METHOD FOR CRACK CHARACTERIZATION WITH NOISE INVARIANCE FOR EDDY CURRENT INSPECTION OF FASTENER SITES

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Abstract. This paper explores feature extraction and signal classification for crack characterization in eddy current inspection of fastener sites. Using simulated studies, a promising feature extraction method with broad noise invariance is presented associated with changes in the eddy current response in the circumferential direction. An experimental study is also presented demonstrating the ability of this measure to improve the capability to detect and potentially size cracks around fasteners while maintaining a low false call rate.

Keywords: cracks, eddy current, fastener hole inspection, noise invariant features, modeling
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INTRODUCTION

The characterization of cracks around fastener sites in multi-layer structures continues to be an important problem for the aging aircraft NDE community. There are two competing tasks for the NDE research community: to develop inspection techniques to reliability detect, locate and size subsurface fatigue cracks around fastener holes while minimizing the cost and time for inspection. Although both eddy current (EC) and ultrasonic methods have been employed for practical use, eddy current methods are of particular interest when the sealant condition between layers has degraded or does not exist to permit the transmission of ultrasonic waves into deeper layers. However, limitations concerning depth of penetration, poor resolution at low frequencies, and overall sensitivity to cracks near fastener sites for EC methods must be overcome. To improve EC capability for this problem, a design approach incorporating computational methods is proposed encompassing numerical models, data analysis and classification algorithms, and design optimization tools. Prior work has explored the development and application of numerical models for the inspection of cracks around fastener holes in multilayer structures using electromagnetic NDE methods based on the boundary element method [1] and finite element method [2-4]. Recently, the development and validation of numerical models based on the volume integral method [5] for the eddy current fastener crack problem have been presented [6-7]. This design strategy is directed at improving the source field characteristics, measurement sensor design, and data analysis and classification algorithms.

Although an asymmetry observed for a hole feature in an eddy current image from 2D raster scan data is typically used to distinguish crack and no crack conditions, there are a variety of potential sources of coherent noise features with similar asymmetric responses. In particular, irregularities in the fastener hole fit condition such as asymmetric gaps between the fastener and hole due to shifted or skewed fasteners, or oblong holes due to poor drilling can produce asymmetric image results. In addition, variability in probe lift-off related to the scanning system hardware alignment or part surface conditions can cause variability in the signal. The consistency of windings in eddy current probe due to difficulty in manufacturing can also be a source for measurement asymmetry. Lastly, the presence of adjacent fastener sites can produce an irregular response and complicate the data interpretation problem. Clearly, the presence of these examples of coherent noise can increase false call rates and likewise limit the detectable crack size. Thus, there is a need to develop advanced data analysis approaches and reliable features that are sensitive to the crack condition yet invariant to such coherent noise signals also present in real data. The use of invariant features has been shown to be valuable for other problems in eddy current nondestructive evaluation. A classic approach to reduce sensitivity to liftoff during EC measurement of surface breaking cracks concerns adjusting the phase during calibration so as to isolate liftoff to the horizontal measurement component while a threshold is applied to the vertical measurement component in order to make a call. Also, feature extraction methods were developed to address unknown permeability variation through an invariance transformation of flux density measurements incorporating radial basis functions [8]. The performance of neural network classifiers were found to significantly benefit from the use of such invariant signal features.

The objective of this work is to develop feature extraction and classification algorithms for crack characterization with invariance to noise features for eddy current inspection of fastener sites. Model-based parametric studies are performed to explore potential features under a wide array of crack, noise and material conditions. Through these studies, a particularly promising feature with noise invariance was found through analysis of changes in the eddy current response along a circumferential direction away from the hole center. A model-based optimization approach is also presented to evaluate the best signal processing algorithm design to distinguish between several classes of crack size. In addition, experimental studies are presented that further explore the reliability of this feature in the presence of experimental noise and adjacent holes in close proximity. Through the development of an automated algorithm to quantify this feature, results for the experimental study demonstrate an improved capability to detect small cracks around fasteners while maintaining a low false call rate. Relations between the best feature measures and the size of the radial crack are also presented indicating the potential for sizing subsurface cracks.

