Demonstration of Model-Assisted Probability of Detection Methods – A White Paper

This document has been prepared by the
Model Assisted POD (MAPOD) Working Group in consultation with its sponsors.

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Table of Contents

1. Definition of Model Assisted POD 1
2. Objectives 1
3. Approach 2
4. Factors Affecting Inspection Reliability 2
    4.1. Equipment Characterization (probe, instrument, etc.) 2
    4.2. System Calibration 3
    4.3. Human Factors 3
5. Test Protocols 3
    5.1. Model Validation 3
    5.2. XFN Validation 4
6. Design 4
    6.1. Experiment Design 4
    6.2. Specimen Design 5
    6.3. Inspection Artifacts: Cracks and Notches 5
7. Evaluation 6
    7.1. Evaluation of MAPOD Methods 6
8. Work Breakdown Structure 7
    8.1. Task 1 - Project Management 7
        8.1.1. Task 1.1 – Kickoff Meeting and Protocol Development 7
    8.2. Task 2 – Target Specimen Selection and Definition 7
    8.3. Task 3 – Inspection Technique Definition 7
    8.4. Task 4 – Experiment Design 8
    8.5. Task 5 – Specimen Manufacture 8
    8.6. Task 6 – Model Development and Validation 8
    8.7. Task 7 – Inspections of Specimens 8
    8.8. Task 8 – XFN Predictions of POD, Sensitivity Analyses 8
    8.9. Task 9 – FMA Predictions of POD, Sensitivity Analyses 9
    8.10. Task 10 - Factor Sensitivity Study 9
    8.11. Task 11 – Evaluation 9
    8.12. Task 12 - Reporting 9
9. Schedule and Cost Estimates 10
        9.1.1. Probe/Transducer Characterization 2

Introduction

The United States Air Force fleet is maintained by the Aircraft Structural Integrity Program, the Engine Structural Integrity Program, and analogs for other systems and components. Within these programs, nondestructive testing (NDT) is required in many cases to preserve safety of critical components. The performance of NDT is characterized by the probability of detection (POD) of the discontinuity of interest, as a function of the discontinuity size. The POD, whether characterized by a single number (usually the 95% confidence bound on the 90%POD size, the so called "90/95" size) or the entire POD function, is used to determine the required inspection scheduling.

A wave of new inspection requirements is anticipated in the coming years, accompanied by an increase in the number of candidate inspection techniques available to meet those requirements. Qualification of these techniques would require a rapidly increasing number of POD studies. However, the empirical nature of those studies, as currently defined in MIL-HDBK-1823, makes them very costly in terms of both time and dollars. Hence an alternate approach is sorely needed.

With financial support provided by the Air Force Research Laboratory NDE Branch, the FAA Technical Center, and the NASA NDE Branch, a meeting was organized by NTIAC to plan for the formation of a consortium to carry out a cooperative research and development program on Computational NDE for Modeling Probability of Detection.

The outcome of the original meeting in Austin was the establishment of a Model-Assisted Probability of Detection (MAPOD) Working Group, with the joint support of the Air Force Research Laboratories, Federal Aviation Administration Hughes Research Laboratories, and NASA Langley Research Center.

The MAPOD approach is based on the idea that insight from physics-based models can be incorporated into the POD determination process in a way that will reduce the number of empirical tests that need to be conducted and hence reduce the cost and increase the speed of the process.

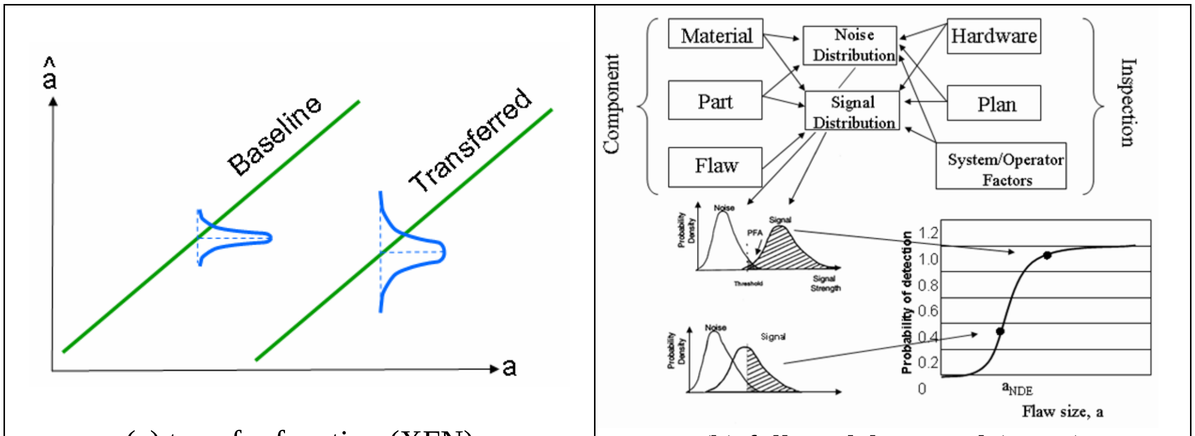
This document describes the study to be performed to validate the methods proposed by the MAPOD Working Group. This study must encompass a MIL-HDBK-1823 style POD study with well characterized NDT instrumentation, model validation, specimen development to support transfer function methods, and a final evaluation phase with criteria developed by the MAPOD Working Group and stakeholders.

