PARAMETRIC STUDIES AND OPTIMIZATION OF EDDY CURRENT TECHNIQUES THROUGH COMPUTER MODELING

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ABSTRACT. The paper demonstrates the use of computer models for parametric studies and optimization of surface and subsurface eddy current techniques. The study with high-frequency probe investigates the effect of eddy current frequency and probe shape on the detectability of flaws in the steel substrate. The low-frequency sliding probe study addresses the effect of conductivity between the fastener and the hole, frequency and coil separation distance on detectability of flaws in subsurface layers.

Keywords: Eddy current testing, computer modeling, nondestructive inspection optimization, probe parametric studies
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INTRODUCTION

A major characteristic of current procedure and technique developmental process is constantly decreasing time between formalizing the inspection requirements and providing reliable assessment of various NDT techniques performance. Another dominating factor is always present drive for reduced developmental costs and budget constraints. Computer modeling [1] can shorten significantly the developmental process, reduce the subjectivity in technique assessments, and optimize procedure and equipment performance.

During the past 5 years, the NDT group at Edison Welding Institute (EWI) has incorporated modeling and simulation tasks in many projects based on the ultrasonic inspection technique. To develop further EWI NDT capabilities, project work was initiated in the area of eddy-current inspection modeling and simulation.

Two typical inspection techniques were optimized in this study – pencil probe high-frequency inspection of steel under protective conductive coating and sliding probe low-frequency inspection of multilayer structure with fasteners. The study with high-frequency probe investigates the effect of eddy current frequency and probe shape on the detectability of flaws in the steel substrate. The low-frequency sliding probe study addresses the effect of conductivity between the fastener and the hole, frequency and coil separation distance on detectability of flaws in subsurface layers.

The eddy-current parametric studies are conducted with three-dimensional (3D) finite-element modeling (FEM) software. The software package has extensively been validated in the past for various NDT tasks. In addition, the software was subjected to very thorough and comprehensive benchmark tests before acquisition. For this reason, the modeling results were mainly compared to past field experience or well-documented eddy-current practices and procedures. A limited number of verification measurements were conducted for qualitative rather than quantitative verification of modeling results. It is realized that thorough experimental model validation is necessary for any practical task. This activity, however, is outside the scope of this stage of the modeling efforts.

SURFACE PENCIL PROBE OPTIMIZATION

Operating Frequency

Detection of flaws under highly conductive protective coatings might be challenging using typical surface high-frequency eddy current probes [2]. It addition, very small variations of coating thickness may produce strong signals that will mask larger substrate crack signals and will indeed be false indications where no substrate crack is present.

The 3D model in Fig. 1 (left) shows a scan pattern and a typical shielded pencil high-frequency probe (coil with ferromagnetic core) over carbon steel substrate (dark base) covered with aluminum coating (light top). The dimensions of coating, substrate, coating thinning, substrate notch and coating conductivity used in the model have been specified earlier [2]. Electrical conductivity $\sigma = 2$ MS/m and magnetic permeability $\mu = 17.25$ were assigned to the steel substrate for this study.

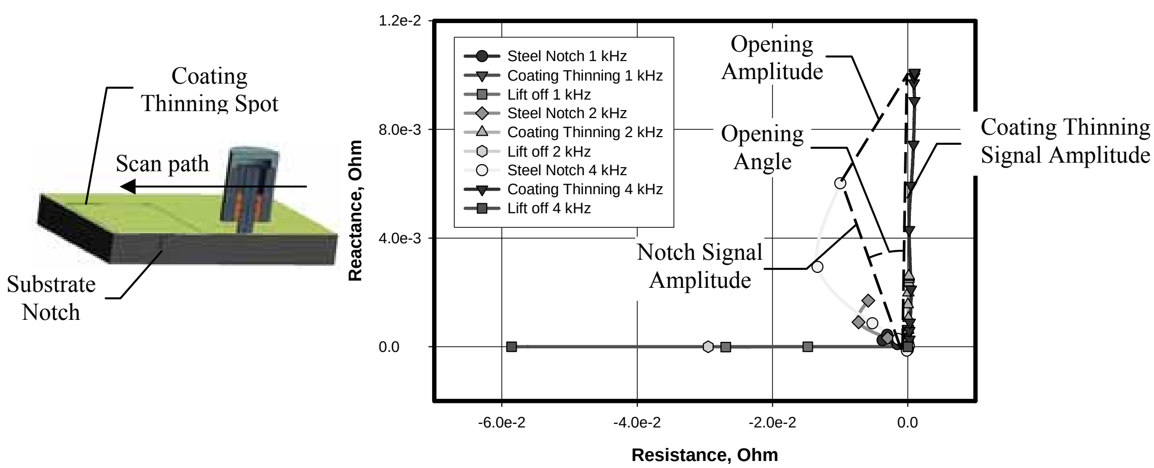


FIGURE 1. Solid model (left) and simulated notch and coating thinning signals (right) for pencil probe over steel substrate with aluminum alloy coating at three frequencies.

