AFRL-ML-WP-TP-2006-494

INVESTIGATION OF A MODEL-ASSISTED APPROACH TO PROBABILITY OF DETECTION EVALUATION (PREPRINT)

J.S. Knopp, J.C. Aldrin, E. Lindgren, and C. Annis

SEPTEMBER 2006

MATERIALS AND MANUFACTURING DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*
September 2006

2. REPORT TYPE
Conference Paper Preprint

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
INVESTIGATION OF A MODEL-ASSISTED APPROACH TO PROBABILITY OF DETECTION EVALUATION (PREPRINT)

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62102F

6. AUTHOR(S)
J.S. Knopp and E. Lindgren (AFRL/MLLP)
J.C. Aldrin (Computational Tools, Inc.)
C. Annis (Statistical Engineering)

5d. PROJECT NUMBER
4349

5e. TASK NUMBER
RG

5f. WORK UNIT NUMBER
M04R1000

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Nondestructive Evaluation Branch (AFRL/MLLP)
Metals, Ceramics and NDE Division
Materials and Manufacturing Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson AFB, OH 45433-7750

Computational Tools, Inc.
4275 Chatham Avenue
Gurnee, IL 60031

Statistical Engineering
Palm Beach Gardens, FL 33418

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-ML-WP-TP-2006-494

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Materials and Manufacturing Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson AFB, OH 45433-7750

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL-ML-WP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-ML-WP-TP-2006-494

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Conference paper submitted to the Proceedings of 33rd Annual Review of Progress in Quantitative Nondestructive Evaluation (QNDE) 2006.

The U.S. Government is joint author of this work and has the right to use, modify, reproduce, release, perform, display, or disclose the work. Paper contains color. PAO Case Number: AFRL/WS 06-2444; Date cleared: 12 Oct 2006.

14. ABSTRACT
This paper presents a model-assisted probability of detection (MAPOD) study for inspection of a two-layer airframe structure. Eddy current measurements for varying crack length around fastener holes in a two-layer aluminum structure are studied using both experimental and model-generated data. New statistical algorithms are used to calculate the probability of detection. Good agreement was achieved between empirical and model-assisted approaches.

15. SUBJECT TERMS
model-assisted probability of detection (MAPOD), eddy current

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor) / 19b. TELEPHONE NUMBER *(Include Area Code)*
Unclassified	Unclassified	Unclassified	SAR	14	Jeremy Knopp / N/A

INVESTIGATION OF A MODEL-ASSISTED APPROACH TO PROBABILITY OF DETECTION EVALUATION

J. S. Knopp[1], J. C. Aldrin[2], E. Lindgren[1], and C. Annis[3],

[1] Air Force Research Laboratory (AFRL/MLLP), Wright-Patterson AFB, OH 45433, USA
[2] Computational Tools, Gurnee, IL 60031, USA
[3] Statistical Engineering, Palm Beach Gardens, FL 33418, USA

Abstract. This paper presents a model-assisted probability of detection (MAPOD) study for inspection of a two-layer airframe structure. Eddy current measurements for varying crack length around fastener holes in a two-layer aluminum structure are studied using both experimental and model-generated data. New statistical algorithms are used to calculate the probability of detection. Good agreement was achieved between empirical and model-assisted approaches.

Keywords: model-assisted probability of detection (MAPOD), eddy current
PACS:

INTRODUCTION

The United States Air Force (USAF) anticipates dramatic increases of inspections required for maintaining the aging aircraft fleet; therefore, faster and cheaper implementation of new inspection technologies is required. The reliability of these new inspection technologies will be assessed by a probability of detection (POD) study. POD is a metric used to quantify the reliability of inspection systems. POD provides engineers with the minimum flaw size that can be reliably detected and can also be used as an input for probabilistic risk assessment analysis. Traditional POD evaluation methodologies are entirely empirical. In most cases, the cost of manufacturing the number of samples required for a traditional POD study is prohibitive and may delay or prevent a new inspection procedure or new technology from being implemented. Alternative methodologies have been proposed that incorporate modeling to reduce the number of samples required. Statistical analysis methods have also evolved since the standard method for conducting POD studies was codified in MIL-HDBK-1823. This study investigates a class of aerospace structural inspection problems and considers the use of models and new statistical analysis methods in POD evaluation.