1. Definition of Model Assisted POD

Figure 1 illustrates two variations of the MAPOD approach: the transfer function approach (hereafter labeled XFN) and the full model assisted POD approach (hereafter labeled FMA).

XFN is illustrated in part (a), and is based on using empirical data and/or models to help transfer POD data obtained in one set of experiments under a particular set of conditions to another situation in which one or more of those conditions have changed.

FMA is illustrated in part (b), and is based on using models intimately from the beginning, designing a minimum set of experiments to tie down parameters not controlled by well understood physical phenomena and using models to study variations that can be understood in terms of known physics.



(a) transfer function (XFN)

(b) full model assisted (FMA)

Figure 1. Graphical illustrations of two methods for model assisted POD estimation.

2. Objectives

The objectives of the work described in this white paper are to:

- evaluate feasibility and limitations of using MAPOD for transferring POD from one geometry to another in generic multilayer fastened structures
- evaluate feasibility and limitations of using MAPOD for transferring POD from notched samples to actual cracked multilayer fastened structures
- evaluate feasibility and limitations of using MAPOD for transferring POD from laboratory to depot and field inspection of multilayer fastened structures
- evaluate sample size requirements for MAPOD studies
- evaluate the potential for providing additional inspection performance information such as ROC curves and crack size quantification from MAPOD
- evaluate the feasibility and limitations of using the FMA approach to MAPOD in the problem areas listed above
- evaluate cost/benefit of MAPOD for POD estimation

3. Approach

The approach which will be used to meet the objectives is based on the following:

- teaming of experts including modeling, reliability, instrumentation, & users
- selection of a specific multilayer inspection problem based on biggest requirement (ROI), cross-platform commonality
- providing useful demonstration example(s) for expanding scope of MIL-HDBK-1823 to support MAPOD approaches
- rigorous design of experiments (DOE) approach
- transfer function emphasis
- physics-based model validation
- both eddy current and ultrasonic inspection techniques to be demonstrated
- progress to be monitored by an advisory committee convened by the sponsors

The short-term emphasis of the program is to demonstrate the applicability of the transfer function methods that are already in use by many organizations. XFN methods need to be validated and documented in order to achieve the acceptance of the existing MIL-HDBK-1823 methods.

This project will also provide the opportunity for the demonstration of the FMA methods. Detailed characterization of the inspection equipment and specimens will provide the data necessary to for “benchmark” problems for models of NDT. This data will allow the validation and documentation of FMA methods, at the level required to achieve broad acceptance of FMA as an additional possible approach to POD estimation.

Section 4 immediately following is a detailed description of the many factors that may affect inspection reliability. Section 8 is a high level Work Breakdown Structure, describing the program required to implement the above approach.

4. Factors Affecting Inspection Reliability

The MAPOD group has identified a number of factors that are believed important with respect to inspection reliability. These factors will be investigated as part of the program described in this document. A brief description of the factors is provided in the following.

4.1. Equipment Characterization (probe, instrument, etc.)

It is recognized that for success of MAPOD methods, and more generally for control of NDE processes, the performance of the NDE equipment must be characterized. Nominal values provided by equipment manufacturers are generally not sufficiently accurate for use in model validation or model predictions.

The exact methods of characterization will depend on NDE technique. For the purposes of this project, an Equipment Characterization Protocol will be developed for ET and UT systems. This protocol will encompass probe, cable, and instrument performance parameters that affect the NDE signal.

4.2. System Calibration

Once the physical equipment associated with the NDE system is characterized, a rigorous calibration procedure will also be implemented to ensure repeatability and reproducibility of the NDE system outputs. MAPOD methods require quantitative NDE, not simply hit/miss outputs. The calibration process for a measurement system that is linear over the region of desired response is described in detail in the NIST/SEMATECH e-Handbook of Statistical Methods, and is excerpted below:

> "Instrument calibration is intended to eliminate or reduce bias in an instrument's readings over a range for all continuous values. For this purpose, reference standards with known values for selected points covering the range of interest are measured with the instrument in question. Then a functional relationship is established between the values of the standards and the corresponding measurements."
>
> "For linear calibration, it is sufficient to control the end-points and the middle of the calibration interval to ensure that the instrument does not drift out of calibration. Therefore, check standards are required at three points; namely,
> at the lower-end of the regime
> at the mid-range of the regime
> at the upper-end of the regime."

