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Technical Notes

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Detection of Corrosion Using Piezoelectric Impedance-Based Structural Health Monitoring

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I. Introduction

CORROSION is an extremely costly problem for industries and business sectors throughout the world and results in severe economic impact. In 1998, Congress funded the Department of Transportation and the Federal Highway Administration to estimate the total cost of corrosion on the U.S. economy and provide corrosion prevention guidelines. The final results of the survey estimated the extrapolated total direct corrosion cost to be \$278 billion per year, which is 3.14% of the gross domestic product in the United States [1]. In 1996, the U.S. spent \$1.7 billion on commercial aircraft maintenance and lost \$0.3 billion due to corrosion downtime [2]. The "find it and fix it" maintenance practices of the airline industry are costly and, in some cases, inadequate. The present note will focus on identifying a detection method for the galvanic type of corrosion that plagues aircraft.

Many techniques exist for detecting corrosion in aircraft; however, these methods are typically inadequate due to the intrinsic human error present and are difficult and time-intensive to implement. Two general categories of corrosion monitoring techniques exist, nondestructive evaluation (NDE) and structural health monitoring (SHM). NDE methods include techniques such as visual, eddy current, ultrasonics, electrochemical impedance spectroscopy, color visual imaging, radiography, and infrared imaging [3]. The second class of detection is SHM and is typically superior due to the automated nature of the sensing system. Examples of SHM systems used in aircraft include the monitoring of pH and humidity, acoustic emissions, ion concentration, and chemical potential detectors.

The present study will provide results on a series of tests performed using piezoelectric-based impedance techniques, which are a newer and less developed method of performing SHM. These methods use the electromechanical coupling present in piezoelectric materials to determine when structural changes have occurred. When the piezoelectric material is bonded to the structure, its electrical impedance is coupled to the mechanical impedance (a function of the mass, stiffness, and damping) of the structure, providing a means for characterizing it. As damage occurs or progresses, the electrical impedance measured from the piezoelectric materials shifts, which can be quantified using statistical methods, providing a method of measuring the damage present. For a detailed review of the impedance method and it application see Park et al. [4] However, the ability to use this technique to measure the small changes associated with the onset of corrosion has not been identified.

This note will experimentally evaluate the use of piezoelectric materials in conjunction with the piezoelectric-based impedance method to detect, locate, and quantify precrack surface corrosion damage. The impedance variations caused by changes in corrosion location, pit depth, and surface coverage will be correlated to the damage metric, which is calculated from the measured impedance signatures.

II. Experimental Procedures

In most cases, corrosion develops slowly on a time scale not conducive to laboratory testing. Thus, to accelerate corrosion growth, environmental chambers and corrosive sprays have been developed allowing testing to be performed more quickly. For this study, chemical corrosion techniques were used because they can be easily applied, result in almost immediate corrosion, can be controlled, and are most similar to the galvanic corrosion found in aircraft. To quantify the extent of corrosion present, the corrosion classification index proposed by Groner [5] is used, which defines light (25.4 μm or less), light/moderate (25.4 μm–76.2 μm), moderate (76.2 μm–254 μm), and moderate/severe (greater than 254 μm) corrosion in terms of the average pit depth. The corrosion depth is used as a scale because it is a good predictor of the number of cycles till crack formation. For all tests performed here, the pit depth was held within the light classification of 25.4 μm or less. The pit depth was measured before corrosion using a PDI Surfometer Series 400 profilometer.

The process of performing SHM typically tracks the variation between data obtained under healthy conditions and its current state. Therefore, the ambient shift in the measurement over time can result in the false measurement of damage. One major environmental change that can induce significant variation in the impedance of piezoelectric materials is temperature and has been well documented by Park et al. [6]. To minimize these effects, a piezoelectric material such as PZT-5A that has a lower thermal dependence can be used. Additionally, the analysis of the real portion of the impedance can reduce this variation because the imaginary portion is highly related to the temperature-dependent capacitance of the device. The effects

