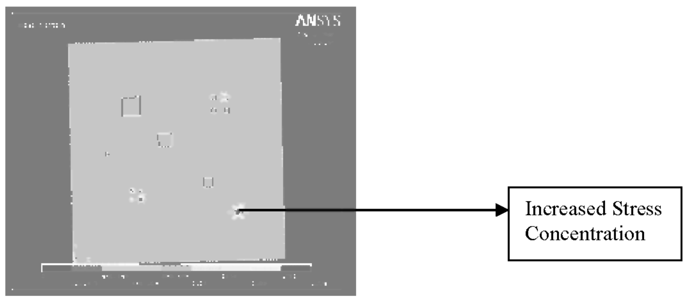


FIGURE 6. Von-Mises stress plots for corrosion under paint.

SUMMARY

From the results obtained in this investigation, it can be seen that data fusion resulted in a comprehensive snapshot of corrosion under paint and in hidden layers such as in lap joint like structures. Fusing data obtained from multiple anomaly detectors also improved detection capabilities and effectively reduced false alarm rates. Corrosion thickness under paint, evaluated using the microwave data, was used effectively for structural analysis purposes. This opens up avenues for future studies on examining different fusion algorithms to further improve on the automatic detection of hidden corrosion in aircraft structures.

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