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COMPUTATIONAL METHODS IN NONDESTRUCTIVE EVALUATION: A REVOLUTION IN MAINTENANCE (POSTPRINT)

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14. ABSTRACT
The primary objective of this research program is to improve the characterization of small discontinuities (cracks, corrosion) using eddy current and ultrasonic methods for complex structures using computational methods in NDE. The research approach concerns the development and validation of efficient 3D models that accurately represent complex eddy current (EC) and ultrasonic (UT) inspection problems. Simulated studies can then be used to gain a fundamental understanding of the NDE characterization problem for differentiating and sizing small discontinuities in the presence of coherent noise features present in complex structures. With this understanding and modeling capability, research on novel data analysis and classification methods is conducted exploring multi-dimensional signal processing using data from scanning systems and array sensors and model-based classifiers via inverse methods. The benefits of this program address minimizing disassembly, improving reliability, and maximizing availability of aircraft.

15. SUBJECT TERMS
modeling, ultrasonic inspections, eddy current, nondestructive evaluation, model-assisted probability of detection (MAPOD), economic service life management

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Computational Methods in Nondestructive Evaluation: A Revolution in Maintenance

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Abstract. The primary objective of this research program is to improve the characterization of small discontinuities (cracks, corrosion) using eddy current and ultrasonic methods for complex structures using computational methods in NDE. The research approach concerns the development and validation of efficient 3D models that accurately represent complex eddy current (EC) and ultrasonic (UT) inspection problems. Simulated studies can then be used to gain a fundamental understanding of the NDE characterization problem for differentiating and sizing small discontinuities in the presence of coherent noise features present in complex structures. With this understanding and modeling capability, research on novel data analysis and classification methods is conducted exploring multi-dimensional signal processing using data from scanning systems and array sensors and model-based classifiers via inverse methods. The benefits of this program address minimizing costs, minimizing disassembly, improving reliability, and maximizing availability of aircraft. A probabilistic risk analysis method for assessing the value of NDE capabilities in maintenance strategies and the impact of NDE characteristics on maintenance cost and reliability tradeoffs is also presented.

KEYWORDS: modeling, ultrasonic inspections, eddy current, nondestructive evaluation, model-assisted probability of detection (MAPOD), economic service life management

1. Introduction

The service life for several types of US Air Force aircraft is being extended beyond the design life of these systems. Therefore, additional inspections are needed for complex, buried structure that was not anticipated during the design and development process. This will lead to an increased maintenance burden by requiring additional inspections that can only be accomplished by disassembly of structures when using the inspection processes currently available in production environments. As a result, new inspection technologies and strategies are being investigated to mitigate the cost and time required for maintenance of aircraft structures. Currently the USAF uses Damage Tolerance Assessment (DTA) to manage the structural integrity of aircraft and the US Navy uses the Safe-Life approach. DTA requires time-phased inspections to detect damage before it can grow to a critical size. New concepts in maintenance include Condition-based Maintenance (CBM). CBM will require the detection and characterization of flaws in aircraft [1] to identify when maintenance is required. This approach intends to minimize the number of inspections and the associated disassembly and reassembly of aircraft required for these inspections. In the last several years, research efforts at AFRL developed capabilities to detect cracks in locations with very limited access. Other efforts are focusing on providing the science base necessary to achieve CBM.

A strategy to produce the science base necessary to achieve progress on aging aircraft

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maintenance problems is presented in Figure 1. Specific areas of research include the following:

- Forward model development for electromagnetic and ultrasonic methods
- Rigorous benchmark experiments for model validation and discovery
- Model-assisted probability of detection (MAPOD) methods for NDE validation
- Model-based inversion for damage and material characterization
- Probabilistic methods in probe design and optimization
- Probabilistic methods for economic value analysis in NDE applications

