**Review of Progress on Methods for Model-Assisted Probability of Detection (MAPOD) Evaluation with Reduced Empirical Testing**

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ABSTRACT

The preparation and testing of POD samples with representative damage in real parts is frequently considered a burden in the validation of new NDE techniques. The model-assisted probability of detection (MAPOD) evaluation process has been developed, documented through best practices, and verified through comparison with empirical studies. However, the wider use of MAPOD has been limited due partly to the complexity of following the current practices and existing limitations in NDE simulation capability. This paper presents a review of progress on improved methods on MAPOD evaluation with an emphasis on strategies to reduce empirical testing while maintaining study quality.

**Keywords:** Probability of detection (POD), model-assisted POD (MAPOD), models, testing

INTRODUCTION

The build-up of specimens and experimental testing are frequently considered a significant burden in the validation of new inspection techniques. The preparation of POD samples with representative damage, such as fatigue cracks, in real parts, and the process to acquire a statistically significant number of measurements are often very time-consuming and expensive. A model-assisted probability of detection (MAPOD) approach for the design and execution of POD studies has been proposed to help mitigate the validation costs and to also improve the POD evaluation by addressing a wider array of inspection variables [1-5]. Fundamentally, there is a significant opportunity in using either numerical simulations or empirically developed models to address variables that cannot be easily recreated in experimental studies.

Several methodologies have been proposed that can be classified as model-assisted POD evaluations. The transfer function (TF) approach leverages an existing POD model for one inspection to address another similar inspection based on a limited number of new experimental measurements, studying a specific varying parameter. This straightforward approach has the potential to address minor differences concerning the part material, flaw type, or even shape changes of the part under test; however, care must be taken to ensure that the transformation is appropriate given a limited set of experimental data. This requires verifying the statistical assumptions used in the analysis. This approach has been successfully demonstrated to transform POD results for EDM notch measurements in engine components [6], aircraft structures [7] to parts with real cracking conditions and materials with different grain noise levels [8]. The full-model assisted approach uses computer simulations to represent the inspection process and determines the POD for the inspection technique through a combination of experimental and simulated data. This process can be found in an appendix of the MIL-HNBK 1823A [4]. For any POD study, the scope of the evaluation must be assessed, and all critical factors for the NDT technique, part material, part geometry, and discontinuity characteristics that control signal and noise must be identified. As well, the amount of variability, ideally as distribution functions, must be assessed through expert knowledge, experimental results and/or model-based studies. At the final stage of the POD evaluation, experimental and simulated measurement results are jointly evaluated to produce a combined estimate of the POD curve.

CHALLENGES WITH PRACTICAL APPLICATION

While the MAPOD evaluation process has been documented in best practices [4-5] and MAPOD studies have been verified with experimental data [3,6-10], the wide use of MAPOD has been limited to date. Partly, this is due to some misunderstanding of what a MAPOD evaluation involves. There are a number of papers in the academic literature on NDE and SHM validation that infer that MAPOD can be a “Model Only” evaluation, but this is an incorrect assumption. Fundamentally, there are certain aspects of the NDE and SHM techniques that cannot be represented through simulation perfectly, or there exists a good deal of uncertainty on the degree of variation in the NDE hardware/sensors, the part under test or expected discontinuities (shape, dimensions) of interest. Because of this, some experimentation will be needed. Alternatively, because there is some “lack of experience” or possibly a “lack of trust” with the MAPOD process, organizations are often still relying on full empirical POD studies. POD studies are inherently a conservative endeavor, and it is not surprising that organizations would be hesitant to rely on MAPOD if they do not have much experience with the process.

A related issue is there are still some limitations with current NDE modeling and simulation capability. Once key factors have been determined for the evaluation, an assessment is needed on whether to pursue a model-based POD evaluation based on the cost of a fully experimental study and the performance of available NDE simulation tools. Knowledge of the accuracy and speed of NDT simulations is a critical part of this assessment process. Thus, an evaluation of the model quality is often necessary at this stage. For many applications, there will be a mix of simulated and empirical studies that will provide the greatest coverage of the key factors for an inspection technique. For example, certain parameters such as the dimensions and location of a crack in the test part can be more easily controlled and varied through simulated studies. Alternatively, noise data from material specimens and measurement system noise can be evaluated quickly through low-cost experimental studies. From this perspective, a model-assisted POD evaluation has the potential to not only reduce the cost of a POD study through reduced test samples but also to improve the quality of the assessment by including physics-based models that fully address the key factors driving the evaluation process. Before models can be directly applied in POD evaluations, two steps are needed to ensure their performance. First, model calibration involves model adjustments to variables in a way that mimics the NDE technique procedure. In many cases, gains and thresholds are set based on the desired response to a known calibration standard. The parameters of the model are essentially fit to obtain the best match with a limited set of empirical data acquired per a calibration procedure. Second, model validation is a critical step that ensures the simulated results do agree with well-controlled studies for the appropriate range of conditions expected in practice. One approach is to simply require a certain level of agreement between a limited set of experimental and simulated results. However, it may be very difficult for models to achieve a fixed level of accuracy over the entire parameter range(s) of interest. Thus, statistical evaluation of ‘model error’ with uncertainty bounds for the key varying parameters should be carefully assessed and clearly reported. Thus, the numerical model error can be properly included in the model-assisted POD evaluation process. This level of model validation requires great care, which takes considerable time and engineering resources.

