Finite Element Modeling of Pulsed Eddy Current Applied to Ferrous and Titanium Fasteners in F/A-18 Airplane Wing Structure

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Abstract: Pulsed eddy current (PEC) is being developed to detect stress corrosion cracks between fasteners on the inner wing spars of the F/A-18 Hornet aircraft. The spars are located below a thick carbon/epoxy wing skin, and so cannot be detected by conventional eddy current techniques without disassembling the wing structure. Wing disassembly may cause collateral damage, and increase the downtime as well as maintenance costs. PEC signals are strongly influenced by the electromagnetic properties of fastener materials. Fasteners may be either titanium (Ti) or ferrous, which causes changes in flux penetration depth and corresponding generation of eddy currents in deep layers. This may necessitate different probe designs for different fasteners. The present work explores the difference between the PEC signal in the presence of ferrous and Ti fasteners. It also investigates the effect of a slight off-centered probe for the two fastener materials. The results are in qualitative agreement with experiment.

Keywords: Nondestructive testing, pulsed eddy current, transient eddy current, electromagnetic modeling, transient electromagnetic fields.

1. Introduction

Stress corrosion cracks (SCC) develop between fasteners in the inner wing spars of the F/A-18 Hornet aircraft. These spars are located below a 9.1 to 21.3mm (0.36 to 0.84inch) thick carbon/epoxy wing skin. Because of large lift-off and presence of ferrous fasteners, these cracks cannot be detected by conventional eddy current (EC) techniques. Crack detection by EC inspection requires removal of both skin and fasteners to access the bolt holes in the inner layer. Disassembly of the structure, however, increases downtime of the aircraft and risk of collateral damage to wing structures, in addition to increasing the total maintenance cost and rendering the aircraft unusable for longer periods.

Pulsed eddy current (PEC) testing is an emerging technology that is being developed for investigation of deep defects in multilayered wing structures without the need of removing the fasteners or outer layers [1-6]. It utilizes a square pulse to generate a driving magnetic field that links with the conducting structure to induce transient eddy currents within the structure. A set of sensing coils or GMR sensors, placed on the component surface in the vicinity of the driving coil, are used to sense the resultant transient electromagnetic interactions. Differences in response between regions containing discontinuities and those where they are absent may be used to identify the presence of cracks within the structure [5]. The key component of a PEC system is a probe that is specifically designed to take into consideration the sample/defect geometry under investigation. Examples of the particular probes used in this work are reported in the literature [5, 7]. For a given sample/defect geometry, the PEC signals are also sensitive to the nature of fastener material. The inner wing spars of the F/A-18 Hornet have fasteners that are made up of both titanium (Ti) and steel (ferrous) and, so, a single PEC probe will respond differently in the two cases [7]. For the case of ferrous fasteners, the fastener will act like a conduit for the magnetic flux from the driving coil, permitting flux to penetrate deeper into the structure [8], while this is not true for a Ti fastener. Since there are two types of fasteners, the development of an optimal PEC probe requires information about the influence of the magnetic nature of fasteners on depth of penetration of magnetic flux into the structure.

The application of PEC for non-destructive testing has been successfully modeled using the finite element (FE) method [9-14]. FE modeling has proven useful in demonstrating the feasibility of flaw detection under given inspection conditions and, therefore, has the potential to aid in probe design. The present work investigates differences in behavior of ferrous and Ti fasteners by comparing the penetration of the excitation field in the two cases as a function of time and the corresponding generation of eddy currents in the neighboring conducting structure. It also investigates the change in PEC signal caused by an off-centered probe, which is a common occurrence in a practical setting. Modeling results provide an explanation for observed differences in experimental results [6, 7].