Note that for the purposes of this document, the regime of interest is crack sizes.

For this program, a NDE System Calibration Protocol will be developed and documented based on a three point calibration as described above. This is a fundamental requirement to ensure that the data collected during this study is of sufficient quality and traceability to use to demonstrate the MAPOD methods.

4.3. Human Factors

- what and how are we going to study?
    - varying levels of automation
    - inspector populations
        - training, age, favourite football team, etc.
    - field, depot, lab?
    -

5. Test Protocols

5.1. Model Validation

The validation of the models of NDE is a key outcome of this program. The physical specimens and NDE data generated in this program will provide a benchmark problem for NDE models that will have value much beyond the life of this short program.

As part of the model validation, factors related to NDE system performance must be identified, and it also must be identified which factors are included and which factors are not included in the model. The uncertainties in the inputs to the model as well as in the NDE system measurements used for validation must be characterized. Sensitivity analyses should be used to assess model sensitivities to these uncertainties and to factors not modeled. Finally, the target requirements for model performance in order to achieve reasonable POD estimation must be known.

For this program, a Model Validation Protocol will be developed and documented to ensure the data captured will be sufficient to support validation, and to ensure the validation steps are clear, consistent, and repeatable to allow the outputs of the MAPOD Demonstration Program to be used now and in the future to support the development and validation of improved NDE models.

5.2. XFN Validation

As with the validation of NDE models described above, the validation of the XFN methods of POD estimation is a key outcome of this program. The XFN approach is conceptually simpler than the FMA approach, but still must be validated in a rigorous manner. The XFN validation in this program will be analogous to the validation of the FMA approach.

One of the questions that must be answered is the range of validity of the XFN method. As illustrated in Figure 1, XFN methods should provide the ability to modify the relationship of NDE system output to discontinuity size, and also to modify the variability of NDE system output if required. To define this range of validity, the factors related to NDE system performance must be identified, and it also must be identified which factors are included and which factors are not included in the XFN method. The uncertainties in the inputs as well as in the NDE system measurements used for validation must be characterized. Sensitivity analyses should be used to assess the XFN sensitivities to these uncertainties and to factors not modeled.

For this program, a XFN Validation Protocol will be developed and documented to ensure the data captured will be sufficient to support validation, and to ensure the validation steps are clear, consistent, and repeatable. This protocol will enable the assessment of the XFN range of validity which is a key outcome.

6. Design

6.1. Experiment Design

Appropriate experimental designs must be in place to achieve the objectives of this program. The generic types of specimens, the variable factors included in their design, their numbers, and other similar parameters will be chosen based upon the desired program outputs. There are three specific objectives identified by the program sponsors as being of interest:

- evaluate feasibility and limitations of using MAPOD for transferring POD from one geometry to another in generic multilayer fastened structures
- evaluate feasibility and limitations of using MAPOD for transferring POD from notched samples to actual cracked multilayer fastened structures
- evaluate feasibility and limitations of using MAPOD for transferring POD from laboratory to depot and field inspection of multilayer fastened structures

The required specimen sets to achieve these three objectives will be defined, and reviewed for redundancy.

For this program, an Experiment Design Document will be developed and reviewed by the advisory committee early in the process.

6.2. Specimen Design

The physical characteristics of the specimens will be largely defined by the actual article that is chosen as the study target: for example, cracks in the fastener holes in the rainbow fitting from the C-130. The main physical specimen variables are:

- material
    - vintage, heat treat, product form, directionality, em properties, coatings/sealants, age of assembly, etc.
- machining
    - tolerances, surface finish, residual stress, hole condition, similarity to original, etc.
- sample assembly method

For this program, a Specimen Manufacture Protocol will be developed and documented to ensure the manufacture of specimens will be performed in a consistent, known fashion; and to ensure that any deviation in manufacturing processes from the target application are documented and understood.

The generation of fatigue cracks in specimens is also a very important issue. This is addressed in the next section.

6.3. Inspection Artifacts: Cracks and Notches

There are at least three categories of cracks or crack-like features used in POD studies:

1. articles removed from service containing fatigue cracks induced in service
2. cracks grown in laboratory using load frames, in representative structure and material
3. EDM notches placed in representative structure and material

Category 1 is the most desirable, but usually not available in quantities associated with POD studies. Category 2 is the next most desirable, but can be very expensive depending on the part of interest. Category 3 is easiest, and the ability to perform studies on category 3 samples and use the XFN method to estimate POD on the actual part in service is a key outcome of this program.

It is obvious that there will be differences in NDE system response, whether ET or UT, between a notch and a fatigue crack. What is less obvious is the difference in response between the category 2 and category 1 cracks as defined above, and just as important the difference in the variability in response.