Logically, the reduction of frequency will provide better penetration of electromagnetic field in the steel substrate through highly conductive aluminum coating, thus improving the detectability. Comparison between modeled signals from steel substrate notch and coating thinning at several frequencies – 1, 2, and 4 kHz is presented in Fig. 1 (right). As expected, the notch signal increases and separates from the large coating signal as the frequency decreases. The coating thinning signal decreases with the reduction of the frequency.

Optimization parameters such as "Opening Amplitude", "Opening Angle", and the ratio of "Notch Signal Amplitude" to "Coating Thinning Signal Amplitude" were defined in an attempt to quantify the optimization process. The higher the optimization parameters, the better the separation between the coating thinning and substrate flaw signals.

Frequencies below 6 kHz provided relatively large opening angle and good modulus ratio. On the other hand, the overall sensitivity and resolution drops significantly at very low frequencies.

Shape Optimization

Following the frequency determination, a shape optimization of probe design may improve further the detectability of substrate notches or flaws respectively. Three shape parameters were optimized – Core Diameter, Coil Width, and Coil Offset from ferrite tip. The outside ferrite field concentrator (tube), metal shaft probe holder, and probe movement were not modeled to speed up the optimization process. The simplified probe was fixed over and centered on the substrate notch while the shape parameters were varied. In addition, the probe shape effects were also calculated with and without (not shown here) ferrite core. The coil electromotive force (product of number of turns and current through the coil) was kept constant. Two values were assigned to each shape parameter: dimensions used in initial surface probe design and twice larger value. According to the rules of factorial experiments, the 2^3 experiment of three variables with two levels for each variable will require 8 model runs. To illustrate the optimization results, small image of probe shape for each run is shown in Fig. 2. The vertical axis of Fig. 2 diagrams shows the difference of probe impedance modulus with and without notch in the substrate.

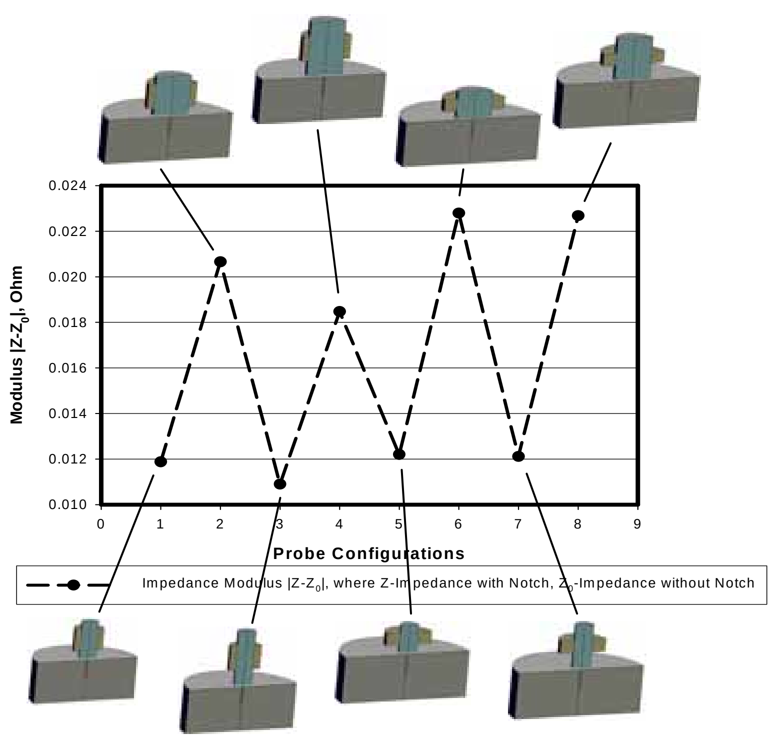


FIGURE 2. Simulated effect of probe geometry (core diameter, coil offset, and coil width) on notch sensitivity for probe with ferrite core field concentrator at 6 kHz.