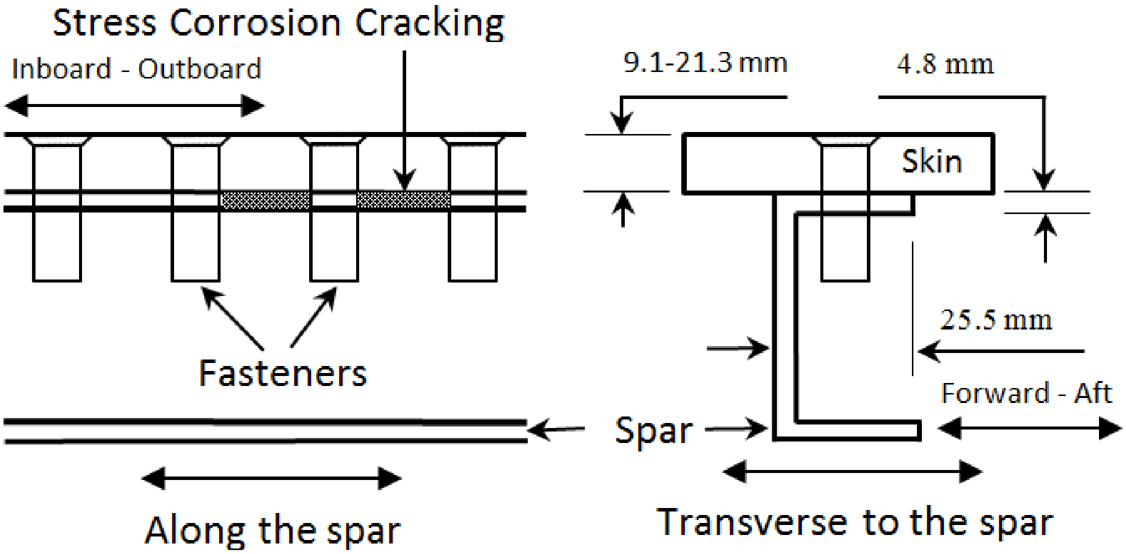

Figure 1. Typical inner wing spar lower cap fastener cross-section and side view.

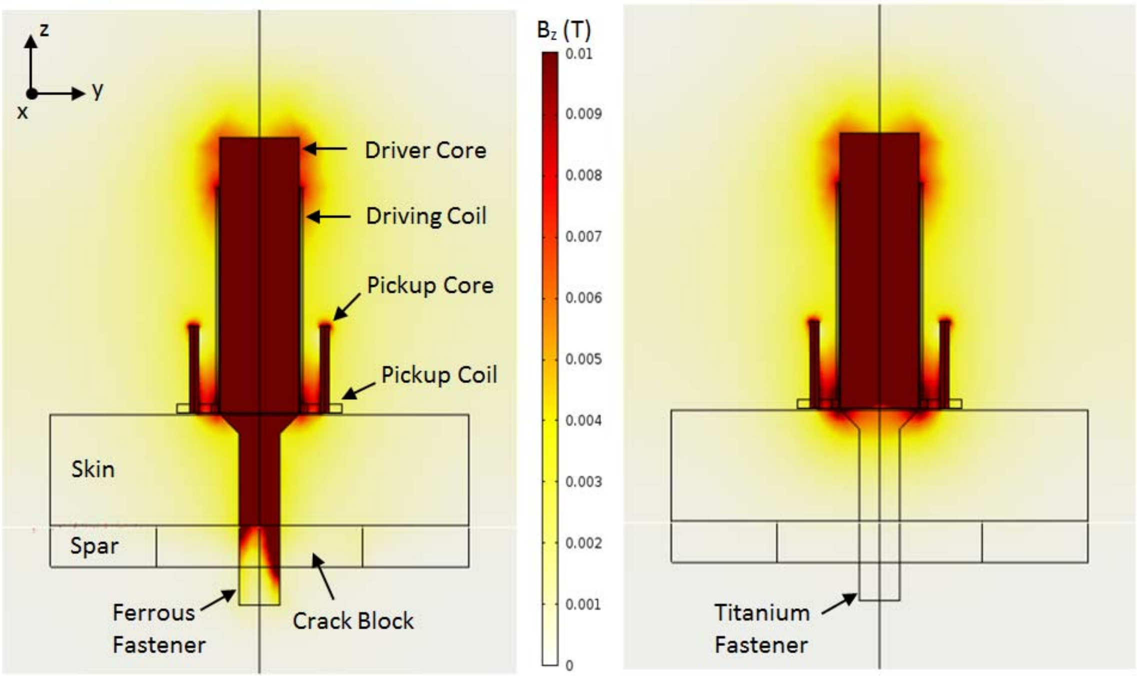

Figure 2. Magnetic flux density (B_z) distribution through ferrous versus titanium fastener at t = 0.5ms.