It is well known that crack closure affects detectability for both ET and UT inspection techniques. Crack closure is a function of residual stresses (due to manufacturing) as well as loading. It is believed that crack opening and bridging effect across crack faces (both mechanical and electrical) are the key contributions to the difference from notches and the variability within crack populations. Crack orientation is also very important, and is again a function of the applied loading.

Within this program, it will be critical to understand how fatigue cracks are created in fielded structure or constructed specimens, and to measure the variabilities associated with these populations and the differences between crack populations and EDM artifacts.

Characterization of the cracked specimens without destructive inspection is a desirable feature. This may be possible via x-ray computed tomography, or by performing replica or "reverse penetrant" on specimens under load to open cracks. In any case, some destructive tests must be performed to validate any nondestructive characterization.

For this program, a Crack and Notch Manufacture Protocol will be developed and documented to ensure the manufacture of cracks and notches will be performed in a consistent, known fashion; and to ensure that any deviation from the loading parameters experienced by the target application are documented and understood. Characterization methods will also be documented in the protocol.

7. Evaluation

7.1. Evaluation of MAPOD Methods

The final aspect of this program is the evaluation of the performance of the MAPOD methods in terms of their ability to estimate POD, and also in terms of their ability to provide a reduced cost in comparison to the standard methods of POD estimation as outlined in MIL-HDBK-1823.

The fundamental comparison will be made against the results of a complete empirical study, as per MIL-HDBK-1823, that will be performed within this program. Both the NDE system response to cracks and the resulting POD will be evaluated.

The evaluation will also dig deeper to determine:

- within what limit/confidence
    - can FMA/XFN methods accommodate key factors
    - can FMA/XFN methods accommodate complicating issues
        - for example, via the addition of empirical corrections from specialized experiments.

These issues will be evaluated for the realistic conditions obtained by the use of service-retired specimens with in-service induced fatigue cracks.

For this program, an Evaluation Protocol will be developed and documented to ensure the evaluation of MAPOD methods will be performed in a consistent, known fashion.

8. Work Breakdown Structure

The tasks proposed to meet the above objectives are detailed in the following.

8.1. Task 1 - Project Management

There are unique aspects to the project management requirements of the work described in this white paper. Because of the broad nature of this subject, the potential impact on DoD and civil aviation, and existing funded programs addressing related issues; this work must be performed by a group of organizations who can bring the required skills and background to bear.

An advisory group will be formed, composed of program sponsors and program participants including a representation from the organizations that have supported the development of MAPOD. This advisory group will meet at least three times during the course of this work, once for a Kickoff Meeting, once for a Design of Experiments Review Meeting, and once for an Analysis Review Meeting. Periodic telecons in addition to meetings will be scheduled to ensure project performance is on target.

This group will ensure that the detailed project plans will satisfy the objectives of the program sponsors. The involvement of this group will also facilitate the acceptance of the MAPOD approach by the larger aerospace community.

8.1.1. Task 1.1 – Kickoff Meeting and Protocol Development

One of the key outcomes of the kickoff meeting will be the final documentation of the protocols and other associated documents described in this report. These documents have been, and continue to be assembled by the MAPOD Group, although on a volunteer basis. These documents will be given their final review at the kickoff meeting, and completed at the onset of the program.

8.2. Task 2 – Target Specimen Selection and Definition

A target specimen must be selected by the program sponsors. The parameters of interest for this specimen must be determined in detail. These include materials parameters, manufacturing processes, and loads in service. Naturally occurring cracks from in-service components should be obtained.

8.3. Task 3 – Inspection Technique Definition

- define inspection techniques, calibration methods to be used

8.4. Task 4 – Experiment Design

Based on the protocols developed by the MAPOD WG, the experiments required to achieve the program objectives:

- evaluate feasibility and limitations of using MAPOD for transferring POD from one geometry to another in generic multilayer fastened structures
- evaluate feasibility and limitations of using MAPOD for transferring POD from notched samples to actual cracked multilayer fastened structures
- evaluate feasibility and limitations of using MAPOD for transferring POD from laboratory to depot and field inspection of multilayer fastened structures

will be defined.

1. assess approach for study of each important controlling factor
    1. some factors will be studied using both empirical and simulated studies to support validation purposes
    2. some factors will only require 'empirical' or 'simulated' studies when one approach is more appropriate (cost, quality of data)
2. define specimen and testing requirements

8.5. Task 5 – Specimen Manufacture

Based on the outcome of the Experiment Design task described above, the required numbers and sizes of Category 2 (laboratory grown cracks) and Category 3 (EDM notch) specimens will be manufactured representative of the target specimen.

Category 2 (laboratory grown cracks) and Category 3 (EDM notch) specimens will be manufactured in coupons of simplified geometry, in all other aspects representative of the target specimen, in the required numbers and sizes.