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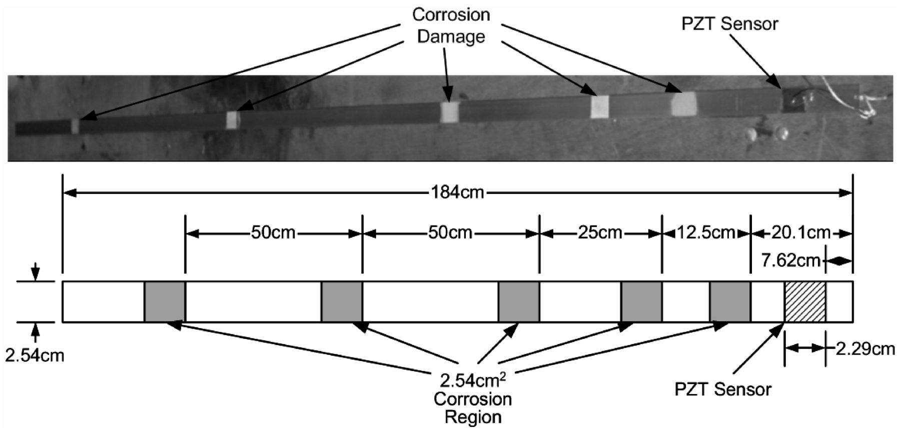

Fig. 1 Picture and schematic of the aluminum beam showing the corrosion damage along the span of the beam.

of environmental changes cannot always be directly accounted, making the use of statistical measures necessary. To reduce the effect of ambient variation and increase the confidence in each set of measurements, the "undamaged" baseline measurement was repeated 30 times over a period of 5 days. Each of the other "damaged" baselines was repeated 30 or more times over a 1 d period, such that the total testing time is less than the original baseline measurement. This procedure quantifies the impedance variation over a week-long period and so the week-long variation can be captured to provide an accurate confidence interval.

A. Quantifying the Damage

To compress the data, a damage metric is used, which provides a single value defining the variation between two measurements. The damage metric also allows a statistical analysis to be easily performed, such that the confidence interval of a measurement can be made. For the study presented in this note, the root mean squared deviation (RMSD) was used as the damage metric and is defined as

$$\mathrm{RMSD} = \sum_{i=1}^{n} \left[\frac{[Re(Y_{i,1}) - Re(Y_{i,2})]^2}{[Re(Y_{i,1})]^2} \right]^{\frac{1}{2}} \tag{1}$$

where n is the number of samples, and each real impedance of the first measurement $Re(Y_{i,1})$ is subtracted from the corresponding real impedance of the second measurement $Re(Y_{i,2})$.

B. Experimental Setup for One-Dimensional Corrosion Testing

A 6063 T5 aluminum beam with dimensions shown in Fig. 1 and a thickness of 0.159 cm was selected for corrosion testing. Thirty-three baseline impedance measurements were made over a 5 d period to capture the ambient variation and noise in the confidence interval. After the baseline tests were finished, five 2.54 cm^2 regions of the beam were chemically corroded with hydrochloric acid at distances of 12.5, 25, 50, 100, and 150 cm from the PZT sensor (2.54×2.29 mm), as shown in Fig. 1. After each individual level of corrosion was added, a new baseline measurement of at least 30 sweeps was collected over a 1 d period. The original beam had a surface roughness of 0.799 μm, and the surface corrosion depth ranged from 4.375 μm to 12.85 μm for the five levels of damage. In all five instances of damage, the corrosion depth falls in the light corrosion range.

Impedance measurements made on the beam will initially be presented from a sweep over a range of frequencies (20–132 kHz), which is then used to find damage-sensitive regions of the response, such that confined regions can be analyzed. Six different frequency ranges were chosen after analyzing the data based on high peak density (5–15 peaks) and the sensitivity to small structural changes. Each smaller frequency band consisted of a 2000 Hz range measured with 1 Hz resolution. During each sweep, the frequency, real impedance, and imaginary impedance were measured with an HP 4194 Impedance Analyzer controlled using a LabView GPIB interface.

III. Corrosion Detection and Results

Initially, corrosion is a very slight surface defect, making it unclear if the impedance method has the sensitivity to effectively sense the small changes in mechanical impedance. The measurement of corrosion is further complicated due to the impedance measurement's dependence on environmental conditions, including temperature and humidity. This section will discuss the experimental design and results of the corrosion detection test.