Current research and development integrates these six areas. Forward modeling research involves the development and improvement of models to accurately simulate the interaction of eddy current and ultrasonic NDE methods with relevant materials properties, damage, degradation, deformation, and failure mechanisms under laboratory or realistic conditions. Rigorous benchmark experiments address the verification and validation of the accuracy and applicability of numerical and analytical models. In addition, this facilitates the discovery of new relationships between NDE methods with different material and/or flaw states. Model-assisted probability of detection (MAPOD) research addresses the development of stochastic methods with NDE models to mitigate the high cost and improve the quality of NDE technique validation studies. Model-based inversion targets the primary objective of material and damage state characterization where model parameters associated with the material and/or damage condition are solved in an iterative fashion until agreement between the model and measured data for the sample under test is achieved. Probabilistic methods research explores how to best address uncontrolled variability and uncertainty in NDE design and optimization to improve reliability, minimize costs, and maximize availability of the fleet. Finally, probabilistic risk analysis methods are used, together with NDE capability models, cost models, and multiobjective optimization techniques, to assess the effects of technology and human factors in NDE applications on figures of merit such as maintenance cost and system reliability and availability. In this paper, three case studies are presented where computational methods were used in the discovery, design and validation of NDE techniques. In addition, a demonstration case will be presented on probabilistic risk and value analysis tools for an NDE application for optimal service life management.

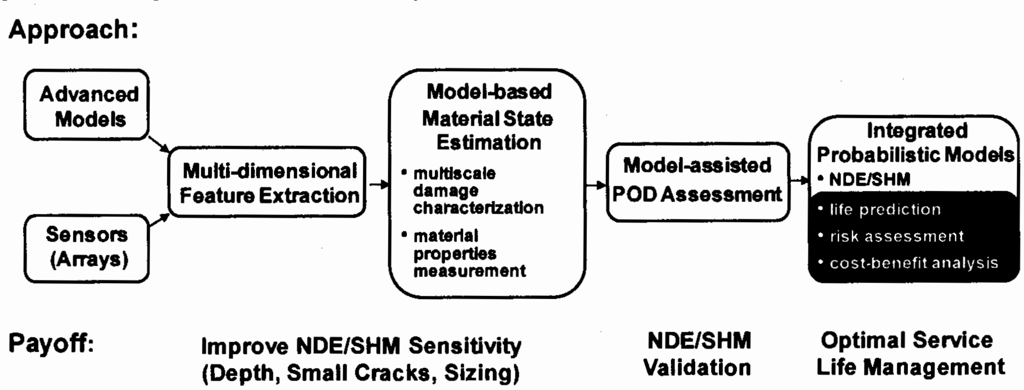

Fig 1. Strategy for Computational Methods in Nondestructive Evaluation

2. Modeling and Simulation

An NDT measurement model functions to predict the measurement response of a material under test for an NDT technique using the appropriate physics. NDT simulation is defined as the operation of the NDT model across the measurement domain of interest, for example in the time, frequency and/or spatial domains. A complete system model encompasses three major components: a source, a sample, and a receiver. The source component of the model defines the incident field in the sample through representation of the input signal, source hardware, electrical connection, source transducer, and the transducer interface condition with the sample. Given the incident field, the scattered field can be calculated by the sample component model, given the material properties, sample geometry and discontinuity (often cracks or corrosion) characteristics. Depending on the measurement technique, significant material properties can include elastic properties, electrical conductivity, magnetic permeability, dielectric permittivity, thermal conductivity, stress, and density. Sample geometry including domain size (finite or infinite) guides the selection of the appropriate model. Discontinuity characteristics include type (cracks, voids, porosity, corrosion, disbonds), geometry, and condition (such as the interface condition between crack faces). The reception component transforms the scattered field into measurement data through a relationship defined by the transducer interface condition, receiver transducer, electrical connections and data acquisition hardware. The model for each component is typically designed in order to provide the most accurate representation of a measurement technique while minimizing computational effort.

Models can produce significant benefits at several stages of the NDT technique development process (see Figure 1). First, models can be used to aid in the interpretation of raw measurement data. With this understanding, modeling can be beneficial in selecting the appropriate features of the measurement for evaluation and classification. Probe design and optimization, whether it be ultrasonic transducer characteristics or eddy current coil parameters, can greatly benefit from parametric studies using accurate measurement models. For the development of automated inspection techniques, models can augment the training data set, thus reducing sample costs. Models can also be directly incorporated into automated signal classifiers through inverse methods. During the validation process, models can be used to verify the robustness of the classification technique while again reducing sample costs. MAPOD procedures have the potential to evaluate the reliability of an NDT technique at a lower cost with respect to conventional POD studies. Concerning the transition of a new technique to a practical application, models can be quite beneficial in displaying a fundamental understanding of the inspection problem to project sponsors and helpful during the instruction of the inspectors. Lastly, NDE and structural health monitoring (SHM) reliability models are crucial, together with system probability of failure models and inspection and maintenance cost models, to achieve a capability to design and implement optimal service life management strategies for structures.