8.6. Task 6 – Model Development and Validation

8.7. Task 7 – Inspections of Specimens

- characterize equipment, inspector population
- inspect specimens to have sufficient data to do:
    - 1823 on Category 1,2,3 specimen sets
    - some factor sensitivity studies

8.8. Task 8 – XFN Predictions of POD, Sensitivity Analyses

- using defined XFN approach, so no fudging
- exercise XFN on various sets of data to show
    - notch vs lab crack vs crack
    - geometry
    - lab vs depot vs field

8.9. Task 9 – FMA Predictions of POD, Sensitivity Analyses

- third party to use models delivered by vendors? may not be possible for developmental programs
- exercise models to predict POD for the Category 1,2,3 specimen sets

8.10. Task 10 - Factor Sensitivity Study

One of the key benefits of the MAPOD approaches is the reuse of data. The DOE techniques of the previous tasks will allow the estimation of the relative contributions of a number of potential factors to variability in inspector performance. The ability of XFN and FMA approaches to address these factors will also be evaluated. This data can then be used to optimize future studies: expensive experiments can be used to evaluate the factors that are most significant and least amenable to XFN of FMA.

In addition, understanding the sources of variability and their magnitudes allows a statistical determination of sample sizes and associated confidence bounds required to achieve desired fidelity in the final POD estimates.

The work items in this task are:

- Evaluate significance of factors using data from Tasks 2 to 4 (statistical analyses)
  - factors and first order interactions
- Evaluate sample sizes required to support XFN, FMA
- Evaluate confidence bound methods for XFN, FMA

8.11. Task 11 – Evaluation

- evaluate modeling capabilities for the significant factors
- validation of transfer functions
- demonstrate and evaluate quality of full model assisted POD assessment

8.12. Task 12 - Reporting

The final report will provide a quantitative assessment of the MAPOD methods in terms of their performance in POD estimation and their relative cost. This will be performed according to the Evaluation Protocol document developed at the program onset.

In addition, complete documentation and databases will be provided to the sponsor to provide for the maximum benefit and reuse of the data and outcomes of this program.

9. Schedule and Cost Estimates

A proposed schedule for the work is shown in the form of a Gantt chart in the figure below.

*** to do

A functional task list including possible task leaders and ROM level of effort is provided in the following table.

*** to do

Annex A – Equipment Characterization Protocol

(ISU, Gray, Patton, Broz, EWI, Rummel)
- probe
- geometry, impedance
- cables
- impedance analyzer
- instrument

PROBE CHARACTERIZATION

1. Geometry

Spot, sliding, pencil, ring, external, internal, others

Coil and core dimensions and juxtaposition

Number of turns

Copper wire diameter

Strand factor

Ferrite (ferromagnetic) core

Outside case material metal or plastic

2. Electrical

Type of probe
    Parametric, transformer
    Absolute or differential (in performance and/or electrically)

Input instrument circuit (full- half-bridge, voltage or current source, other)

Connection of coils – floating or fixed ground, common point trough the shielding or separate, shielding connected to the case or not, inductive or not-inductive connection others

Resonance frequency with and without cable

Stray capacitance assessment

Cable capacitance, inductance and resistance assessment

Impedance as function of frequency with and without cable

Properties of ferrite (ferromagnetic) core field concentrator
    Initial magnetic permeability
    Coercive force
    Magnetization curve and hysteresis loop where available
    Conductivity or resistivity

3. Tools for characterization

X-ray micro-focus and high resolution CT for geometry and juxtaposition

Precision impedance analyzers for electrical measurements

Special cabling and fixtures to eliminate the effects of scanning, cables and connectors on electrical probe characterization

9.1.1. Probe/Transducer Characterization

Reliable NDE model predictions require input parameters of high fidelity. Two classes of controlling input parameters, among others, stand out as particularly important. One is the instrument transfer function and the other class involves probe/transducer characterization parameters.

An important example of the instrument transfer function is the efficiency factor for ultrasonic instrumentation, which relates the transducer response voltage to the instrument output voltage. There is an analogous instrument transfer function for eddy current instrumentation as well, which is a system-dependent complex factor that relates small probe impedance deflections to the corresponding instrument output voltage deflections. The functional role of the instrument transfer function is to establish the theory-experiment identity

$$Q^{\mathrm{EXPT}} = Q^{\mathrm{TH}} \qquad (1)$$

between the measured signal Q^{EXPT} and predicted signal Q^{TH}. As one example, Q may be thought of as a point in the complex impedance with a particular instrumental setup. It is important to note that the transfer function is a system parameter rather than an intrinsic probe parameter, and requires its determination for each given measurement setup and configuration. The determination of the instrument transfer function is also relevant to the model validation, and should be considered again in the subsequent section 4.3.