2. Use of COMSOL Multiphysics

The present work employs commercial three-dimensional (3D) FE modeling software, COMSOL 4.3a, to simulate the sample as well as the PEC probe. The mirror symmetry in the model geometry is utilized to produce half-models instead of full-models in order to reduce the computation time. A schematic diagram showing cross-sectional and side views of an F/A-18 Hornet wing spar is shown in Figure 1. It consists of a non-conducting upper skin of thickness 9.1-21.3mm (thickness of 12.8mm was used in the model) and a lower aluminum strip of thickness 4.8mm. The two layers are held together by a series of fasteners, which may be magnetic (ferrous) or non-magnetic (Ti). The modeled fastener has a length of 22.0mm and a diameter of 4.74mm (3/16inch) at the narrow end. The electromagnetic properties of various components are given in Table 1. The stress-corrosion cracks develop in the aluminum spar between the fasteners. Models were run on a HP Z800 Dual Quad Core Workstation with 54 GB of RAM.

Table 1: Properties of sample components

Component	Electrical Conductivity (S/m)	Relative Permeability
Aluminum Plate	2.6×10^7	1
Ferrous Fastener	3.6×10^6	66
Titanium Fastener	2.0×10^6	1
Top Skin	1.0×10^{-3}	1

A schematic view of the mid-section of a solved FE model is shown in Figure 2. The upper part of the model shows a PEC probe that consists of a driving coil centered between two pickup coils in a 180° configuration. The coils have a liftoff of 0.23 mm from the top surface of the sample. The detailed probe specifications are given in Table 2. The ‘Multiturn Coil’ feature of COMSOL is used to model each coil. On the right side of the spar, there is a through-crack block of length 10.6 mm and width 0.2 mm that originates from the boundary of the fastener. A ‘no crack’ region of the same dimensions as the crack is modeled on the other side of the fastener to produce a symmetric model mesh. Therefore, the pickup coil located on the crack side generates a defect signal and the one on the other side generates a reference signal. The two absolute signals are subtracted to produce a differential signal that may provide more information about the defect than an absolute signal. A typical 3D model mesh constitutes about 89,555 mesh elements. A non-linear step voltage of 4.5V with a rise time of 0.5μs is used to trigger the drive coil. The total time varies from 0 to 2ms in steps of 5μs. A direct time-dependent solver (MUMPS) was employed to solve the model.

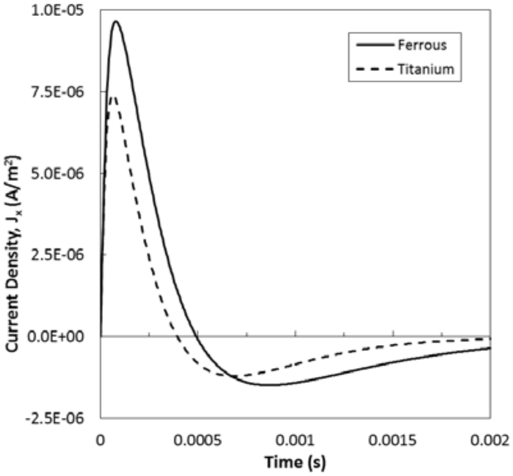

Figure 3. Differential pickup signals from perfectly centered probe for ferrous and Ti fasteners.

3. Results and Discussion

A comparison of flux density distribution through the sample in the presence of a ferrous fastener and a Ti fastener at t = 0.5 ms is shown in Figure 2. The flux density penetrates much deeper into the ferrous fastener than in the Ti fastener in the same time interval, thus causing the generation of much stronger induced eddy currents in the surrounding aluminum structure at greater depths in the crack region. In the case of the Ti fastener, on the other hand, flux density penetration is limited to shallow depths (Figure 2), so the defect signal is expected to be weak. Figure 3 shows the differential pickup signals for ferrous and Ti fasteners when the probe is perfectly centered over the fastener. As expected, the signal in the presence of the ferrous fastener is stronger than the one for the Ti fastener.