3. Case Study 1: Crack Detection in Vertical Riser Structures using UT

A significant challenge in NDE is the ability to discern signals originating from a crack and a geometric part feature when they are closely spaced or superimposed in time. An example problem is the ultrasonic inspection of aircraft holes in vertical riser structures with limited accessibility for a transducer from an external wing surface. Figure 2 shows an example of the NDE problem. Characteristics of the path of the ultrasonic signal and the contact condition between the fastener and hole can hinder the use of traditional amplitude dynamics for signal classification and crack detection [2]. To address this issue, models based on the boundary element method (BEM) were used to develop a signal processing technique called the local correlation method to detect the relative shift of signals in time for adjacent transducer locations [3].

A simulation is shown in Figure 3 for the case of a hole with a notch with an incident shear wave pulse. (Also, see Animation 1.) The hole contains an elastic insert representing the fastener in fixed contact with the hole surface. First, there is primary reflection and transmission of longitudinal and shear waves. The transmitted shear waves propagate within the elastic solid (i.e. fastener), reflect from the boundary, and then produces a second transmission back into the surrounding solid occurs. Signals due to the notch are observed when the transmitted shear signal becomes incident at the notch. Both shear and longitudinal wave scattering occurs within the elastic insert. These signals re-transmit into the elastic solid where they may be detected by transducers. Interface waves are also generated and propagate about the cylindrical hole and are the critical phenomena for this crack detection technique. Reflection of these interface waves by the notch is clearly observable. As the interface wave propagates back from the notch, circumferential shear waves are generated that can be detected by the pitch transducer. Under certain conditions, it can be difficult to separate the reradiated insert signals from the fastener with the scattered creeping wave from a crack.

To address this problem, the signal processing approach is based on the varying echo dynamics from crack and part geometries. This approach analyzes a series of signals from a moving transducer by accurately aligning the signals to the primary part signal using a correlation method and subsequently measuring the shift of secondary signals of interest within multiple time windows. This novel methodology detects the relative shift of signals in time for adjacent transducer locations resulting from differing echo dynamics from cracks and part geometries. To generally address such classes of problems, amplitude dynamic measures were supplemented with both change in time measures and signal variation measures to generate robust signal classification methods. This approach was successfully implemented to assist in the analysis of data for a very complex aerospace component and the technique was validated via a probability of detection study [4].

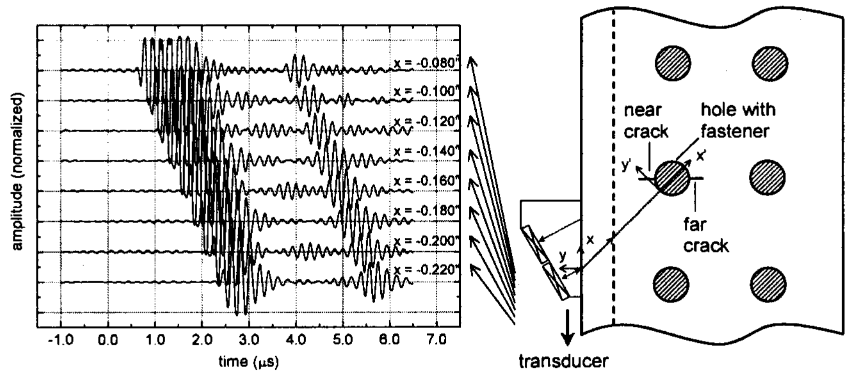

Fig. 2. Diagram of inspection problem and associated plot of a series of experimental pulse-echo signals from a moving transducer (far crack case presented in plot.)