SIMULATED PARAMETRIC STUDY

A parametric study using simulation were designed to investigate potential features in the eddy current signals with sensitivity to fatigue cracking and invariance to several coherent noise features. The model design was based on a prior benchmark problem of an eddy current inspection of a two layer structure with a fastener site and a crack [6]. VIC-3D®, a commercial software package based on the volume integral method [5], was used to perform the simulations. For this study, three potential non-flaw sources of an asymmetric eddy current response were explored: a) presence of asymmetric gaps around the fastener, b) an asymmetric response due to a linear varying liftoff condition with respect to probe position relative to the fastener and c) a non-axisymmetric probe response due to an internal design variable such as tilt in the coil windings (relative to a normal position at the layer surface.) Figure 1 displays diagrams of these three potential sources of asymmetric eddy current response from fastener sites with the additional case for (d) a fatigue crack. The value used for the gap, 0.04 mm (-0.0015"), originates from typical tolerance

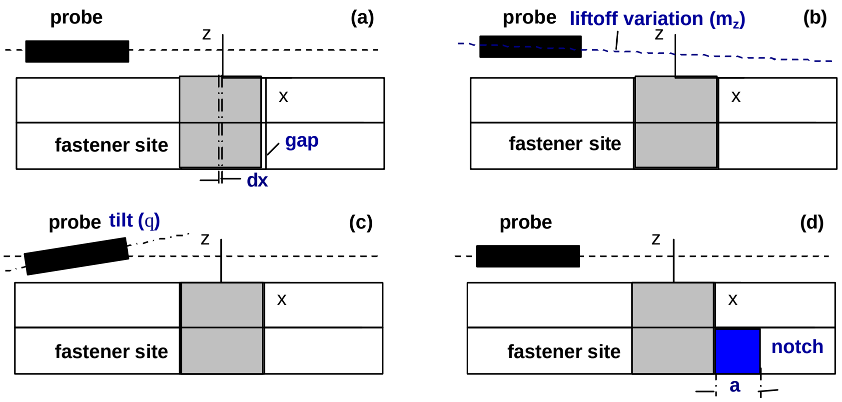

FIGURE 1. Sources of asymmetric eddy current response from a fastener site: (a) asymmetric gap between fastener and hole, (b) probe liftoff variation, (c) probe tilt, and (d) presence of radial crack (notch).

specifications of ±1 – 2 mils for fastener hole interfaces in aircraft structures. The use of probe tilt angles of 2° and 4° is based upon prior experience with eddy current measurement and scanning systems, representing either irregular coil windings or poor alignment with the part surface. Calculation of the eddy current response for a linear liftoff variation with position was performed through first solving for the impedance calculations at three liftoff levels (dz = -0.20, 0.00, and 0.20 mm), and using interpolation to construct results for intermediate probe positions. Simulated data was acquired for all runs over a 2D grid (representing raster scan data) where the x-axis probe positions were varied from -16.0 mm to 16.0 mm at 1.0 mm increments, and y-axis probe positions were varied from 0.0 mm to 15 mm at 1.5 mm increments (using model symmetry along the x-axis.) To ensure that potential features are robust to changes in fastener material conditions, all studies were run with cylindrical inserts of aluminum and titanium. The frequency of 5.0 kHz was used in the study. For this problem, the number of elements used in the 'flaw' region are 128, 64, and 2 in the x, y, and z directions respectively providing adequate element coverage for both the finite crack (notch) width and the gap between the fastener and hole.

CRACK FEATURES IN WITH NOISE INVARIANCE

To better evaluate potential features for sensitivity to cracks and invariance to noise, evaluation of the data in the radial and circumferential directions was performed. Figure 2(a) presents a plot of the difference measure in the radial direction for the reactance component of impedance for varying probe tilt and crack size condition with a titanium insert. For much of the scan region near the hole (x < 8.0 mm), probe tilt is the dominant parameter influencing the response of the reactance component. However, there is a region at x = 10.2 mm where the response becomes insensitive to probe tilt. Although this noise invariant feature presents an opportunity to distinguish the largest crack size for this study, it may be difficult to use in practice due to sensitivity to slight changes in probe position, material properties and geometry of the structure. Similar trends were observed for (a) gaps and (b) liftoff variation; however, the locations for the local region of noise invariance were not at the same location and thus not reliable for application when all noise conditions are considered.