The numerical experimental results in Fig. 2 clearly indicate that coil shape and offset have less effect on probe sensitivity than core (coil) diameter when the coil is used with core field concentrator. Another reason to use ferrite core is that the probe sensitivity with core is almost ten times better than the sensitivity without ferrite core.

Further, it is known from the theory of eddy current testing that changes to probe diameter can have similar effect to changes in frequency and/or electromagnetic properties of inspected material. This is better explained with the generalized eddy current parameter *P* [3]:

$$P = d\sqrt{2\pi f \mu_0 \mu_r \sigma} \qquad (1)$$

where *d* is the probe diameter in *meter (m)*, *f* is the frequency of sinusoidal current through the coil in *Periods per second* (1/*s*), $\mu_0 = 4\pi 10^{-7}$ *H/m (Henry per meter)* is constant magnetic permeability of air or free space, μ_r is the relative magnetic permeability of the material, and σ is the electrical conductivity of the material in *Siemens per meter* (*S/m)*. The probe sensitivity to certain types of flaws and inspected material properties will be similar as long as the generalized parameter is constant. For example, a probe working at 6 kHz will produce a notch signal similar to a probe working at 1.5 kHz with diameter twice larger. Certainly, this rule has many limitations and should be used with caution outside of the contexts of this discussion.

The optimized probe geometry is shown in Fig. 3 (left) where in addition to doubled diameter, the coil size has also been doubled to compensate for the reduced sensitivity due to reduced frequency. Fig. 3 (right) illustrates this so called similarity rule. The effect of coating thinning is identical. Although the substrate notch signal amplitude from the initial and optimized probe does not change significantly, the opening as defined in Fig. 2 is better for the double coil optimized probe.

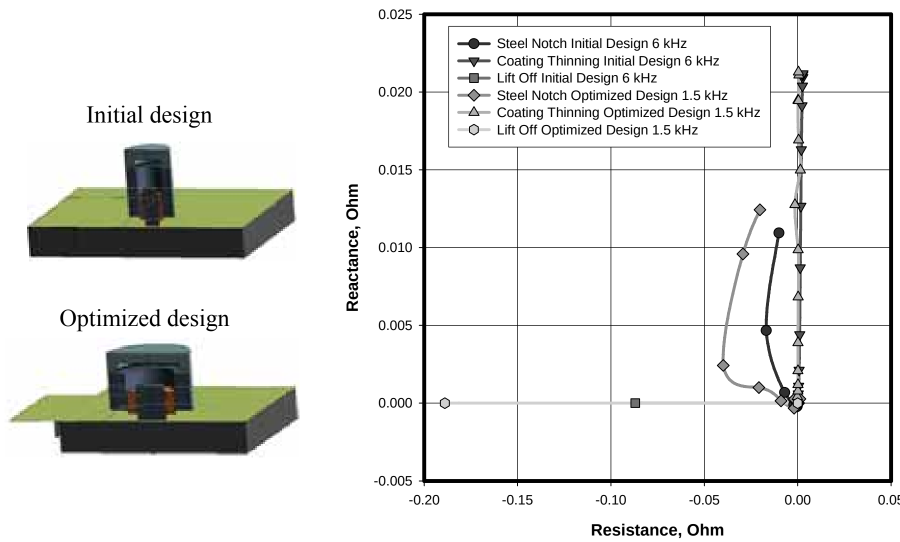
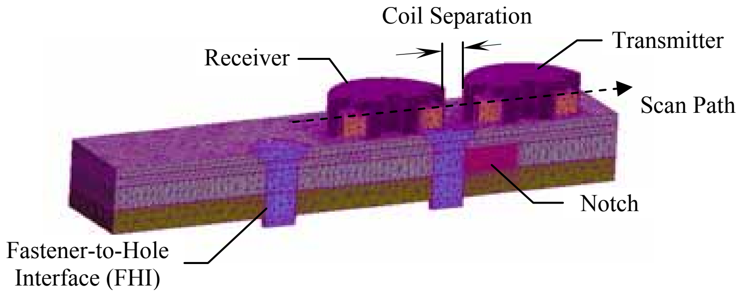


FIGURE 3. Solid models and simulated lift off, coating thinning, and notch under coating signals at frequency of 6 kHz and 1.5 kHz for initial and optimized probe geometry with double coil.

