Laboratory pod data acquisition from inner layer cracks in simulated airframe structures

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Abstract
This paper discusses the acquisition and processing of experimental data collected using a low frequency eddy current sliding probe to inspect aluminum, simulated airframe structure for inner layer cracks. This effort is part of a model-assisted probability of detection (MAPOD) study aimed at complex structure. Since the experimental data will be compared to idealized model-generated data, an automated scanning setup in the laboratory was used to produce results with minimal human factor variables and low measurement uncertainty. While good reproducibility of the data was achieved, the inherent nature of the multilayer, riveted structure resulted in significant scatter in the data. This scatter required special statically processing techniques to produce a meaningful POD curve, which will be discussed in an accompanying paper.

Keywords
crack detection, probability, eddy current braking, QNDE

Disciplines
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Comments
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ABSTRACT. This paper discusses the acquisition and processing of experimental data collected using a low frequency eddy current sliding probe to inspect aluminum, simulated airframe structure for inner layer cracks. This effort is part of a model-assisted probability of detection (MAPOD) study aimed at complex structure. Since the experimental data will be compared to idealized model-generated data, an automated scanning setup in the laboratory was used to produce results with minimal human factor variables and low measurement uncertainty. While good reproducibility of the data was achieved, the inherent nature of the multilayer, riveted structure resulted in significant scatter in the data. This scatter required special statically processing techniques to produce a meaningful POD curve, which will be discussed in an accompanying paper.

Keywords: Eddy Current, Sliding Probe, Inner Layer Cracks, POD
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INTRODUCTION

The use of probability of detection (POD) studies to assess the reliability of inspection techniques is on the increase due in part to a 1995 U.S. Air Force initiative to upgrade their Engine Structural Integrity Program. [1] However, the FAA, NASA and others are facing similar inspection challenges and there is a growing general consensus in the NDE community that more POD analysis is required. [2]

The detection and characterization of radial cracks emanating from fastener sites in multi-layer structures is an area of interest for the aging aircraft community. The inspection method for this application needs to quickly and reliably detect cracks around fastener sites without the removal of the fasteners. Due to a wide variety of variables, such as material thickness, oblong holes, fastener fit, etc., this inspection is disposed to a significant amount of signal noise. Several studies have been conducted that demonstrate the feasibility of using both the volume integral method and the finite element method to simulate the subject inspection and gain understanding about the signal noise when a simple air core probe is used. [3,4]

This paper discusses the acquisition and processing of experimental data collected using a low frequency eddy current sliding probe to inspect fastener sites for inner layer cracks in simulated airframe structure. This is the first step of a model-assisted probability of detection (MAPOD) study that will use a boundary element method to further advance
the understanding of noise source variables and investigate how the modeling results can be used in POD analysis of this complex structure. Since the experimental data will be compared to idealized model-generated data, an automated scanning setup in the laboratory was used to produce results with minimal human factor variables and low measurement uncertainty.

SPECIMEN DESCRIPTION

A set of 16 inner-layer crack panels was used for this study. A representative panel from the set is shown in Figure 1. The panels were produced by the Airworthiness Assurance NDI Validation Center at Sandia National Laboratories to simulate the lap slice of a Boeing 737. The specimen consists of a top sheet, a bonded internal doubler, a lower skin and a mock tear strap in four locations. The material was 0.89mm (0.035”) and 1.02mm (0.044”) thick, 2024-T3 Alclad sheet with a conductivity that ranged from 18.68 to 19.66 MS/m (32.2 to 33.9% IACS). In all cases the thickness of the inner skin and the tear straps was nominally 1.02 mm (0.040”). The combined thickness of the outer skin and the doubler was varied using different combinations of 0.89mm (0.035”) and 1.02 mm (0.040”) sheet. Three rows of 5D5 A1 flush head rivets were used to fasten the sheets together along a 76.2mm (3 inch) overlap. In tear strap areas the rivets were alodined, otherwise they were anodized.

Prior to assembly of the specimens, artificially induced fatigue cracks were grown from the lower row of fastener holes in the inner skin. [5] The cracks were initiated by placing starter notches at the edges of undersized holes at selected locations. The skin panels were then cycled until a fatigue crack of the desired length was reached. The starter notches were removed when the holes were drilled to the proper diameter for fastener installation. The cracks were through thickness and ranged in length from 0.25mm (0.010”) to 12.7mm (0.500”) and some holes had cracks emanating from both sides.