Figure 2(b) presents a plot of the reactance component of impedance with respect to angular location in the circumferential direction with the radial position set to 9 mm. Two levels of probe tilt (0 degrees and 2 degrees,) and three crack sizes (of 0 mm, 1 mm and 2 mm in length) are presented. Of particular interest is a significant localized peak whose magnitude is related to crack length. There is also a second peak due to an increased probe

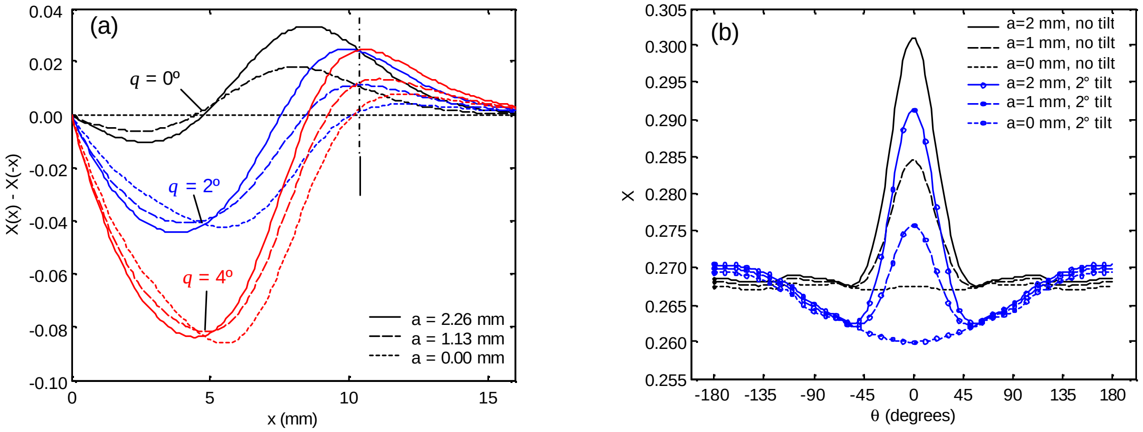

FIGURE 2. Plots of (a) difference in reactance component (about x = 0) along line of symmetry (at y = 0) and (b) reactance component along circumferential direction at r = 9 mm, for varying probe tilt and flaw size condition (with titanium inserts).

tilt in the reactance data; however, it is much broader with much similarity to a cosine function in profile and period. Although not presented, very similar trends were also observed for the cases of an (a) asymmetric gap between fastener and hole (with an aluminum fastener) and (b) linear liftoff variation (with a titanium fastener) shown in Figure 1. These localized responses due to the presence of a radial crack can also be found in experimental measurements by Dogaru et al., produced by rotating a D-shape coil and GMR sensor about a fastener site, although the characteristic magnitude response consists of a double peak due to the nature and orientation of the field measurement sensor [10-11].

To extract a measure of this localized crack feature found in the circumferential direction, an approach is proposed using a nonlinear least squares estimation of a corresponding parameter in a model characteristic function. For this simulated study, the feature vector in the circumferential direction can be represented by four model components, (1) a sinusoidal function representing an asymmetric response of a typical non-flaw condition, (2) a Gaussian function representing a localized response associated with a radial crack, (3) constant offset value related to the overall axisymmetric response due to probe, sample geometry and material properties, and (4) random measurement noise. The characteristic sinusoidal and localized Gaussian features are clearly observed in Figure 2(b). For our initial study, the following ‘four parameter’ characteristic model was used,

$$f(q) = A\cos(q) + B\exp\left(-Dq^2\right) + C\,, \tag{1}$$

where only the presence of a single crack or no radial crack is considered, and all phase angles were set equal to zero, given the alignment of the crack, gap asymmetry, probe skew and probe liftoff asymmetry with the x-axis. To evaluate these parameters, a nonlinear least-square estimation approach was used to minimize the error between the characteristic model and the simulated data. To address any ill-posed characteristics of the minimization problem, constraints were applied to the parameter *D*, the width of the Gaussian function, to limit the circumferential extent of the peak response to a typical range associated with a crack region. It was found that good results are achieved when the variable *D* is included in the estimation process, since the width of the Gaussian response does vary with both radial location and the select impedance component. Through this analysis process, *B*, the magnitude of the crack characteristic function, will be explored as a measure for crack detection and sizing.