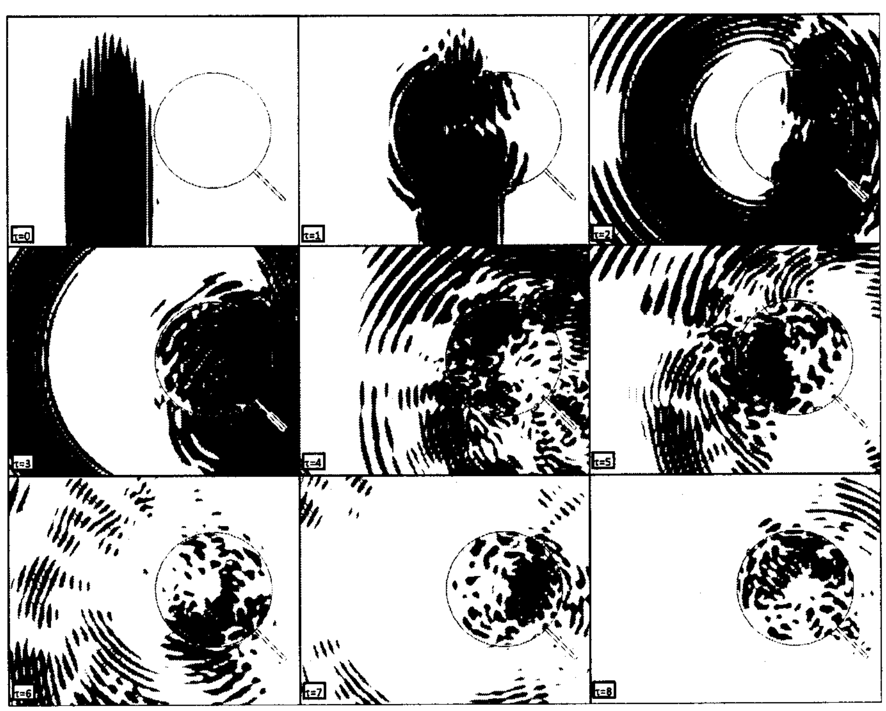

Fig. 3. Contour plots of the total displacement field generated by an incident in-plane shear pulse on a 3/16" diameter rib clip hole with a 0.070" notch and containing an aluminum insert – elastic contact between insert and hole (smooth contact) - for nine time steps, τ = 0,1,2,3,4,5,6,7,8. (Movie: http://www.jsm.or.jp/ejam/Vol.1.No.4/AA/Fig.3.html)

4. Case Study 2: 3D Spiral Creeping Wave Discovery

Another general problem for the USAF is the inspection of fastener sites in multilayer horizontal joints in aircraft structures. For some cases such as the one shown in Figure 4, 360 degree coverage is necessary. To achieve 360 degree coverage without mechanically rotating the transducer around the hole, the concept of generating and detecting "spiral" creeping waves at a fastener site was investigated. Both analytical and 2D BEM models have been developed to approximate the behavior of spiral creeping waves as they propagate around a cylindrical hole [5], but 3D models are essential to fully study this complex ultrasonic scattering problem when fatigue cracks are present [6].

Figure 2 presents the transient finite element response of an ultrasonic wave scattering around a fastener site with a radial notch (in the shadow region of the hole) in 3D. (Also, see Animation 2.) Three select times-of-flight are displayed: (a) the main shear wave incident at the hole surface, (b) the propagating spiral creeping wave reflecting from the hole bottom edge and (c) the reflected spiral creeping wave propagating upward from the far surface. Of particular interest, in Figure 2 (a), the incident shear wave on the hole surface not only simulates the specular reflection from the hole but as generates a surface wave that both propagates around and leaks away from the hole. As shown here, numerical methods such as the finite element method can accurately represent the complex scattering and propagation of ultrasonic waves at 3D geometries. The insight from this model has provided a greater understanding of both the potential benefits and inherent limitations of the technique. Further modeling studies are under investigation to optimize incident angle, transducer location, and transducer focusing for subsurface crack detection applications.

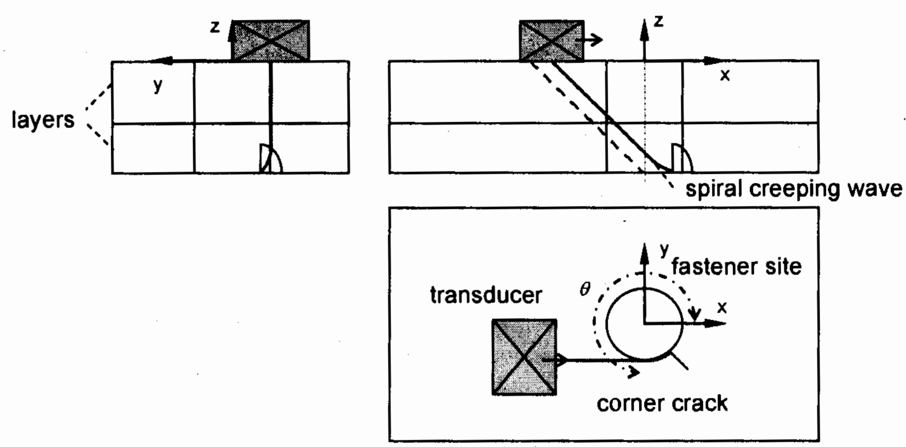

Fig. 4. Schematic diagram of the ultrasonic inspection of fastener sites for corner cracks in multilayer structures using spiral creeping waves to detect cracks in the shadow region of the hole.