PRIOR WORK

The concept of using models to assist in quantifying the performance of eddy current inspection systems has been proposed and used with some success in the past. Martinez et al. used basic 1-D analytical models and limited experimental signal-to-noise data to compare different eddy current systems [1]. This work was limited to air-cored probes and flat plate geometries with surface breaking notches. Beissner et al. and Nakagawa used more sophisticated models based on the boundary element method to predict the POD for different 3-D surface breaking notches [2,3]. Again, limited experimental data was used to characterize and incorporate the signal-to-noise ratio. For more examples of model-assisted POD work, the reader is directed to the papers by Gray et al. and Thompson [4, 5]

EXPERIMENTAL STUDY

For this study, two-layer aluminum specimens were used. Each specimen contains 10 countersunk fasteners. 90% of the fasteners are titanium and 10% are steel. The steel fastener sites were excluded from this study. All fatigue cracks are at the top or bottom of the fastener site (i.e. they are not in between the fastener sites). A subset of specimens with cracks located in the second layer at the faying surface was selected for use. Crack lengths range from 0.027” (0.69 mm) to 0.169” (4.29 mm). There were a total of 171 fastener sites in the study and 38 of the fastener sites had cracks. A reflection eddy current probe operating at 600 Hz was used throughout the study. Teflon was placed in between the probe and the sample. Both the in-phase and quadrature components of the voltage were recorded in the format of a C-scan with a scan step size of 0.010" (0.254 mm). Interpolation was used to determine the voltage at points along different radii around the fastener site. The quadrature component of the voltage at a fixed distance from the center of the hole was extracted and plotted as a function of the swept angle around the fastener site [6]. In cases where a large enough crack is present, a perturbation in the form of a localized Gaussian response appears as shown in Figure 1(b). This peak measure was used for the signal response (â) throughout the study.

MODEL-ASSISTED POD (MAPOD) APPROACH

Two protocols have been proposed to incorporate model-assisted approaches: 1) transfer function (TF) and 2) full-model assisted (FMA) [7]. This study investigates a modified FMA approach. A protocol proposed by Bruce Thompson with inputs from the MAPOD working group was followed in this work. The protocol consists of 11 steps designated as follows [8]:

1) Identify the scope of the POD study,
2) Identify factors that control signal and noise,
3) Evaluate quality of physics-based models,
4) Acquire, develop, and validate simulation tools,
5) Acquire input parameters and parameter distributions,