An analysis was performed to evaluate the best measure to distinguish the three crack conditions in the design study with invariance to a variety of noise conditions. Two measures in particular, the difference measure along the radial direction, dZ, and the circumferential crack measure, B, were evaluated as a function of radial position, r, to optimize sensitivity to crack length, a. These measures were evaluated with respect to variation in multiple noise conditions: asymmetric gap, probe liftoff, probe tilt, and probe linear liftoff variation, given by Figure 1. Insert material was also varied between the case of aluminum and titanium, resulting in a total of 20 different measurement conditions. To quantify the ability of a measure to distinguish between two data classes, a Fisher linear discriminant function was used [12]. To adapt this approach for our case with three different data classes to separately distinguish (no crack, 1.13 mm crack, 2.26 mm crack), the Fisher linear discriminant function was evaluated for the three combinations of crack length: 0.00 and 1.13 mm, 0.00 and 2.26 mm, 1.13 and 2.26 mm.

Refinements in the ability to discriminate crack size are possible through the use of data on the insert material condition in the circumferential crack feature model. Figure 3(a) presents a comparison of all of the circumferential crack measure (B_X) samples comparing differences in crack size and insert material type for the probe location of r = 13 mm. Of particular interest is that for this measure, as probe positions are far from the hole, the vast majority of variation is due to the insert material type with very little variability due to the other noise factors. Since the insert material can be ascertain from eddy current measurements made at the center of the fastener, this trend provides a robust feature for crack sizing with excellent noise invariance. Based on a first order model between crack size and the circumferential crack measure (B_X) with dependence on the fastener material,

$$B_X(a, s') = b_o + b_1(s')a, \tag{2}$$

a linear model can be defined to estimate crack size. In Figure 3(a), the circumferential crack measure (B_X) is found to be more sensitive to crack size with titanium fasteners. This difference in sensitivity is likely due to the much lower conductivity for titanium with respect to aluminum, where less eddy currents are generated in the insert, and higher concentrations of eddy currents are produced in a region near the hole boundary where titanium essentially acts as a large void.

Figure 3(b) displays a comparison of the mean Fisher linear discriminant function for the resistance and reactance components of the circumferential crack measures, B_R and B_X, and the difference impedance measures along the x-axis, dR and dX, repsectively. Separate assessments of the Fisher linear discriminant were performed for the data samples from the aluminum and titanium cases, and averaged to obtain a single mean of the six Fisher linear discriminant functions values. Clearly, the circumferential crack measure of the reactance component, B_X, produces the best classification results. Again, the best results are found when the probe is far from the hole center. Although these locations are not where the maximum interaction between the eddy current densities and crack occur, the relative response is greater to the crack with respect to the array of noise features present in this study.

Although the results for this approach are promising, consideration must also be given to the strength of the signals with respect to background measurement noise. If the noise is purely random as considered in Equation (1), the evaluation of B_X using nonlinear least square estimation will essentially filter reasonable levels of random noise given enough data samples in the feature vector. However in practice, weak signals and the magnitude of coherent measurement noise must also be considered in optimizing the design of a feature extraction algorithm. Experimental studies can be used to study this problem.

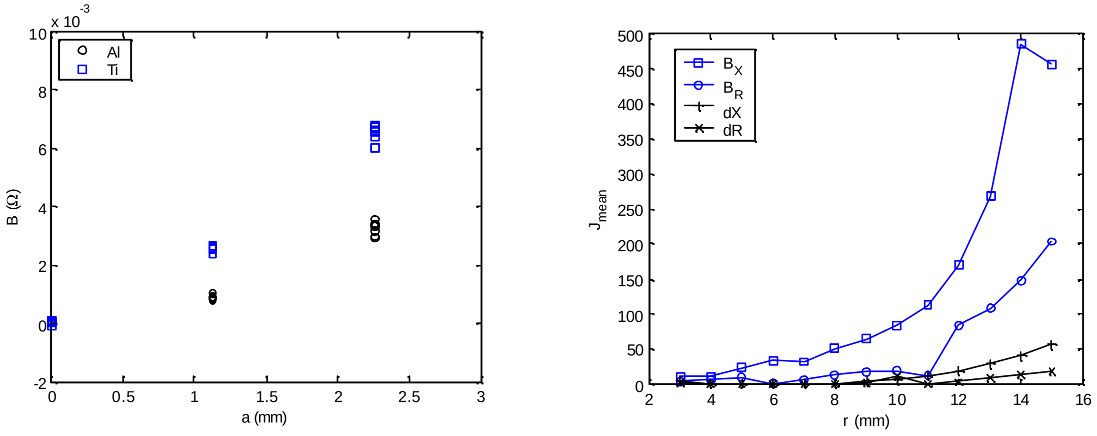

FIGURE 3. (a) Plot of all circumferential crack measure (B_X) results comparing differences in flaw size and insert material type at r = 13 mm, and (b) plot of the mean Fisher linear discriminant function with respect to radial probe position for both the circumferential crack measure and the difference measure.