Lastly, better procedures are needed at this stage to ascertain the precise specimen and testing requirements to fill any gaps present with the model or knowledge on the technique variability. A necessary component of a MAPOD evaluation is the assessment and propagation of variability in the parameter conditions and the uncertainty in the POD assessment. Experimental-based POD evaluations always consider the impact of limited samples on the confidence bounds for a POD model fit. However, with numerical models, statistical uncertainty (quantified by confidence bounds) can clearly be driven to zero through performing a large number of simulations. There are other sources of uncertainty in the model predictions that are also present. These sources will affect the predictions of POD, and must be handled properly. As part of quantifying the effects of changing the key factors, the amount of variation of each factor must be well understood. Variability in NDE measurements is prevalent due to varying part geometries, material properties, surface conditions, flaw morphology, NDE hardware and human factors. A typical representation of variability for an input factor or condition is a probability density function (pdf). In addition, confidence bounds for the pdf may be considered as variation measures of the pdf distribution parameters. Unfortunately, this rigor is needed, but it clearly can be a burden when getting started on a MAPOD evaluation.

GENERAL METHODOLOGY FOR MAPOD WITH REDUCED EMPIRICAL TESTING

To mitigate specimen number and testing requirements, new protocols for Limited Set POD [11] and Transfer Function POD [12], potentially incorporating models [13], have been proposed to minimize validation cost and time. Building on past and this recent work, Figure 1 highlights a new comprehensive approach to implementing model-assisted POD evaluation with various strategies for reducing empirical testing. The process considers key factors, NDT modeling capability for these factors, and any available test specimens or related POD studies that have been performed. At this stage, the opportunities for the application of models are considered. For example, Limited Set POD is a highly desirable approach to minimize validation cost and time [11]. However, the feasibility of a limited set POD study is dependent on an understanding of the physics of the NDE technique and sensitivity for varying flaw sizes. Models have the potential to guide limited sample selection and consider if a limited sample study is even feasible. Replacing a linear statistical model fit with a physics-based model will reduce confidence bounds on assessment and could help reduce specimen requirements. Second, the transfer function (TF) approach can leverage an existing POD model for one inspection to address another similar inspection based on a limited number of new experiments, addressing differences for example flaw type and/or part state. To support this approach, models and statistical methods can be used to verify that the transformation is appropriate and that assumptions are met. Care must be taken to ensure the transform between the ideal (e.g. EDM notches) and real flaws (fatigue cracks) works well. Third, Bayesian estimation is well suited to integrate limited empirical data with NDE models including prior information and parameter distributions for POD evaluations. Bayesian analysis is a statistical approach for evaluating a “posterior” distribution of model parameters through combining information in the prior distribution with new evidence according to Bayes’ theorem. Bayesian methods can be leveraged here for the evaluation of three key components of the methodology: (1) evaluation of variability for an input factor or condition as a probability density function (pdf), (2) model calibration, and (3) revised measurement model estimates with limited experimental data [9, 14]. Lastly, the use of adaptive POD studies is also proposed. By breaking up traditionally large empirical POD studies into a series of smaller studies with possible off-ramps, it may be feasible to achieve the desired evaluation result with limited testing, if the performance criteria and sample assumptions are verified. Additional empirical data would only be acquired as needed.



**Figure 1. Proposed methods for improved model-assisted POD evaluation with reduced empirical testing.**

FUTURE DIRECTIONS

Research and engineering work is planned to improve the overall methodology of MAPOD. For example, work is planned on the design of a limited set and adaptive POD studies by leveraging NDE models. As well, work is planned to develop best practices for managing variability and uncertainty for transfer function (TF), full-model assisted evaluation and hybrid (experiment + model TF) approaches. Lastly, the work will investigate benchmarking studies assessing NDE model capability, accuracy and computational time, for a select set of case study problems.

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