Optimized larger probe sensitivity though comes at a price of reduced resolution and sensitivity to shorter cracks than probe diameter. It is worth noting that this is one possible way of optimization shown here for demonstration purposes. Other probe configurations and probe designs are possible (e.g. introduction of another coil in Transmit-Receive arrangement, differential coils, introduction of additional coils with different orientation, core shape optimization and others).

SUBSURFACE SLIDING PROBE OPTIMIZATION

The sliding probe is used extensively for inspection of multilayer aerospace structures. The solid model and finite element meshing pattern of the probe, multilayer specimen, fasteners and notch (simulating flaw) in the third layer are shown in Fig. 4. The low frequency sliding probe consists of two usually identical coils (transmitter and receiver) with ferrite core. The probe is slid along the scan path as shown in Fig. 4. The specimen consists of aluminum alloy layers with titanium or aluminum alloy fasteners [2,4]. The effects of three parameters are investigated: operating frequency, conductivity of interface between the fastener and the fastener hole, and separation between transmitter and receiver coil.



Data for the probe model is courtesy of GE Inspection Technologies

FIGURE 4. Sliding probe over multilayer structure with notch in the third layer. Location of two variable parameters – fastener-to-hole interface and coil separation.

Operating Frequency

The frequency is the major factor that determines the depth of penetration, sensitivity, and resolution of inspection. The ability to identify the optimal frequency is directly related to the success or failure of the inspection.

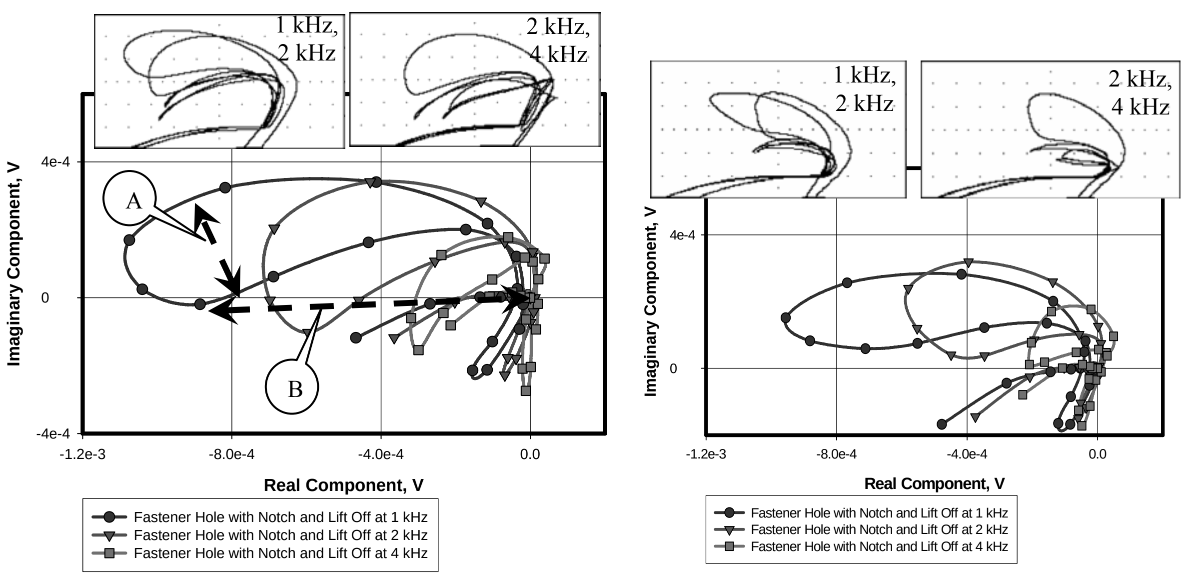


FIGURE 5. Simulated and actual fastener holes signals with notch in the third layer obtained with sliding probe at 1, 2 and 4 kHz. Aluminum (left) and titanium (right) alloy fasteners. Conductivity of FHI is assumed "0" (no contact).