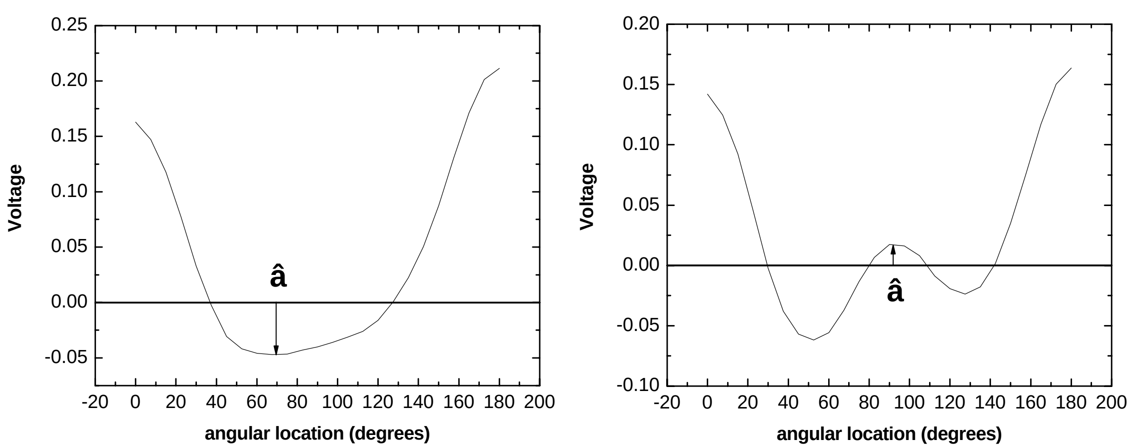

FIGURE 1. (a) Response from unflawed titanium fastener site in a two-layer aluminum structure and (b) perturbed response due to the presense of a fatigue crack.

6) Conduct flaw signal distribution simulations and noise signal distribution simulations,
7) Acquire remaining information on factors empirically,
8) Acquire marginal information on independent factors,
9) Acquire covariance information on dependent factors,
10) Combine 6, 8, and 9 into full signal and noise distributions,
11) Compute POD, POFC, and ROC.

This protocol is still in development and is subject to change by the time of publication of this paper. Some deviations from a strictly full-model assisted approach were made. For example, empirical data were used to quantify noise and engineering judgment was applied to estimate the effect of crack closure and crack aspect ratio. Human factors, which typically have a tremendous impact on POD have been eliminated from this study by using an automated data collection system and relying on software to extract and classify features from the data pertinent to this particular inspection.

MAPOD DEMONSTRATION

The first step in the FMA protocol is to identify the scope of the POD study. The goal of this work is to establish the feasibility of a MAPOD evaluation for structural applications. Eddy current will be used exclusively in this study. The problem of interest is the detection of cracks under installed countersunk fasteners in the second layer of airframe structures. Comparison of empirical POD results with model-assisted results will determine the feasibility of MAPOD for this class of problems.

Factors that control signal and noise include the NDE technique, part material, part geometry, and flaw characteristics. For this problem, the key factors to include in the evaluation were identified from experience with the inspection problem and experimental studies. The probe characteristic response, lift-off, and scan resolution are important factors concerning the NDE measurement. The surface condition of the samples, thickness of the layers, type of fastener, fastener fit, and distance between adjacent fasteners and edges are identified as significant factors related to part geometry and material. The dimensions, aspect ratio, location around fastener site, and morphology are important flaw characteristics to be considered. Evaluation of the quality of the physics based models has been the focus of previous work [9]. VIC-3D® has the capability to handle the generic two-layer structural problem of interest, is computationally efficient, and was used for this study [10]. Other factors not considered in this study include cracks at other locations around the fastener site and multiple cracks around a single fastener site.

Quantitative data on the range of expected values for all of the factors that control signal to noise are necessary for the input parameters to the simulations and experimental studies. Some of these parameters are known, others need to be determined empirically. In particular, conductivity of the materials, coil dimensions, liftoff, and scan resolution were known before the experiment was conducted. The only parameter known about the flaws was the length. The probe characteristic response, measurement noise, and surface condition (paint) needed to be determined empirically. Some input parameters such as crack aspect ratio and crack morphology were unknown and could not be determined empirically, so approximations were made based on engineering judgment. In future work, information from destructive tests may be useful in making decisions about unknown input parameters.

The next steps (6-10) were addressed through a series of experimental and simulated studies evaluating the sensitivity of the key factors on signal and noise. The probe was first characterized using a calibration procedure developed in previous work to efficiently relate simulated impedance calculations with measured voltage data [11]. A nonlinear least squares estimator (NLSE) is used to determine two complex parameters related to gain and bias which are then used to provide a transformation from the model generated impedance data to the experimental voltage data or vice versa. Five unflawed hole responses for titanium were taken from the experimental data and then averaged. These two complex parameters remained constant throughout the rest of the study. The results are displayed in the Figure 2. Since the basic shape of the simulated data matches the shape of the empirical data, there is good reason to be confident that this transformation was appropriate.