In contrast, there are probe/transducer characterization parameters that are fundamentally intrinsic to its design and construction. Let $\mathbf{p}$ denote the collection of the characterization parameters of a given probe. For the ultrasonic case of a cylindrical piston transducer, for example, $\mathbf{p}$ may be the diameter and focal length, and for a bicylindrical piston transducer, $\mathbf{p}$ may consist of the diameters and focal lengths in the two directions [1]. Or, for a simple solenoid EC coil, $\mathbf{p}$ may involve the inner diameter, outer diameter, height, and number of windings of the coil, as well as the built-in lift off. The parameter space is significantly larger for any practical EC probe [2]. Unlike the transfer function, the parameter set $\mathbf{p}$ is intrinsic to the sensor itself. Hence, once determined by, say, characterization experiments, the values of the parameters in $\mathbf{p}$ can be re-used in subsequent model validations and further applications.

Indeed, experimental characterization has been practiced for classes of ultrasonic piston transducers [1]. Fundamentally, the characterization methodology starts with designing an appropriate characterization experiment for which both experiment and model calculation are actually performed. In calculation, the parameters $\mathbf{p}$ are treated as variables, and their optimal values are determined by minimizing the error estimator of the form

$$\chi^2(\mathbf{p}) = \sum_j w_j \left| Q_j^{\mathrm{EXPT}} - Q_j^{\mathrm{TH}}(\mathbf{p}) \right|^2 \qquad (2)$$

where the index j runs over the data points obtained, and where w_j are appropriate weight factors. It should be remarked that this formula (2) implicitly assumes the existence of the transfer function. Thus, more strictly speaking, the transfer function and the parameters $\mathbf{p}$ should be simultaneously determined by the $\chi^2(\mathbf{p})$ minimization. Since the transfer function can generally depend on $\mathbf{p}$, the minimization procedure is inherently non-linear [Margetan et al., 2002]. As stated above, the $\mathbf{p}$ values thus determined are re-used in subsequent calculations, while the transfer function is not because it is specific only to the particular characterization experiment.

The EC probe characterization is fundamentally more involved. It is beyond the scope of this document to explain the origins of the complication, but briefly, there are two basic reasons, first because eddy current inspection always involve near-field interactions, and second because all practical EC probes include (ferrite) cores on which reaction fields are generated, making the probe-induced EC field configuration-dependent. This complication makes the impedance-data-based characterization impracticable, except, perhaps, for a limited class of probes where the parameter space size is somewhat constrained. See, for example, Ref. [Rao and Nakagawa, 2005] for the class of cylindrical absolute probes of a single inner ferrite core. Even in this example, the parameter space is larger than ten-dimensional, and the data inversion was performed by a neural network approach rather than the traditional error minimization. For most practical EC probe classes, the parameter space dimension is even larger, and it is therefore unlikely that similar data-based characterization is practicable. In this situation, the current ISU modeling practice calls for explicit probe internals characterization by taking cross-sectional X-ray images, from which the corresponding probe CAD model is constructed by hand [Nakagawa et al., 2000]. It is an active field of research to look for alternative EC probe characterization methods, or perhaps hybrid methods, which are more field-friendly and operationally inexpensive.

1. F. J. Margetan, R. Roberts, C.-P. Chiou and R. B. Thompson, "Determination of the effective focal characteristics of bicylindrically-focused ultrasonic transducers," in Review of Progress in Quantitative Nondestructive Evaluation, Vol. 21, eds. D. O. Thompson and D. E. Chimenti, American Institute of Physics, Melville, NY, 2002, pp. 791-798.
2. B. P. C. Rao and N. Nakagawa, "An Approach for Characterization of Eddy Current Probes," in Review of Progress in QNDE, Vol. 24, *op. cit*. 2005, pp. 455-462.
3. N. Nakagawa, T. A. Khan, and J. Gray, "Eddy Current Probe Characterization for Model Input and Validation," in Reviews of Progress in QNDE, Vol. 19, *op. cit*. 2000, pp. 473-480.

Annex B - NDE System Calibration Protocol

Once the physical equipment associated with the NDE system is characterized, a rigorous calibration procedure will also be implemented to ensure repeatability and reproducibility of the NDE system outputs. MAPOD methods require quantitative NDE, not simply hit/miss outputs. The calibration process for a measurement system that is linear over the region of desired response is described in detail in the NIST/SEMATECH e-Handbook of Statistical Methods and is excerpted below:

> "Instrument calibration is intended to eliminate or reduce bias in an instrument's readings over a range for all continuous values. For this purpose, reference standards with known values for selected points covering the range of interest are measured with the instrument in question. Then a functional relationship is established between the values of the standards and the corresponding measurements."
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> "For linear calibration, it is sufficient to control the end-points and the middle of the calibration interval to ensure that the instrument does not drift out of calibration. Therefore, check standards are required at three points; namely,
> at the lower-end of the regime
> at the mid-range of the regime
> at the upper-end of the regime."