EXPERIMENTAL VALIDATION

To validate the proposed feature extraction methodology, a set of experimental data for hidden cracks around fasteners in multilayer structures was analyzed. The samples used in the study were made by the Lockheed Aircraft Corp. in 1980 representing C-5A wing splice configurations. The first and second layer thickness were 0.156" and 0.100" respectively and made of 7075-T651 aluminum. A number of 14" by 2" specimens were designed with 10 countersunk 1/4" straight shank fasteners. Real fatigue cracks were manufactured in the samples, using starter notches, applying cyclic loading and resizing the holes. The faying surfaces were sealed, the fasteners were wet installed with sealant, and a paint coating was applied. Raster scan data was acquired from these samples using a conventional eddy current probe at 600 Hz. The phase was rotated to isolate liftoff along the horizontal direction for all scans. For this analysis, select data was analyzed for samples having corner cracks at the near surface of the second layer, with the near side of the crack 0.156" from the top measurement surface. This data set provides the opportunity to explore the reliability of the proposed feature extraction methodology in the presence of experimental noise and adjacent holes in close proximity (distance between holes ~0.73").

Figure 4(a) shows a diagram of a select sample (A1-16) from the C5 sample set with corner cracks oriented to both upper and lower hole locations. Note that hole 1 contains a steel fastener while holes 2-10 contain titanium fasteners. Prior research into signal processing and classification methods for the same data set using difference-based features vectors and neural network classifiers only consistently found the largest flaws (> 0.100") with a false call rate at an unacceptable level. The proposed approach of analyzing eddy current features in the circumferential direction was implemented as part of an automated signal processing and feature extraction routine. The algorithm first locates the center of each fastener site using a 2D correlation method with interpolation between grid points using cubic splines to minimize error in the circumferential gradient feature analysis. The circumferential response is presented in Figure 4(b) as a separate line plot for each fastener site shown in Figure 4(a). First, there is a very strong response associated with the adjacent holes located at 0° and 180° for each line plot. This provides a particular challenge over coherent noise features studied in the previous section since the adjacent fasteners also produce a localized asymmetric response. Of highest interest for the two crack cases, a smaller localized Gaussian response can be found at 90° for hole 3 and 270° for hole 6. Another noise feature found is a step change in the circumferential direction response occurring at hole 8. In addition, Figure 4(c) presents a transformation of the radial and angular component of the response into a 2D image, further highlighting local features associated with the presence of crack relative to the adjacent hole and noise features.

An automated signal classification algorithm was developed with sensitivity to the localize Gaussian response above and below the hole associated with the presence of a s crack while rejecting any step changes in the response. The analysis routine was applied to a total of 132 no crack fastener sites and 39 crack cases with lengths ranging from 0.027" to 0.169". In particular, two features, a relative peak to peak measure of the localized Gaussian response and an absolute measure of peak level, were used to classify the data as shown in Figure 5(a). When flaws greater than 0.067" are considered and a simple threshold classifier is applied to the absolute measure of the peak level (*Bmax*), all flaws were detected in this range and a false call rate less than 1% was achieved. Figure 5(b) plots this absolute measure as a function of crack length, providing an indication of the potential to estimate the size of the crack using eddy current measurements.