Simulations were then conducted according to the method reported in [12]. VIC-3D® was used for all simulations [13]. All measurable parameters for the probe and samples were included in the model. The dimensions 0.156” (3.96 mm) and 0.100” (2.54 mm) for the top and bottom layer respectively. A conductivity of (1.87 x10^7 S/m) for the aluminum was used in the model. A conductivity of (1.79 x10^6 S/m) was used for the titanium fasteners. The diameter of the fastener was 0.025” (0.635 mm) and had a 100 degree cone head. The distance between each hole is 0.73” (18.5 mm). A diameter of 0.118” (3.0 mm) and 0.236” (6.0 mm) for the inner and outer radius respectively was used for probe parameters. A coil height of 0.236” (6 mm) was used and a ferrite cup core with a permeability of 1000 was included. Two flaw conditions were simulated: a through notch and a corner notch. The aspect ratio of the corner notch was assumed to be 1:1, so it follows that the notch will be a through notch when the length of the notch exceeds 0.100”. Since little information is available on the range of crack aspect ratios to expect in multi-layer structures, the choice of 1:1 was made for simplicity. Destructive studies to determine the distribution of the aspect ratio of cracks in multi-layer structures could improve the model-assisted POD process. For this study, all cracks were treated as notches, so it assumed that there is no electrical contact between crack faces. Again, this is a simplification and more studies would be beneficial. After the simulations were conducted, the feature extraction technique described in the experimental section was used to determine the value of â [6].

The results of the simulations along with the experimental data are displayed in Figure 3. Although there is good qualitative agreement between the simulated data and the empirical data, there are weaker than expected responses for some of the larger cracks. This is likely due to variation in crack aspect ratio or crack morphology. The unflawed data is clearly visible at flaw sizes equal to zero in Figure 4(a) and the probability density of the unflawed responses is shown in Figure 4(b). The noise has a basic Gaussian distribution. To analyze this data, a threshold was set at -0.02. Only data above this value was used in the analysis. A single outlier for the unflawed case was also removed from the analysis. It is apparent that the data above the threshold does not have a constant variance due to some weak responses for larger cracks; therefore, only hit/miss analysis will be conducted since *a* vs. *â* analysis requires constant variance in the data. Note that various transforms were applied in an unsuccessful attempt to achieve constant variance.

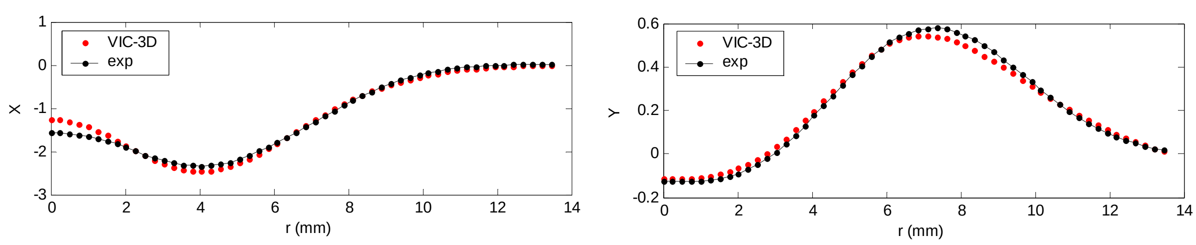

FIGURE 2. Comparison of empirical and model-generated response from fastener after transformation has been performed. X: in-phase component. Y: quadrature component.