The modeling results with aluminum and titanium alloy fasteners are presented in Fig. 5 for three frequencies 1, 2, and 4 kHz for the fastener holes with notch in the third layer. Actual signals acquired at 1, 2, and 4 kHz are presented in Fig. 5 top for the same structure and probe. Concerning the sliding probe optimization, the objective of the efforts is to maximize the ratio A/B (see Fig. 5 left), where B is the signal component associated with the fastener hole (noise in this case) and A is the signal component related to the flaw superimposed on fastener hole signal. Both, the model and the actual data clearly indicate that the optimal frequency for this application is 2 kHz. This is the frequency used in the field procedure where this probe and specimen were specified. The small discrepancies between the simulated and actual signals are explained with the fact that the actual conductivity of FHI is higher than zero. There is electrical contact between the fastener and the hole.

Interface Conductivity Effect

The alodine treatment, aluminum alloy corrosion protection coating on fastener surface, provides increased FHI electrical conductivity as opposed to anodized surface [5]. As a result, the eddy currents generated around the fastener hole and possible flaw propagating from the hole are shortened through the FHI and the fastener. This causes reduction of the effective length of the eddy current contour disturbance associated with the fastener hole and the flaw. Finally, the reduced effective length of the eddy current disturbance produces smaller signal in the receiver coil [4,5]. The electrical conductivity of FHI will depend on the installation procedure, environmental impact, and other factors. Although more accurate and representative, an attempt to investigate the effect of various installation procedures on FHI conductivity through specimens will take significant time and resources. A numerical experiment might provide data for initial assessment of FHI conductivity effect.

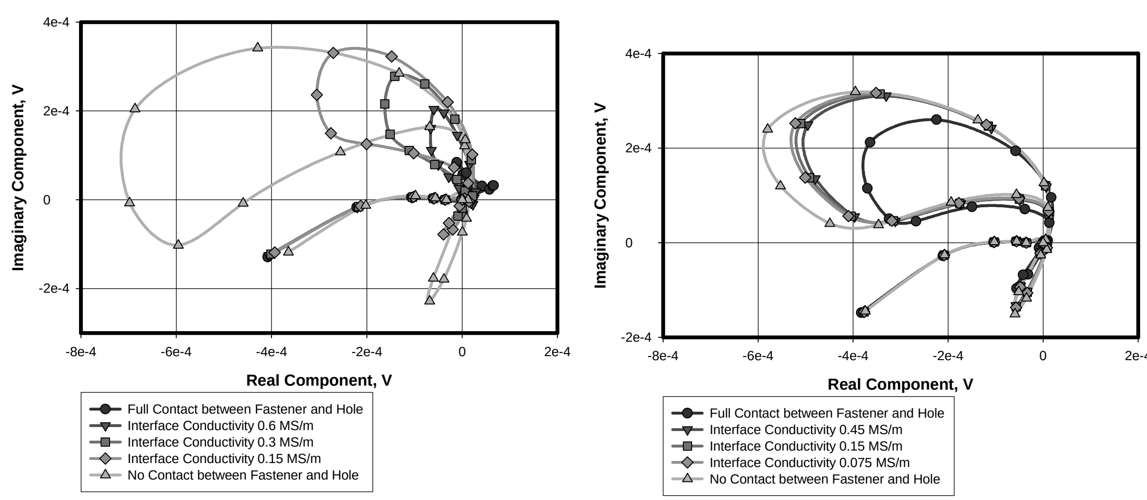


FIGURE 6. Simulation of fastener-to-hole interface conductivity effect on signals from fastener holes with notches in the third layer with aluminum (left) and titanium (right) alloy fasteners at 2 kHz.

Results from simulation of FHI conductivity variations are shown in Fig. 6. The FHI conductivity ranges from 0 MS/m (no contact) to 17.7 MS/m (full contact) between the fastener and the hole. Intermediate values of FHI conductivity – 0.15, 0.3 and 0.6 MS/m (aluminum fasteners) and 0.075, 0.15 and 0.45 MS/m (titanium fasteners) distributed uniformly on the interface surface have been modeled as well. The model shows that the signal from the fastener will almost disappear at “full contact” condition when aluminum alloy fasteners are used. On the other hand, the structure with titanium alloy fasteners is much less affected by increased conductivity (up to full contact) of FHI as shown in Fig. 6 right. It is possible to miss a flaw if the interface conductivity is high for structures with alodine aluminum fasteners. This finding agrees well with previous field experience [5]. Another important practical conclusion is that experimental and field calibration specimens should be representative of fastener installation procedure. The model speeds up significantly the analysis of FHI conductivity effect which is difficult and costly to study through specimens.