For this program, a NDE System Calibration Protocol will be developed based on a three point calibration as described above. This is a fundamental requirement to ensure that the data collected during this study is of sufficient quality and traceability to use to demonstrate the MAPOD methods.

(Forsyth, Rummel, Goldfine, Drennen)

- machine
- drift, freq response, ...
- cabling/connectors
- impedance
- Scan plan, increments, digitization, coverage, couplant

Annex C – Model Validation Protocol

The validation of the models of NDE is a key outcome of this program. The physical specimens and NDE data generated in this program will provide a benchmark problem for NDE models that will have value much beyond the life of this short program.

As part of the model validation, factors related to NDE system performance must be identified, and it also must be identified which factors are included and which factors are not included in the model. The uncertainties in the inputs to the model as well as in the NDE system measurements used for validation must be characterized. Sensitivity analyses should be used to assess model sensitivities to these uncertainties and to factors not modeled. Finally, the target requirements for model performance in order to achieve reasonable POD estimation must be known.

For this program, a Model Validation Protocol will be developed and documented to ensure the data captured will be sufficient to support validation, and to ensure the validation steps are clear, consistent, and repeatable to allow the outputs of the MAPOD Demonstration Program to be used now and in the future to support the development and validation of improved NDE models.

(Knopp, Vukelich, ISU, Gray, Todorov)

- factor identification and statements of testable hypotheses
- Benchmark problem
- Error analysis
- Uncertainty in inputs
- Uncertainty in measurements used for validation
- Need target requirements
- Need accurate estimate of POD – this will define requirements in terms of model accuracy

PHYSICAL MODEL VALIDATION

The model validation procedure is highly dependant on the specific application

Validation should be done in well controlled laboratory conditions

All possible types of model validation may be considered as specified in “Thoughts-Protocol_Spencer Feb04-05”, MAPOD Meeting, February 2005.

List of potential essential parameters needed

List of potential essential parameters not included in the model needed

Error analysis

Uncertainties in measuring input parameters and statistical distribution - How accurate the input parameters to the model are known (with and without measurement), range, tolerance etc.

Uncertainties in the validation measurements – How accurate is the instrumentation used to measure the input and output parameters of the physical model

Validity of certain simulation tool may be determined through comparison with other simulation tool. For example, the results generated from BEM may be compared to FEM results for the same geometry and conditions. Both, BEM and FEM may be compared to analytical solutions where available.

Another area of model validation is to identify how accurate the model predicts changes in output parameters to changes in input parameters. This sensitivity study will also provide data for the range of model validity and importance of input parameters considered essential.

Annex D - XFN Validation Protocol

As with the validation of NDE models described above, the validation of the XFN methods to POD estimation are a key outcome of this program. The XFN approach is conceptually simpler than the FMA approach, but still must be validated in a rigorous manner. The approach to XFN validation in this program will be analogous to the approach for the validation of NDE models.

One of the questions that must be answered is the range of validity of the XFN method. As illustrated in Figure 1, XFN methods should provide the ability to modify the relationship of NDE system output to discontinuity size, and also to modify the variability of NDE system output if required. To define this range of validity, the factors related to NDE system performance must be identified, and it also must be identified which factors are included and which factors are not included in the XFN method. The uncertainties in the inputs as well as in the NDE system measurements used for validation must be characterized. Sensitivity analyses should be used to assess the XFN sensitivities to these uncertainties and to factors not modeled. Finally, the target requirements for model performance in order to achieve reasonable POD estimation must be known.

For this program, a XFN Validation Protocol will be developed and documented to ensure the data captured will be sufficient to support validation, and to ensure the validation steps are clear, consistent, and repeatable. This protocol will enable the assessment of the XFN range of validity which is a key outcome.

(Smith, Hugo, Patton, ISU, Annis, Aldrin, Rummel)
- factor identification and statements of testable hypotheses
- Generic range of validity
- Review existing protocol
- Factor interactions – how are they captured
- interferences
- Error analysis
- Uncertainties in inputs, uncertainties in measurements used for validation

Annex E Experiment Design Protocol

(Spencer, Annis)

- Need guidelines on what is required to execute a FMA or XFN approach
- complex, based on
- what factors are included in study
- what variances/uncertainties
- Remember false calls

Appropriate experimental designs must be in place to achieve the objectives of this program. The generic types of specimens, the variable factors included in their design, their numbers, and other similar parameters will be chosen based upon the desired program outputs. There are three specific objectives identified by the program sponsors as being of interest:

- evaluate feasibility and limitations of using MAPOD for transferring POD from one geometry to another in generic multilayer fastened structures
- evaluate feasibility and limitations of using MAPOD for transferring POD from notched samples to actual cracked multilayer fastened structures
- evaluate feasibility and limitations of using MAPOD for transferring POD from laboratory to depot and field inspection of multilayer fastened structures

The required specimen sets to achieve these three objectives will be defined, and reviewed for redundancy.