These panels present a challenging configuration to inspect and model due to the large number of variables. However, this makes for an interesting model-assisted POD study because most of the variables can be modeled to produce a prediction of the noise distribution of the measurement. Some of the possible panel variables include: the thickness of the skins, doubler and tear strap; the conductivity of the skins, doubler and tear strap; the size, roundness and angle of the holes; the depth of the countersink of the holes and resulting height of the rivets; the dimensions and conductivity of the rivets; the

![Figure 1](image-url)

**FIGURE 1.** Overall photograph of the front side of a representative specimen (left) and a close-up photograph of the back side of the sample showing the outers skin, doubler, inners skin and tear strap.
coating condition (anodized or alodined) of the rivets; the contact between the rivets and the holes; the thickness of the nonconductive gap (paint and sealant) between the sheets; the distance between the fasteners and the edges; the size, orientation and location of the cracks (right, left, or both).

EXPERIMENTAL SETUP

The data were collected loosely following part six of Boeing Service Bulletin 53-30-27. The term “loosely” is used because a different probe was used and this required the use of a different drive frequency and signal analysis procedures. Also, the service bulletin is for a manual inspection procedure and in this case line scans were collected using an automated scanning system in an attempt to limit human factor variables. However, basic inspection details such as centering the probe +/- 1.27mm or 0.050” over the fasteners, establishing the null point between two fasteners, and setting the signal rotation were accomplished as specified by the Boeing procedure.

The computer controlled scanning and data collection system that was used is shown in Figure 2. The rivet locations were scanned one-by-one with the probe alignment and position checked at each location. The probe was moved in 0.1mm increments and the voltage output from a commercial flaw detector was recorded at each position. All of the samples were scanned three times with the experimental setup disassembled and reassembled between scan runs to evaluate measurement repeatability.

For this effort a commercial sliding probe, which operates in the reflection mode, was used. This probe has larger coils and operates over a lower frequency range than the probe specified by the Boeing procedure. The particular probe was chosen because it had been previously characterized and modeled for other related studies. The probe was operated at 2.0 kHz and the instrument gain and phase were set to 51.5 dB and 317

![FIGURE 2](image)

**FIGURE 2.** Photograph of experimental setup with the scanning system shown in the main image and the data collection hardware shown in the insert.
FIGURE 3. This set of images shows an example signal trace from two rivet locations. Images A, B and C show how the signal moves from the null point position (probe centered between two anodized rivets) to being centered over an anodized rivet and then to being centered between an anodized and an alodined rivet. Images D, E and F continue the trace as the probe is moved from being centered between the anodized and alodined rivets to being centered over an alodined rivet and finally to being centered between two alodined rivets.

degrees, respectively.

EXPERIMENTAL RESULTS

Typical impedance plane signals acquired at the settings specified in the previous section, are presented in Figure 3. It can be seen from this set of images that as the probe was moved from its null point between two rivets (A), a concave signal trace is produced and the maximum horizontal deflection of the signal is produced when the fastener is centered between the probe coils (B). As the probe moves beyond the fastener and inspects the far side of the fastener location, the signal trace moves back to towards the signal null point (C). If a crack exists on one side or the other of the fastener hole, the distance between the out and back traces is increased. However, in these specimens, alodine rivets were used at the tear strap locations and this caused a downward shift in the second half of the trace as it moved to a different null point (D). When a tear strap location was scanned the alodine rivet caused the out and back signal trace to be shifted down in respect to the areas with anodized rivets (E and F). It can be seen that this inspection produced at least two distinct populations of signals that need to be treated separately in the statistical analysis.

Figure 4 shows a complete set of signals from one of the panels. Since the probe was nulled prior to each individual rivet scan, both areas with and without tear straps, the signals all originate from the zero-zero point. The lighter dashed lines are signals from unflawed fastener locations in areas without tear straps. The darker dashed lines are signals from unflawed fastener locations in areas with tear straps. The top five solid lines are signals from cracked fastener locations in areas without a tear strap. The lower three solid lines are signals from cracked fastener locations in areas with a tear strap. The crack sizes reflected in this set of scans ranges from 0.85mm (0.033”) to 3mm (0.120”).
FIGURE 4. Chart showing a complete set of eddy current signals from one panel. All null points are shifted to the zero-zero point on the chart. The lighter dashed lines are signals from unflawed fastener locations in areas without tear straps. The darker dashed lines are signals from unflawed fastener locations in areas with tear straps. The top five solid lines are signals from cracked fastener locations in areas without a tear strap. The lower three solid lines are signals from cracked fastener locations in areas with a tear strap.