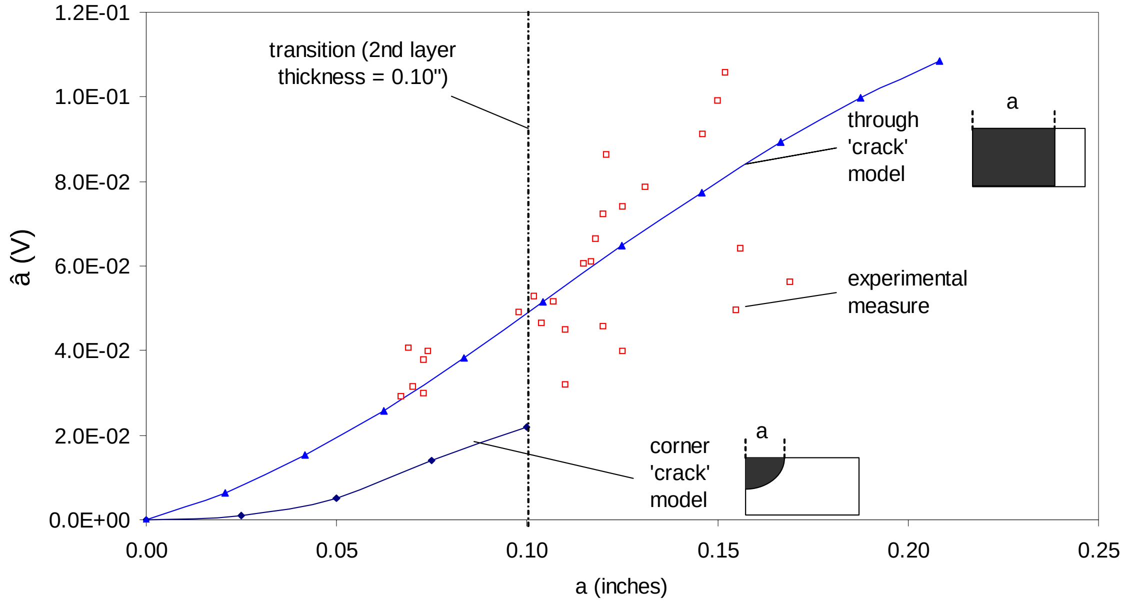

FIGURE 3. Simulated data for both through 'crack' and corner 'crack' responses with experimental data.

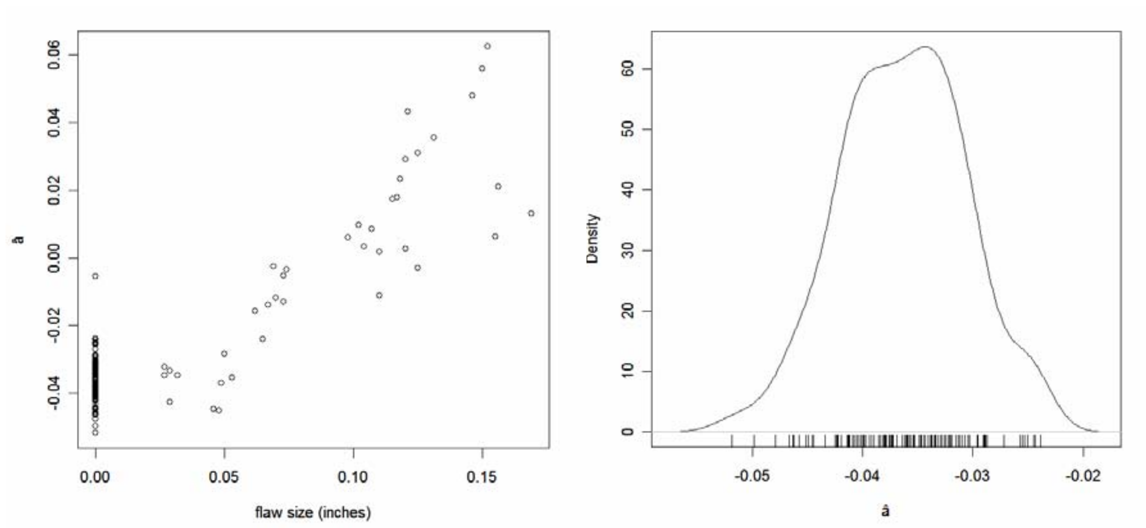

FIGURE 4. (a) Experimental data including unflawed responses and (b) probability density function for unflawed responses showing that the noise follows a basic Gaussian distribution.