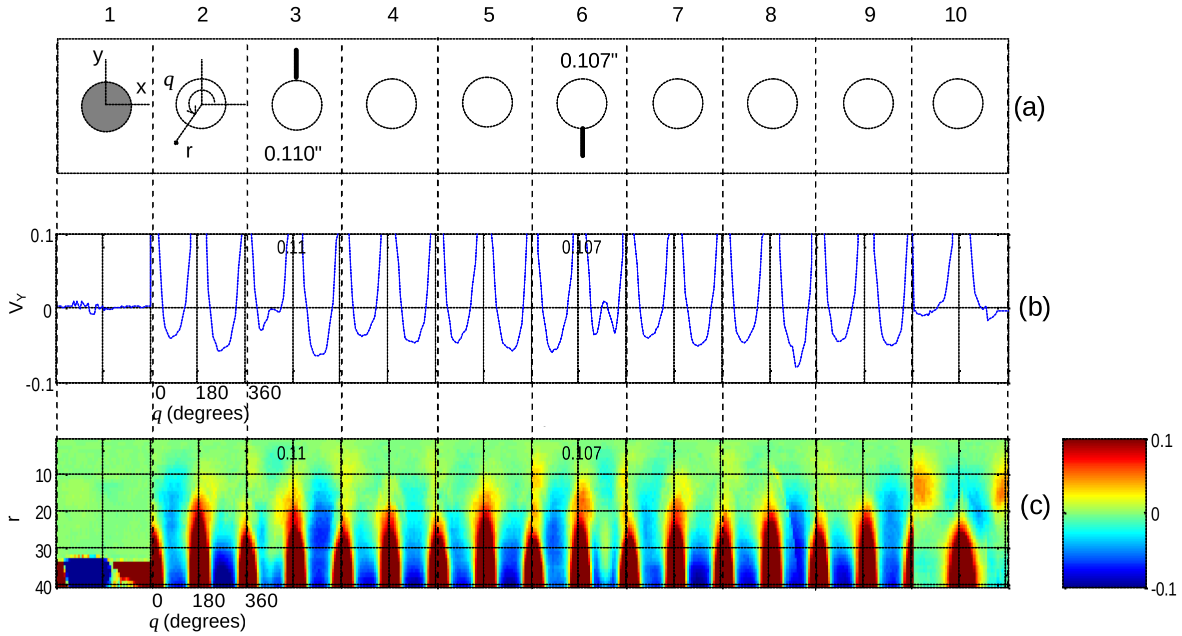

FIGURE 4. (a) Diagram of fastener sites with corresponding (b) plots of circumferential response around hole (r=30) and (c) a 2D image plots transformed from radial and circumferential directions.

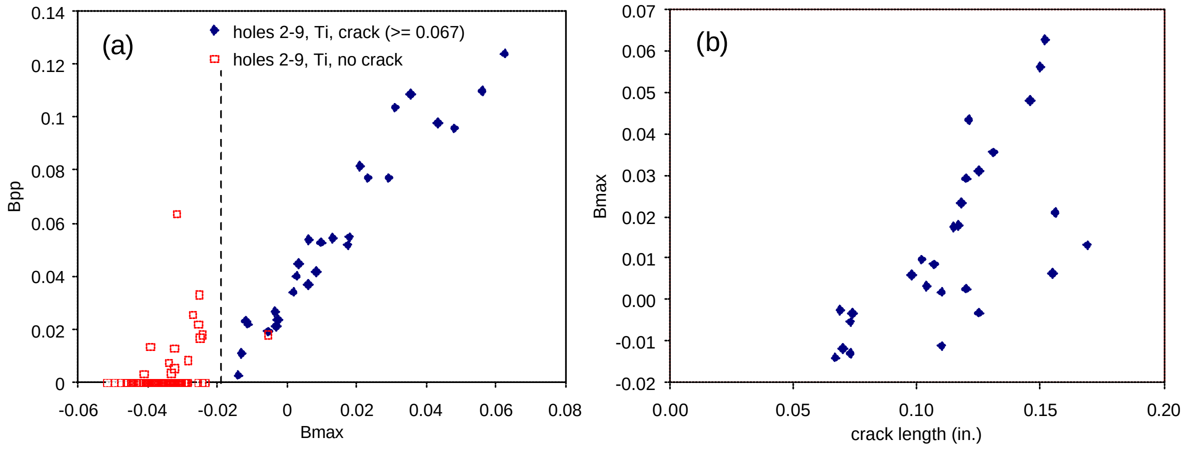

FIGURE 5. Plots of (a) feature space for two measures to differentiate crack and no-crack cases and (b) the best crack measure, *Bmax*, with respect to crack length.

CONCLUSIONS AND RECOMMENDATIONS

Model-based parametric studies were successfully used to discover promising features associated with changes of the eddy current response in a circumferential direction around the hole with sensitivity to crack size and invariance to gaps between fastener and hole, probe liftoff variation, probe tilt, and fastener material. In addition, experimental studies were used further validate this feature extraction methodology in the presence of experimental noise and adjacent holes in close proximity. Results for the experimental study demonstrate the ability to improve the capability to detect small cracks around fasteners while maintaining a low false call rate. Future work will explore the application of this feature extraction methodology for use with linear eddy current array sensors to both improve scan speed and sensitivity at low frequencies. In addition, the development of a model-based inversion scheme for characterizing fatigue crack (in particular through cracks, corner cracks, and eyebrow cracks) around fasteners is of interest.

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