The results presented here studied the progression of damage using a comparison of data to the undamaged measurement. An example of the impedance shift associated with the multiple site corrosion damage is shown in Fig. 2, which depicts 20 measurements at each level of corrosion overlaid on one another. From this figure it can bee seen that as each additional location of corrosion is added, the impedance curve has a definite shift. This shift is quantified using the RMSD damage metric and is shown in Fig. 3 for the cumulative damage (each case compared back to the undamaged data). The figure contains multiple bars, each representing a separate comparison of measurements. The first six bars shown are the baselines, which are the RMSD of like cases. For example, the first bar represents the undamaged baseline and corresponds to the average RMSD of 30 separate undamaged measurements. The five bars at the right of the figure represent the damaged, and are the

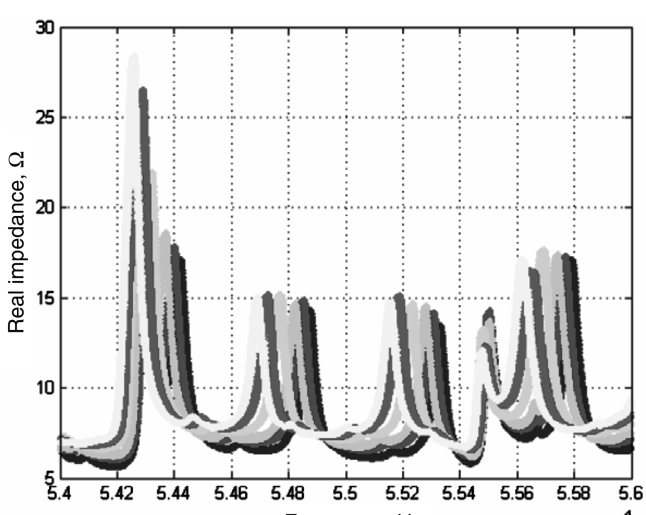

Fig. 2 Plot depicting the shift in impedance as the number of corrosion sites increase.

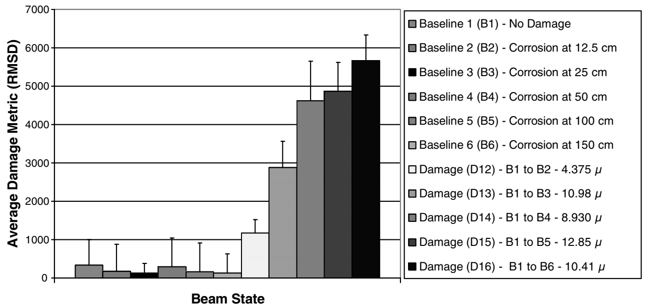

Fig. 3 Plot of the damage metric as the number of corrosion sites increase.

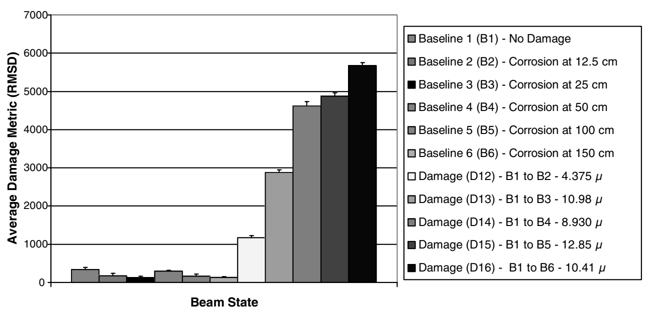

Fig. 4 Beam corrosion damage detection for impedances from 20–22 kHz.