Next, a Monte-Carlo study was conducted to provide data for the model-assisted POD evaluation using the noise distribution for the unflawed fastener sites, the corner crack model, and the through crack model. The Monte-Carlo study was performed using 5000 data points based on these assumptions. The results are displayed in Figure 5. Qualitatively there is excellent agreement between the empirical and simulated data. Again, the only outlier points of concern are the weaker than expected responses for some of the larger cracks. This non-constant variance observed with the larger crack data is most likely related to the effect of crack contact conditions, transition between corner cracks and through notches, and variability of the crack aspect ratios and morphology.

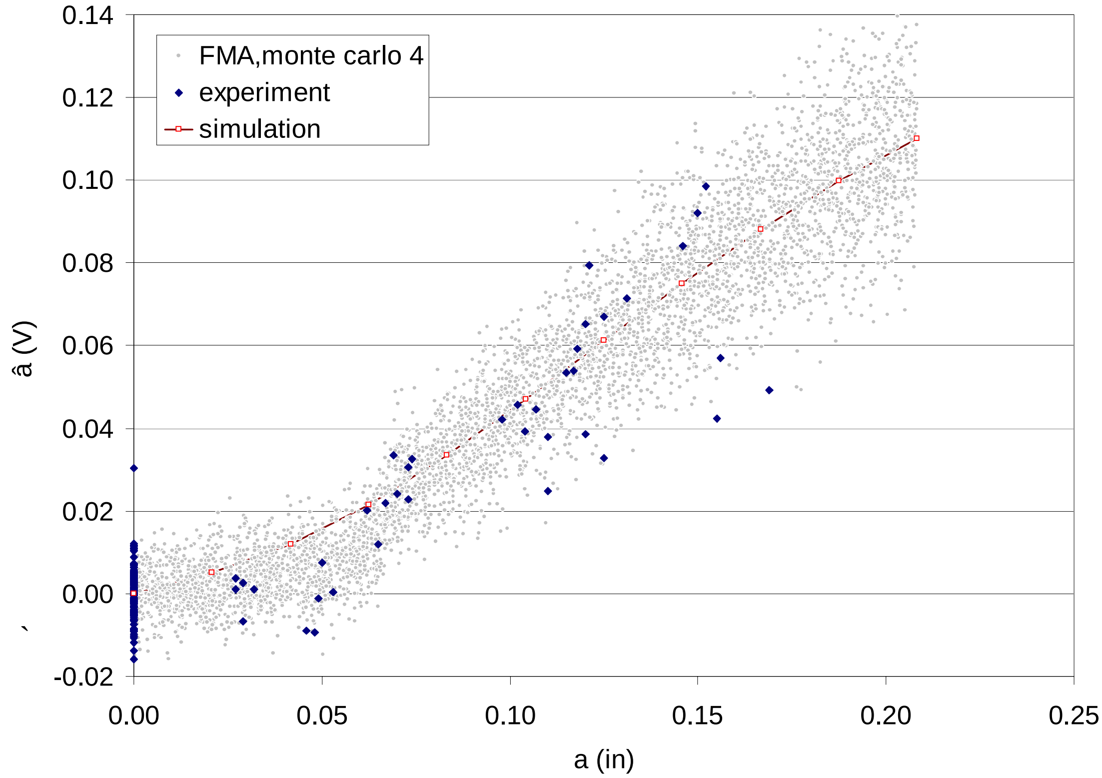

FIGURE 5. Comparison of simulation, experimental data, and Monte Carlo simulation results..

For the quantitative evaluation, a POD curve was generated. The POD calculations were made using the conventional maximum likelihood approach used in the current version of MIL-HNDB-1823 [14]. Recently, it has been determined that the Wald method for calculating confidence bounds for hit/miss data can be anti-conservative [15]. The Loglikelihood Ratio Method was used for the confidence bound calculations. The POD results for both the empirical study and the model-assisted POD approach are given in Figure 6. The curve generated with the MAPOD approach is within the 95% confidence bounds of the empirical curve, demonstrating good agreement between the two approaches. Considering that only the hole response was used to calibrate the model, these results are very encouraging. Note, the confidence bounds on the model generated data are misleading because the uncertainty in the input parameters is not accounted for. The narrow confidence bounds actually show the confidence of the computations (i.e. the bounds are inversely proportional to the square root of the number of simulation runs). More research is needed to include uncertainty properly into the analysis.