Table 2: Probe Specifications

Parameter	Driving Coil	Driving Coil Core	Pickup Coil	Pickup Coil Core
Length, mm	25.0	31.8	1.0	10.0
Outer Diameter, mm	9.8	9.2	4.0	1.0
Inner Diameter, mm	9.2	-	1.0	-
Turns	382	-	400	-
Resistance, Ω	18.3	-	32.0	-
Lift-Off, mm	1.23	0.23	0.23	0.23
Permeability,	-	2300	-	48
Conductivity, S/m	-	0.5	-	0.5

Differential pickup signals were also obtained for a number of probe shifts in the directions along the spar (x-direction) and transverse to the spar (y-direction) to investigate the effect of an off-centered probe with respect to the center of the fastener. Probe misalignment by a fraction of a mm is a common occurrence in a practical setting. Figures 4 and 5 show pickup signals from two different samples, one having a ferrous fastener and the other a Ti fastener, for various probe shifts. The peak amplitude of the differential signal for the ferrous fastener increases as much as 7 times when the probe is shifted along the spar as compared to the corresponding increase of only 1.8 times for the Ti fastener. For either fastener, however, not much variation in the signal is observed when the probe shifts transverse to the spar. This is evident from Figures 6 and 7, which show the peak signal amplitudes normalized with respect to ‘no-shift’ values for both types of fasteners.

The stronger ‘no-shift’ differential signal observed for ferrous fasteners is apparently due to the higher permeability of ferrous material as compared to Ti, since the electrical conductivity of the two materials is only marginally different (Table 1). The higher permeability of the ferrous fastener makes it act like a flux conduit to carry magnetic flux to deeper regions and thereby generate stronger eddy currents in the defect region, which has a strong bearing on the pickup signal. The sharp increase in signal with probe shift along the spar for ferrous fasteners is not due to the relative change in location of the defect with respect to the two coils, rather it is due to the close proximity of one of the pickup coils to the high permeability fastener, while the other coil moves away from it. This type of effect is not expected from a non-magnetic Ti fastener. When the probe shifts transverse to the spar the pickup coils remain equidistant from the fastener center for both fastener types and therefore, not much change is expected in the signal.

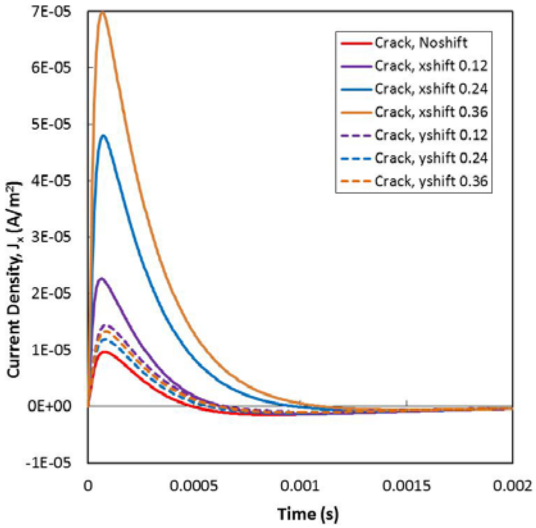

Figure 4. Modeled differential pickup signals for various probe shifts along x and y directions for ferrous fastener.