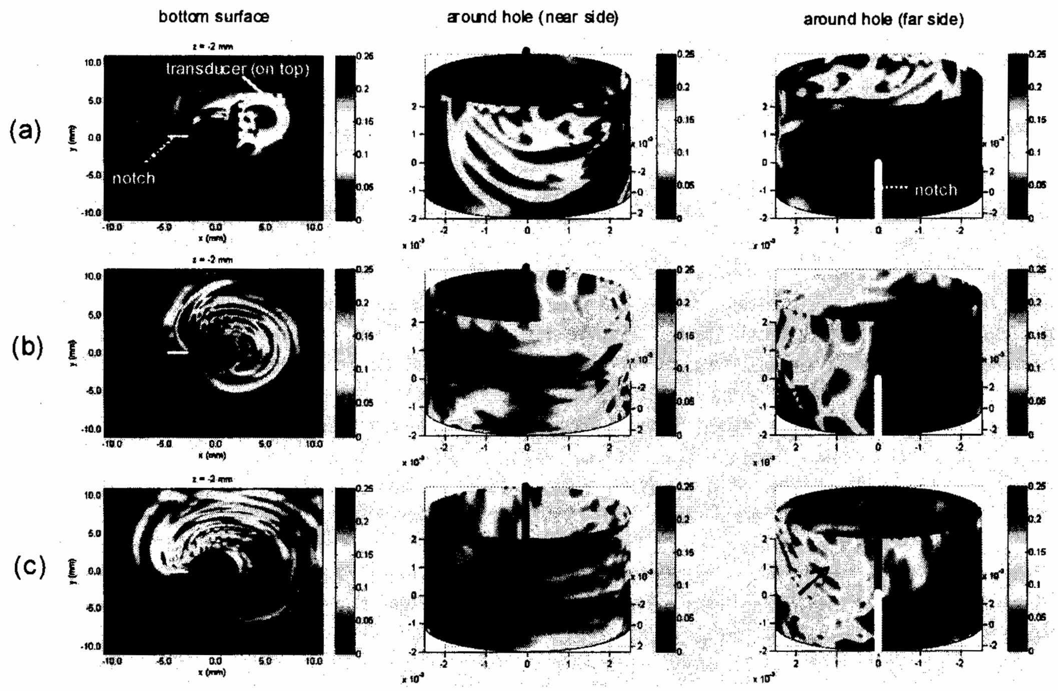

Fig. 5. Simulated response of ultrasonic wave scattering around a hole with a notch in 3D from several views (left column: bottom surface; center and right column; hole surface) and at select times (a) main shear wave incident at hole, (b) spiral creeping wave reflecting from hole bottom edge and (c) spiral creeping wave propagating upward with corner surface wave at scattering at notch. (Movie: http://www.jsm.or.jp/ejam/Vol.1.No.4/AA/Fig.5.html)

5. Case Study 3: Model-Assisted Probability of Detection (MAPOD) via Eddy Current NDE

Probability of detection (POD) studies are used to evaluate the reliability of detecting cracks across a distribution of sizes. Recently the USAF standard for conducting POD studies was revised to incorporate modern statistical techniques [7]-[8]. Software using the R statistical language has been developed to calculate POD [9]. Due to the cost of manufacturing the number of samples required for a traditional study, empirical POD evaluation is often prohibitive. A new strategy for the design and execution of POD studies has been proposed using a model-assisted POD (MAPOD) approach [10]. Demonstration studies have been presented for a class of aerospace structural inspection problems and consider the use of models in the POD evaluation [11]. Eddy current measurements for varying crack length around fastener holes in a two-layer aluminum structure were studied using both experimental and simulated data. General agreement was achieved between experimental and full-model assisted (FMA) results for cracks located at both the first and second layers. However, sensitivity of the POD results was found to be dependent upon the NDE technique design and assumptions used in the model-assisted POD analysis. Parametric sensitivity studies were performed exploring the role of crack feature measures in the image data, model design, the model fit with experimental data and the presence of coherent noise in measurement data on the full-model assisted evaluation. Key insight is presented for improving the quality of future MAPOD evaluation studies. Future work will address uncertainty analysis in MAPOD evaluation, in particular using mixed (experimental and simulated) data sets, and ascertain the precise aspect ratio of the grown cracks [11]. Future work is also planned to explore applying model-assisted probabilistic reliability assessment methods to validate structural health monitoring systems, which will be critical for justifying the value of SHM systems for USAF fleet service life management [12].