There are many opportunities for improvement and further research. It would be beneficial to know at what size the transition from a corner crack to a through crack occurs. This transition depends on the aspect ratio of the crack; thus, a study of aspect ratio distributions from a tear-down study would be beneficial. The effect of contact conditions of the crack faces and crack morphology on eddy current response is still not resolved and a review of the relevant literature will be investigated. Future work is also needed to develop numerical and statistical models that can better represent this observed variability with large cracks.

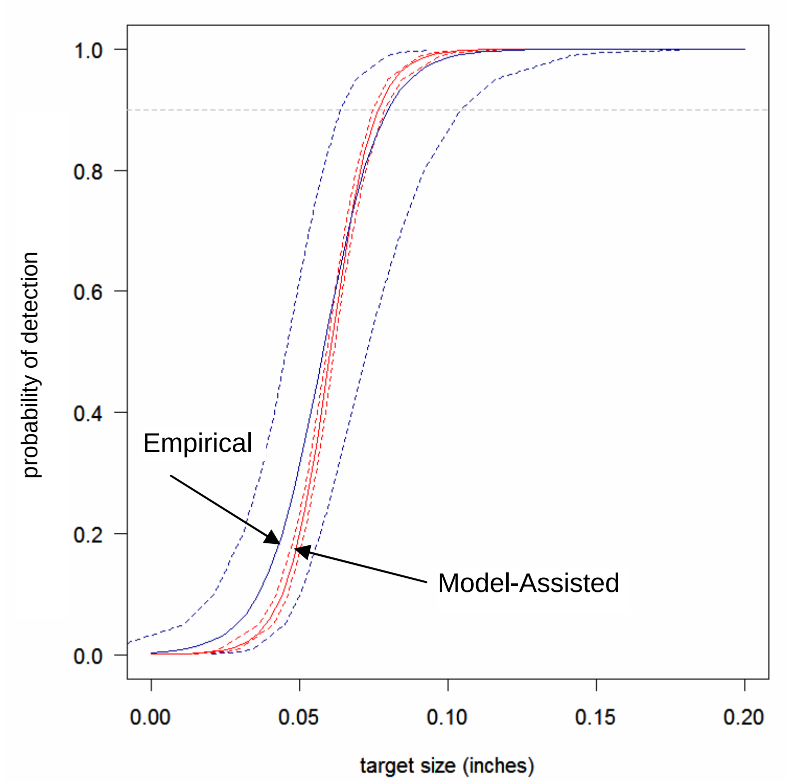

FIGURE 6. POD results for empirical and MAPOD evaluations.

CONCLUSIONS AND RECOMMENDATIONS

The feasibility of model-assisted POD has been demonstrated by the good match between the empirical and model-assisted POD evaluation results. This is the first instance of applying a model-assisted POD methodology to the evaluation of NDE techniques for complex structure applications. The model-assisted POD study only used data from unflawed fastener sites to evaluate the noise distribution and calibration of the probe. Further studies on the variation in crack aspect ratio, transition region between corner and through cracks, and effect of crack face contact conditions will enhance model-assisted POD results. Cracks in between fastener sites also need to be considered through additional simulated studies and signal to noise calculations. New feature extraction techniques address limitations based on location and number of fastener sites and the effect of steel fasteners [16]. The most effective way to calculate confidence bounds for mixed model and experimental data sets is still undetermined and more research is necessary. Uncertainty in input parameters needs to be accounted for in the transfer function and full-model assisted approaches.