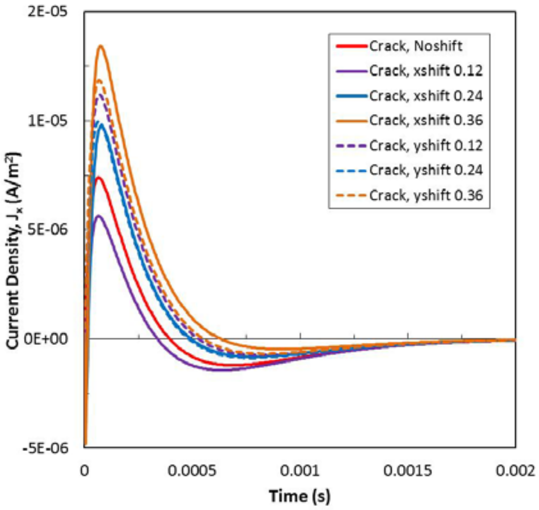

Figure 5. Modeled differential pickup signals for various probe shifts along x and y directions for Ti fastener.

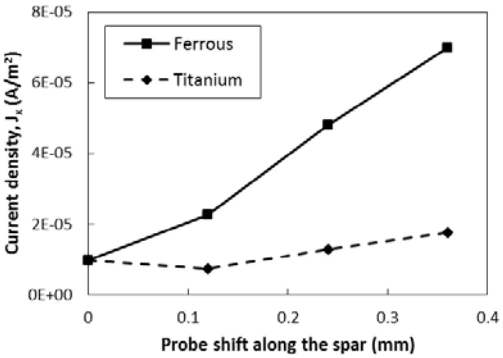

Figure 6. Normalized peak amplitude of pickup signal versus probe shift along the spar.

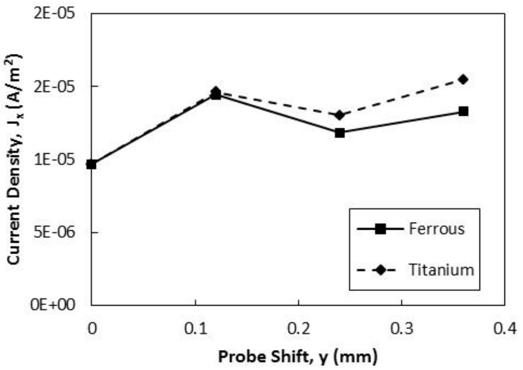

Figure 7. Normalized peak amplitude of pickup signal versus probe shift transverse to the spar.

4. Comparison with Experiment

Figure 8 shows absolute pickup signals from an experimental set-up with similar sample/probe geometry as the model for the no crack side. The signal produced in the case of the ferrous fastener is twice as large as the one from the Ti fastener, consistent with the results shown in Figures 2 and 3. The detailed experimental results from both types of fasteners are reported elsewhere [7].

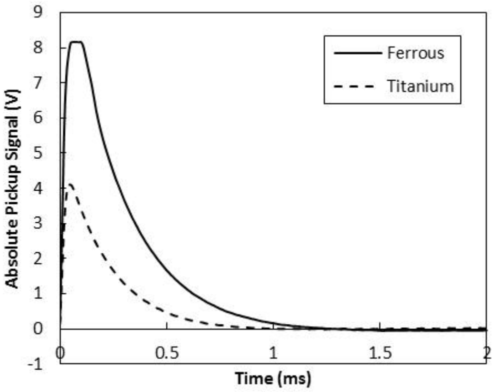

Figure 8. Experimental absolute pickup signals from nearly centered probe for ferrous and Ti fasteners.

5. Conclusions

A PEC method is being developed for detection of stress corrosion cracks between fasteners on the inner wing spars of the F/A-18 Hornet aircraft, where both ferrous and Ti fasteners may occur. The present work uses FE modeling to investigate the effect these two different fastener materials can have on the differential signal recorded by a single PEC probe. It also explores the variation of the output signal recorded by a slightly off-centered probe. The signal at the location of a ferrous fastener is found to be stronger than that at a Ti fastener, which may necessitate recalibration of the PEC probe. Also, a significant increase in the differential signal is caused by a small off-centering of the probe for the case of a ferrous fastener when the probe displacement is in line with the spar with the pickup coils oriented parallel to it in a 180° configuration, while the change in signal is insignificant for a Ti fastener. On the other hand, the off-centering of the probe in a direction transverse to the spar has no significant effect on the differential signal. Thus centering of the probe is more important for the case of ferrous fasteners than for Ti ones.

6. Acknowledgements

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7. References

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