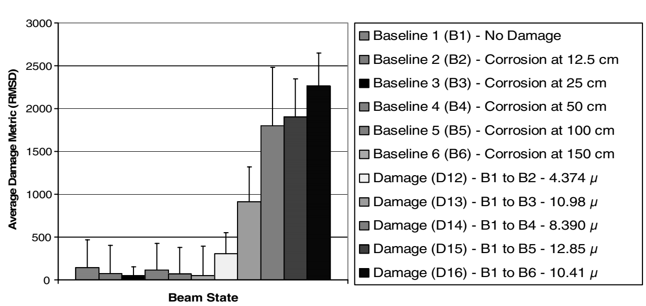

Fig. 5 Corrosion-detection results for beam impedance testing between 103–105 kHz.

average RMSD of the impedance measurements of the damaged specimen with the undamaged data. Ideally, the baseline metric would be zero, because it represents the variation between the same measurement cases; however, noise and temperature variation prevent that from happening. For the baseline cases, the value of the damage metric results from the random variation in the measurements. The five damaged bars compare two baseline metrics to show how one measurement varies from the other as damage is induced on the structure.

From Fig. 3 it can be seen that the impedance method can effectively detect progressing multiple site corrosion damage. As the amount of total damage on the beam increases, the damage metrics increase beyond the initial damage case (D13). Note the vertical error bars on the plot represent the 95% confidence interval for a sample size of 30, the smallest sample size in the test. The 95% interval is large due to random variation, necessitating multiple sweeps to accurately detect corrosion damage. The error bars point out the importance of making many baseline measurements and indicate the potential for the system to make a false positive measurement. This plot shows that a single piezoelectric patch can distinguish the presence of light corrosion damage as far as 1.5 m from the sensor location.

The results presented in Fig. 3 show that the damage can certainly be detected, but because the confidence intervals overlap from one measurement to the next, the increase in damage is not distinguishable on a 95% confidence interval. There is a detectable increase in the sample mean of the damage metric; however, the error bars of D12 overlap B1, so the population mean of D12 and B1 may be indistinguishable damage. Thus, based on our 95% confidence interval, detection is uncertain. The damage metrics calculated in Fig. 3 are composed of the entire set of data and contain all measured frequencies. This comparison method is not ideal, because certain ranges of frequencies are more sensitive to damage than others. Therefore, if a select range of frequencies that have been found to exhibit good sensitivity to corrosion damage are used, it is expected that the error bars could be significantly reduced.

To demonstrate the effect of including a select range of frequencies on the measurement tests were perfumed using six select frequency ranges. The six frequency ranges identified were 20–22, 54–56, 71–73, 95.5–97.5, 103–105, and 126–128 kHz. During the analysis of these frequency ranges, it was found that the lower ranges provided much lower confidence intervals than the higher frequency ranges. To demonstrate this result, Fig. 4 shows the damage metric for the 20–22 kHz range and Fig. 5 shows the resulting damage metric values for the 103–105 kHz range. From Fig. 4 it can be seen that the error bars are very small and do not overlap, indicating that the measurement is detectable and distinguishable on the 95% confidence interval. However, the results shown in Fig. 5 contain large confidence intervals that overlap each other, thus indicating that we cannot distinguish the increase in damage from its previous quantity. The ability to distinguish the damage from it previous level is extremely important in order to reduce the occurrence of false positives, which can be costly and troublesome.

IV. Conclusions

This study has investigated the use of piezoelectric-based impedance measurements to identify the presence of corrosion damage. Corrosion results in significant financial losses to the United States and has been estimated at 3.14% of the gross national product. This burden has been placed on almost every sector of economic development and leads to unsafe structures and potentially catastrophic failures. Current methods of performing corrosion identification use methods that require the system be taken out of operation while a technician manually inspects each potential location of damage. This process is time-intensive and subject to human error, making it less than ideal. Therefore, in an effort to develop methods of interrogating a structure for the existence of damage, the present study has investigated the use of piezoelectric impedance-based structural health-monitoring techniques. The results from testing of an aluminum beam have shown that this method can identify multiple instances of light corrosion at distances up to 1.5 m and can effectively track the progression of the damage. Furthermore, it has been demonstrated that the progression of damage can be distinguished from ambient variation on a 95% confidence interval. This result is important for the reduction of false positives, which can be costly and troublesome. In addition to the one-dimensional work presented here, two-dimensional tests have been carried out showing the feasibility of using the impedance method on aircraft skins; this material has not been presented due to the limited scope of this note.

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