ACKNOWLEDGEMENTS

The authors thank Dr. Claudia Kropas-Hughes, Larry Dukate of AFRL and Dick Martin of the University of Dayton Research Institute (UDRI) for prior acquisition of experimental data and Harold Sabbagh, Elias Sabbagh and R. Kim Murphy for support with VIC-3D®. Funding was provided by the Air Force Research Laboratory – NDE Branch and Air Force Office of Scientific Research. The R software environment for statistical computing and

graphics was used for all statistical computations and used to plot Figure 6. R is open-source (free) software and is available to download here: http://www.r-project.org/.

REFERENCES

1. J. R. Martinez and A. J. Bahr, "Statistical detection model for eddy current systems", *Review of Progress in QNDE*, Vol. 3A, Plenum Press, pp 499-510, (1984).
2. R. E. Beissner, K. A. Bartels, and J. L. Fisher, "Prediction of the Probability of Eddy Current Flaw Detection", *Review of Progress in QNDE*, Vol. 7B, Plenum Press, pp 1753-1760, (1988).
3. N. Nakagawa, M. W. Kubovich, and J. C. Moulder, "Modeling Inspectability for an Automated Eddy Current Measurement System", *Review of Progress in QNDE*, Vol 9, Plenum Press, pp. 1065-1072, (1990).
4. J. N. Gray et al, "Models for Predicting NDE Reliability", *ASM Handbook*, Vol 17, ASM Int, pp. 702-715, (1989).
5. R. B. Thompson, "Using Physical Models of the Testing Process in Determination of Probability of Detection," *Materials Evaluation*, Vol 69, No. 7, pp. 861-865, (2001).
6. J. C. Aldrin and J. S. Knopp, "Method for Crack Characterization with Noise Invariance for Eddy Current Inspection Of Fastener Sites", *Review of Progress in QNDE*, Vol. 25, AIP, pp. 315-322, (2006).
7. R. B. Thompson, L. Brasche, J. Knopp, and J. Malas, "Use of Physics-Based Models of Inspection Processes to Assist in Determining Probability of Detection", *Aging Aircraft Conference Proceedings*, (2006).
8. http://www.cnde.iastate.edu/research/MAPOD/MAPODWG.htm
9. J. S. Knopp, J. C. Aldrin, R. Ko, and H. A. Sabbagh, *Review of Progress in QNDE*, Vol. 23, AIP, 336-343, (2004).
10. J. S. Knopp et al, "Efficient Solution of Electromagnetic Scattering Problems Using Spatial Decomposition Algorithms", *Review of Progress in QNDE*, Vol. 25, AIP, pp. 299-306, (2006).
11. J. S. Knopp, J. C., Aldrin, and P. Misra, "Considerations in the Validation and Application of Models for Eddy Current Inspection of Cracks Around Fastener Holes", *Journal of Nondestructive Evaluation*, (accepted for publication, 2006).
12. J. C. Aldrin and J. S. Knopp, "Crack Characterization Method with Invariance to Noise Features for Eddy Current Inspection of Fastener Sites", *Journal of Nondestructive Evaluation*, (accepted for publication - 2006).
13. R. Murphy, H. Sabbagh, A. Chan, and E. Sabbagh, A volume-integral code for electromagnetic nondestructive evaluation, *Proceedings of the 13th Annual Review of Progress in Applied Computational Electromagnetics*, (Monterey, CA, March 1997).
14. A. Berens, "NDE Reliability Data Analysis", *Metals Handbook*, Vol.17, ASM Int., pp. 689-701, (1989)
15. C. Annis and J. S. Knopp, "Comparing the Effectiveness of $a_{90/95}$ Calculations", *Review of Progress in QNDE*, Vol. 26, AIP, (to be published).
16. J. C. Aldrin and J. S. Knopp, "Case Study for New Feature Extraction Algorithms, Automated Data Classification, and Model-Assisted Probability of Detection Evaluation", *Review of Progress in QNDE*, Vol. 26, AIP, (to be published).