Modeling of Coil Separation Effect

The sliding probe has additional variable to be considered when used for inspection. The coil separation distance is effective tool to increase or decrease the remote field effect with this type of probes at fixed low frequencies. The adjustment of coil separation distance allows manipulation of depth from which the receiver-coil signal is produced at fixed low frequencies. Although the modeled probe has fixed factory coil-to-coil separation (Fig. 4), optimization of this parameter has to be investigated for practical purposes.

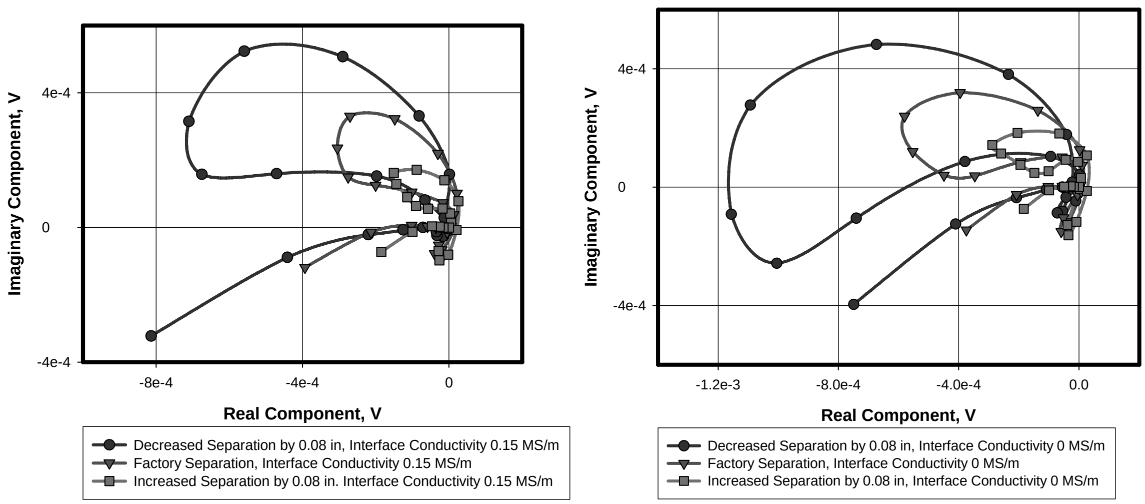


FIGURE 7. Simulation of coil separation effect on signals from fastener holes with notch in the third layer and aluminum (left) and titanium (right) fasteners at 2 kHz.

The modeled signals in Fig. 7 represent the effect of increased and decreased with 2-mm coil separation distance. The FHI conductivity was conservatively assumed to be 0.15 MS/m uniformly distributed for the aluminum alloy fasteners and 0 MS/m for titanium alloy fasteners. Regardless of fastener type, the signals increase when the separation distance is decreased. The ratio though of notch signal component to fastener signal component may be better at increased separation distance. The noise, however, will increase at increased separation distance. Based on the modeling results, probes that allow adjustment of separation distance for optimization might be considered for this task. The field procedure utilized sliding probe that had the separation distance manufactured shorter than the nominal for this probe.

CONCLUSIONS

The modeling results clearly demonstrate the advantages of modeling approach if incorporated into the eddy current technique development optimization and validation process. The availability of reliable modeling tool is particularly important at the initial stage of defining the inspection requirements. Modeling can provide comparison study data across several techniques and probes where no specimens, equipment, or experience exists. Thus, the subjectivity in making inspection decisions and the possibility of costly mistakes later will be reduced significantly. At the following developmental stages, the modeling can easily identify the worst case where large areas are to be inspected and the preparation of large number of specimens accounting for all structure and flaw variables is prohibitively expensive and slow. Finally, the models used in procedure development can address field issues. For example, deviations between calibration specimens and structure in fastener pattern and type, coating thickness, fatigue-induced conductivity changes and others may produce signals that are difficult to classify. Simulation of field conditions might provide answer at minimal cost and service interruption.

In summary, the following is a short list of possible benefits and advantages if modeling tools are used in the developmental process:

- Significantly reduced time for optimization of procedures used for inspection of complex geometry structures where NDT technique performance is unknown
- Significant cost benefits due to elimination and reduction of experimental specimens and mock-ups needed for technique and procedure validation
- Increased inspection reliability and repeatability
- Fast interpretation of field NDE data and reduction of unnecessary repairs
- Quick customer support turnaround

Future work may address the improvement and inconsistencies in the model. It will require more studies focused on FHI and model validation measurements.

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