6. Model-based Inversion and Estimation Theoretic Metrics

Significant advances have been made by the research community on inverse problems in NDE. However, transitions of this research to practical applications have been limited in part due to poor representation or uncertainty of the critical parameters in the forward model and sensitivity of the inverse method performance to noise and test sample variations. First, there is a need in the development and validation of an inverse method for an NDE inspection problem to demonstrate capability using quantitative performance metrics. An overview of metrics has recently been presented addressing the condition of the ill-posed problem, the quality of feature extraction algorithms, and performance of inversion algorithms. In particular, the relationship between metrics found in estimation theory, linear algebra and statistics are presented including Fisher Information, covariance, and Cramer-Rao-Lower-Bound (CRLB). These performance metrics can be used to quantify sensitivity, multi-collinearity, noise invariance, and the general robustness of inversion. Optimization of system parameters using singular value decomposition was compared with the optimal parameters selected by the inversion metrics. The connections and utility of these metrics were illustrated through a series of basic examples of estimating material loss (thickness), conductivity, and liftoff [13]. Another key objective for model-based inverse methods is demonstrating its robustness to the vast array of inspection variables and specimen conditions present for a typical NDE inspection problem. A process for validating inversion sensitivity was developed and applied to a case study problem pit characterization to quantify the impact of potential sources for variation on the performance of NDE procedures [14]-[15]. In particular, the impact of changes to the NDE model, the inversion algorithm design, and experiment conditions are explored with respect to the quality of the inversion results. The long-term goals of this work are to initiate development of a framework for inverse method reliability assessment and demonstrate its practical value to the larger NDE community .

7. Models for Probabilistic Risk Assessment and Economic Service Life Management

The aircraft fleet management problem involves unavoidable tradeoffs between aircraft availability, reliability, and total ownership cost goals. It is often impossible to change one of these variables without affecting one or both of the other two. The success of maintenance approaches currently including NDE and of those expected to complementarily use NDE and SHM in the future depends on the ability to evaluate and establish the optimal tradeoffs between these factors. Value analysis tools including probabilistic risk assessment, cost-benefit analysis and multicriteria optimization can provide the framework for this evaluation. The remainder of this section briefly describes a software approach for applying such tools for (a) evaluating the effects of human factors on the cost and reliability effects of an NDE application, and (b) studying the effects of varying the mean detectable flaw size of a damage-detection SHM system and a secondary NDE system so that an optimal maintenance program can be achieved.

Details of the methodology and software can be found in [16] and the references therein. The general class of problem discussed here is the inspection of fatigue cracks at fastener sites in multilayer aircraft wing structures as found in such aircraft as the C-130 [17]. The life of the component is divided into a number of service intervals separated by inspection and repair events. Precise data on specific cases for the equivalent initial flaw size distribution, the flaw growth model, the POD capability, and cost were difficult to obtain, and therefore values were set based upon a combination of information acquired from maintenance personnel and values cited in the literature for related aircraft components. The POD model for these demonstrations consists of four parameters: a_{50} is the median detectable flaw size, σ controls the slope of the POD curve, FC is the false call rate, and RMC is the rate of random missed flaws.

The first hypothetical maintenance study was performed by varying each of the four POD model parameters between two levels: a baseline and a degraded performance level. Three service intervals with two inspection and repair events were considered, and the same POD model was used for both inspections. The probability of failure (POF) model included both probability of fracture and probability of a crack growing to a critical size of 19.05 mm (0.75 in). The results from the parametric study are displayed as a function of total life-cycle cost and maximum probability of failure in Figure 6.

Degraded performance associated with the experience level of the NDE technician, modeled as an increase in median detectable flaw size, resulted in a higher POF and lower total cost. A reduction in the slope of the POD curve, associated with differences in operator skill and experience, resulted in very small increases in POF and total cost. An increase of 1% in the false call rate, associated with degraded concentration and over-sensitivity to noise, increased the total cost and had little impact on POF. Lastly, an increase in the percentage of random missed calls by 10%, associated with a lack of integrity, poor focus, or a bias concerning the expected frequency of detected cracks, was found to significantly increase the probability of failure with a slight decrease in total cost. Interesting results were also obtained by studying the relative sensitivities of the total cost and POF with respect to varying changes in the POD parameters. It is also important to note that the changes observed should not be construed as absolute trends, but rather they depend on the particular inputs given to the model.