To simplify the data presentation, the signal from just one of the flawed fastener location is presented in Figure 5, along with the signals from the unflawed holes in areas without a tear strap. To show the level of repeatability of the measurements, the data from three scans (gray, solid lines) along with the average of these scans (black, solid line) is presented for the fastener location with the 5mm (0.12") crack. While there is some variability in the signals, it appears reasonable to consider that the average curve is largely representative of the optimal response from the inspection site. It can be seen that the signal from the flawed site falls significantly outside the main band of signals from the unflawed site. The exception is the signal from an unflawed site where the edge of a tear strap encroached upon the null location and this caused the signal to shift upward. This signal shift did not always occur at the expected locations and its cause was not totally apparent during the blind study so this signal and a number of others from similar locations were not treated in any special way and caused some degradation in the POD curve.

Post data processing was performed to provide input to both an a-hat versus a and a hit-miss POD analyses. For the hit miss analysis, the signals were reviewed to determine if maximum vertical signal exceeded a threshold or the opening between the traces was more than 15-percent of the total signal strength. For the a-hat versus a analysis, a numerical value had to be extracted from the eddy current signal. Three options for this value were considered. The first option was a measure of the separation between the signal traces from the right side and left side of the fastener. However, since this separation was highly affected by the null point shift due to the different rivet coatings, this option did not seem viable. The second option is the vertical signal strength at the point where the signal reached its minimum horizontal value. This value is identified as point “A” in Figure 5. The third option is the maximum vertical value of the signal. This value is identified as point “B” in Figure 5. For each fastener location, the values at both points A and B were extracted from a curve produced by averaging the data from three scans.
FIGURE 5. The signals from three scans (gray, solid lines) along with the average of these scans (black, solid line) for a fastener location with the 3mm (0.120") crack. The gray dashed lines are signals from unflawed locations. All the fastener locations were in areas where no tear strap was present. The values at point “A” and point “B” were selected for consideration for the a-hat versus a POD analysis.

FIGURE 6. Plots showing the relationship of the two values extracted from the eddy current signals. The plots show that the vertical voltage at the minimum horizontal point provides a stronger indication of a crack.

To determine whether point “A” or “B” of the signal was a stronger indicator of the presence of a crack, relationship plots of the two measurement points were prepared. These plots are shown in Figure 6. The maximum vertical voltage is plotted along the x-axis and the vertical voltage at minimum horizontal voltage is plotted along the y-axis. The values of signals from uncracked locations are represented by open circles and the values of signals from cracked locations are represented by solid triangles. It can be seen from these plots that the maximum vertical voltage signal provides a stronger indication of the crack at locations with and without a tear strap. Therefore, the values for this point on
the eddy current signal were used in the POD analysis. This choice is contrary to the Boeing procedure that favors the option B.

While good reproducibility of the data was achieved, the inherent nature of the multilayer, riveted structure resulted in significant scatter in the data as can be seen in Figure 6. This scatter required special statically processing techniques to produce a meaningful POD curve, which will be discussed in an accompanying paper by Li and Meeker. The POD curves that were generated from this study are shown in Figure 7. The a-hat versus a data from the tear strap locations produced the best POD followed by the hit/miss data in these same areas. As mentioned previously, the POD curves in the areas without a tear strap were degraded by the signals that were shifted upward due to the tear strap encroaching upon the null location.

**SUMMARY**

Experimental data has been collected from 288 rivet hole locations in panels manufactured to represent a 737 lab splice containing cracks and a variety of manufacturing related variables. The experimental data was carefully collected using a low frequency eddy current sliding probe moved with an automated scanning setup in the laboratory to minimize human factor variables. The data was evaluated to develop an understanding of the affect of sample features on the eddy current signal, and to determine which points on the eddy current signal best indicated the presence of a flaw. From the data, POD curves were generated that will be used in a model-assisted probability of detection (MAPOD) study aimed at complex structure.

![Figure 7](image-url)

*FIGURE 7.* The resulting hit/miss and a-hat versus a POD curves.
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