For this program, an Experiment Design Document will be developed and reviewed by the advisory committee early in the process.

Annex F Specimen Manufacture Protocol

(Forsyth, Goldfine, Brausch, Annis, Spencer, Moore)

1. Based on goal of project
2. FMA, XFN validation
3. material
4. vintage, heat treat, product form, directionality, em properties, coatings/sealants, ...
5. machining
6. Tolerances, surface finish, residual stress, hole condition, ...
7. crack
8. loading (spectrum?), single/multi axial, environment…
9. Shape, size => scan plan

The physical characteristics of the specimens will be largely defined by the actual article that is chosen as the study target: for example, cracks in the fastener holes in the rainbow fitting from the C-130. The main physical specimen variables are:

10. material
11. vintage, heat treat, product form, directionality, em properties, coatings/sealants, age of assembly, etc.
12. machining
13. tolerances, surface finish, residual stress, hole condition, similarity to original, etc.
14. sample assembly method

For this program, a Specimen Manufacture Protocol will be developed and documented to ensure the manufacture of specimens will be performed in a consistent, known fashion; and to ensure that any deviation in manufacturing processes from the target application are documented and understood.

The generation of fatigue cracks in specimens is also a very important issue. This is addressed in the next section.

Annex G Artifact Manufacture Protocol

(Bode, Forsyth, Thompson, Lindgren, Hugo, NRC)
- cracks from in-service
- cracks from lab manufacture
- EDM notches from manufacture
- measure, understand difference

There are at least three categories of cracks or crack-like features used in POD studies:
4. articles removed from service containing fatigue cracks induced in service
5. cracks grown in laboratory using load frames, in representative structure and material
6. EDM notches placed in representative structure and material

Category 1 is the most desirable, but usually not available in quantities associated with POD studies. Category 2 is the next most desirable, but can be very expensive depending on the part of interest. Category 3 is easiest, and the ability to perform studies on category 3 samples and use the XFN method to estimate POD on the actual part in service is a key outcome of this program.

It is obvious that there will be differences in NDE system response, whether ET or UT, between a notch and a fatigue crack. What is less obvious is the difference in response between the category 2 and category 1 cracks as defined above, and just as important the difference in the variability in response.

It is well known that crack closure affects detectability for both ET and UT inspection techniques. Crack closure is a function of residual stresses (due to manufacturing) as well as loading. It is believed that crack opening and bridging effect across crack faces (both mechanical and electrical) are the key contributions to the difference from notches and the variability within crack populations. Crack orientation is also very important, and is again a function of the applied loading.

Within this program, it will be critical to understand how fatigue cracks are created in fielded structure or constructed specimens, and to measure the variabilities associated with these populations and the differences between crack populations and EDM artifacts.

Characterization of the cracked specimens without destructive inspection is a desirable feature. This may be possible via x-ray computed tomography, or by performing replica or “reverse penetrant” on specimens under load to open cracks. In any case, some destructive tests must be performed to validate any nondestructive characterization.

For this program, a Crack and Notch Manufacture Protocol will be developed and documented to ensure the manufacture of cracks and notches will be performed in a consistent, known fashion; and to ensure that any deviation from the loading parameters experienced by the target application are documented and understood. Characterization methods will also be documented in the protocol.

Annex H Evaluation Protocol

(Malas, Vukelich, Thompson, Knopp, Bode)
- Compare FMA, XFN to empirical
- Within what limit/confidence
- a hat vs a
- POD curve
- can model/xfr function accommodate key factors
- can model/xfr function accommodate complicating issues
- add empirical corrections from specialized experiments if model/xfr function is not capable
- hole quality
- crack morphology
- All noise issues

The final aspect of this program is the evaluation of the performance of the MAPOD methods in terms of their ability to estimate POD, and also in terms of their ability to provide a reduced cost in comparison to the standard methods of POD estimation as outlined in MIL-HDBK-1823.

The fundamental comparison will be made against the results of a complete empirical study, as per MIL-HDBK-1823, that will be performed within this program. Both the NDE system response to cracks and the resulting POD will be evaluated.

The evaluation will also dig deeper to determine:
- within what limit/confidence
- can FMA/XFN methods accommodate key factors
- can FMA/XFN methods accommodate complicating issues
- for example, via the addition of empirical corrections from specialized experiments.

These issues will be evaluated for the realistic conditions obtained by the use of service-retired specimens with in-service induced fatigue cracks.

For this program, an Evaluation Protocol will be developed and documented to ensure the evaluation of MAPOD methods will be performed in a consistent, known fashion.