The second hypothetical study explores variations in the detectable flaw size for both an SHM system and a secondary NDE inspection technique. Specifically, the 50% detectable flaw size for the SHM and NDE inspection models were both varied from 0.51 mm (0.02 in) to 2.54 mm (0.10 in) as a full-factorial study. Figure 7 shows the design solution space resulting from the study in terms of maximum probability of failure and total cost, and allows the user to select the Pareto solutions providing the desired optimal tradeoff between the two objectives. Moreover, for this case it is possible to select from this reduced solution set a design that minimizes cost while maintaining an acceptable probability of failure, typically set at 10^{-6}. Using these criteria, the optimal SHM system 50% detectable flaw size was found to be 1.52 mm (0.06 in), with the secondary NDE system 50% detectable flaw size set to any value greater than 1.27 mm (0.05 in).

While simplified in nature, these examples show the capability of the method and software to facilitate analysis of sensitivities and tradeoffs of the various factors involved in designing and implementing NDE and SHM technologies as part of system life cycle management. Finally, it is important to recognize the need for improved data to enable successful application of these powerful methods to optimal economic service life management strategies.

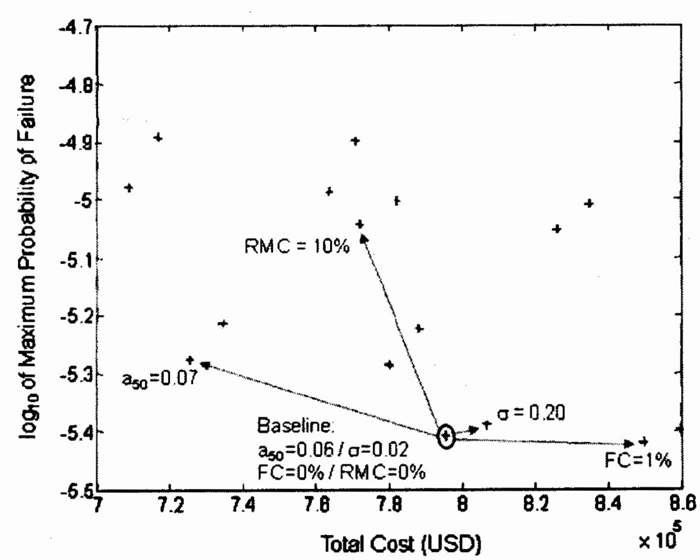

Fig. 6. Effects of varying each of the four POD parameters on the total cost and maximum probability of failure, showing with vectors the main trends with respect to the baseline case.

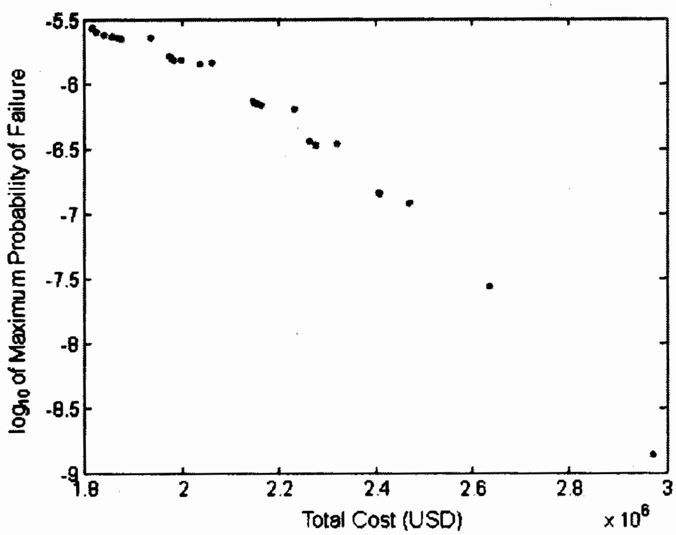

Fig. 7. Design solution space for varying SHM and secondary NDE sensitivity in terms of maximum probability of failure and total cost.

8. Conclusion

Advances in computational methods for NDE are now having an impact on maintenance in many industries. Two case studies of crack detection problems using ultrasonic NDE and one case study using eddy current NDE were presented. For these examples, modeling played a significant role in the development and validation of the inspection techniques. MAPOD and model-based inversion schemes were also discussed and these concepts will surely have a greater impact on maintenance in the future once rigorous demonstrations are fully achieved. Finally, a probabilistic model was introduced to assess the impact of NDE and SHM POD capability on maintenance cost and in-service risk. This is a tool that brings everything together and can be used to manage the risk and maintenance of assets, and also provide guidance in the development of NDE or health monitoring systems.

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References

[1] E.A. Lindgren, J.S. Knopp, J.C. Aldrin, G.J. Steffes, and C.F. Buynak, Aging aircraft NDE: capabilities, challenges, and opportunities, Review of Progress in Quantitative Nondestructive Evaluation: 26B (2007), 1731-1738.

[2] J.C. Aldrin, C.V. Kropas-Hughes, J.S Knopp, J. Mandeville, D. Judd, E. Lindgren, Advanced echo-dynamic measures for the characterization of multiple ultrasonic signals in aircraft structures. Insight 48 (2006), 144–148.

[3] J. C. Aldrin, and J. D., Achenbach, Model and methodology for crack detection on a cylindrical hole containing an elastic insert, Review of Progress in Quantitative Nondestructive Evaluation: 21, (2002), 181-188.

[4] E. Lindgren, et al., "Probability of detection results and deployment of the inspection of the vertical leg of the C-130 center wing beam/spar cap", Aging Aircraft Conf., Palm Springs, California, Jan 31 – Feb. 3, 2005.

[5] J.C. Aldrin, J.R. Mandeville, D. Judd, J.R. Mandeville, and E. Lindgren, Spiral creeping waves in

ultrasonic angled-beam shear wave inspection of fastener holes in multilayer structures, Review of Progress in Quantitative Nondestructive Evaluation: 25A (2006), 187-194.

[6] J.C. Aldrin, and J.S. Knopp, Modeling and Simulation for Nondestructive Testing with Applications to Aerospace Structures, Materials Evaluation: 66 (2008), 53-59.

[7] C. Annis and J. S. Knopp, Comparing the Effectiveness of a90/95 Calculations, Review of Progress in Quantitative Nondestructive Evaluation 26B (2007), 1767-1774.

[8] MIL-HDBK-1823A, Nondestructive Evaluation System Reliability Assessment (2009): https://assist.daps.dla.mil/quicksearch/basic_profile.cfm?ident_number=206122.

[9] C. Annis, (2009). web site: http://www.statisticalengineering.com/.

[10] R.B. Thompson, A unified approach to the model-assisted determination of probability of detection, Materials Evaluation: 66 (2008), 667-673.

[11] J.C. Aldrin, J.S. Knopp, E. Lindgren, H.A. Sabbagh, E.H. Sabbagh, and R.K. Murphy, Model-assisted evaluation of the reliability of an eddy current nondestructive evaluation technique, 25th Annual Review of Progress in Applied Computational Electromagnetics (2009), 598-605.

[12] J.C. Aldrin, E.A. Medina, E.A. Lindgren, C.F. Buynak, G. Steffes, M. Derriso, Model-assisted probabilistic reliability assessment for structural health monitoring systems, Review of Progress in QNDE: 29, (submitted for publication, 2010).

[13] J.S. Knopp, J.C. Aldrin, H.A. Sabbagh, and K.V. Jata., Estimation theory metrics in electromagnetic NDE, Electromagnetic Nondestructive Evaluation Workshop Proceedings, 12, (2009), 321-328.

[14] H.A. Sabbagh, R.K. Murphy, E.H. Sabbagh, J.C. Aldrin, Application of model-based inversion to eddy-current NDE of heat-exchanger tubing, Materials Evaluation: 66 (2008) 764-774.

[15] J.C. Aldrin, H.A. Sabbagh, R.K. Murphy, E.H. Sabbagh, and J.S. Knopp, Sensitivity analysis of inverse methods in eddy current pit characterization, Review of Progress in Quantitative Nondestructive Evaluation: 29, (submitted for publication, 2010).

[16] E.A. Medina, J.C. Aldrin, Value assessment approaches for structural life management through SHM, in: Encyclopedia of Structural Health Monitoring, C. Boller, F-K Chang, and Y. Fujino (Editors), John Wiley & Sons, 2009

[17] E. Lindgren et al, Validation and deployment of automated ultrasonic inspections for the C-130 center wing, ASIP Conference, Savannah, GA, USA, 2–4 December 2004.