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Pulsed Eddy Current (PEC) Characterization of Material Loss in Multi-Layer Structures

S. Giguère *   B.A. Lepine **   J.M.S. Dubois ***

ABSTRACT

Visual inspection is currently the primary means for detecting corrosion in fuselage multi-layered aircraft structures, such as lap splices. This method detects the surface deformations that arise between the rivets (*i.e.*, pillowing) due to the increased volume of the corrosion products between the plates. Enhanced visual inspection methods, generally based on the same principle, provide a more reliable and sensitive means of detecting corrosion and monitoring its condition over time. Deformations not due to corrosion, such as poor quality control during manufacture or previous repairs, however, can give false indications. In addition, as corrosion becomes more of a structural integrity issue, there is the need for more quantitative assessment capabilities in nondestructive evaluation. Recent advances in the pulsed eddy current technique have shown the potential to give a new tool to characterize the material loss in a multi-layer structure. This technique provides the ability to assess a large number of parameters, including defect size and its depth location, in a way far superior to that achievable with conventional eddy current instruments and techniques. This paper will present the current capabilities and developments of the pulsed eddy current technique applied to fuselage lap splices inspections.

Keywords
Nondestructive testing, multi-layer, lap splice, eddy current, pulsed eddy current, transient response.

RÉSUMÉ

La méthode d'inspection visuelle est présentement privilégiée pour détecter la corrosion survenant dans les structures multi-couches tels les joints à recouvrement d'un fuselage d'avion. Cette méthode détecte le boursoufflement de la surface entre les rivets qui est causé par le volume accru des produits de corrosion entre les couches. Les

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LIST OF SYMBOLS

BoB	bottom of bottom plate
BoT	bottom of top plate
EC	eddy current
LOI	lift-off point of intersection
LPI	liquid penetrant inspection
MPI	magnetic particle inspection
NDT	nondestructive testing
PEC	pulsed eddy current
RT	radiography testing
ToB	top of bottom plate
TZC	time-to-zero crossing
UT	ultrasonic testing

INTRODUCTION

The detection and quantification of small metal loss (*i.e.*, less than 10% of one plate thickness) in multi-layered structure has been hampered by limitations associated with traditional nondestructive testing (NDT) methods (BDM Federal, Inc., 1998). In the world of aviation, the interest in this problem lies in the inspection of fuselage lap splices that are two-layered assemblies. This design is such that a crevice exists where conditions are favourable to corrosion. The most promising conventional nondestructive testing method to detect material loss due to corrosion seems to be eddy current (EC) testing. Limitations exist for all other conventional NDT methods. For example, ultrasonic testing (UT) requires coupling for the ultrasound to be transmitted from one medium to another; and, in general, no coupling agent is present at the faying surfaces of a multi-layered structure. Radiography testing (RT), liquid penetrant inspection (LPI) and magnetic particle inspection (MPI) are also inadequate for the detection of material loss in multi-layer structures (Dubois, 2000). Recently, enhanced visual inspection, such as the optical double-pass retroflection surface inspection technique (*i.e.*, D-Sight™), has demonstrated the ability to detect minute changes in surface topography due to corrosion The results obtained with this method rival those obtained with eddy current (Karpala, 1994); however, deformations not due to corrosion, such as poor quality control during manufacture or previous repairs, can give false indications. As a result, many operators using this technology rely on conventional NDT methods to confirm the material loss due to corrosion.

The accepted conventional EC detection sensitivity to

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méthodes d'inspections visuelles améliorées, opérant selon le même principe, constituent un moyen plus fiable et sensible pour la détection et le suivi de la corrosion. Les déformations n'étant pas causées par la corrosion, telles le mauvais contrôle de la qualité lors de la fabrication et les réparations antérieures, peuvent donner de fausses indications. De plus, la corrosion est en processus de devenir une question d'intégrité structurelle, par conséquent, il y a un besoin pour une évaluation quantitative en essais nondestructifs. Les progrès faits dans la technique de courants de Foucault pulsés ont démontré le potentiel de ce nouvel outil pour caractériser la perte de matériel d'une structure multi-couches. Cette technique donne l'habileté d'établir un grand nombre de paramètres, tels la grandeur du défaut et son emplacement, de façon supérieure aux instruments et aux techniques d'inspection par courants de Foucault conventionels. Ce travail présentera l'usage courant et les réalisations de la technique des courants de Foucault pulsés dans le domaine de l'inspection des joints à recouvrement d'un fuselage d'avion.

material loss is between 10% and 15% (of one plate thickness) in the aerospace industry (Ansley, 1992). Better sensitivity is possible by optimizing the probe characteristics and the frequency of inspection. The pulsed eddy current (PEC) technique can take advantage of both and detect material loss in the order of 4% of one plate thickness. The PEC technique differs from the EC technique by its square wave excitation. This pulsed driving current produces an inherently wideband frequency spectrum which can potentially be used to determine a large number of parameters, such as defect size, location, and probe lift-off during inspection.

BACKGROUND

The principle of magnetic induction is the basis on which the pulsed eddy current relies for the inspection of the test object. A magnetic flux is induced by passing a time-varying current through the excitation coil. When a test object is brought adjacent to the transducer, the coil excitation currents induce eddy currents within the test object. The magnetic flux associated with the eddy currents opposes the coil's magnetic flux, thereby decreasing the net flux. The changing magnetic flux produces a voltage in the detection coil that causes current to flow in the detection coil. By constructing a circuit where the detection coil is in series with a resistor, the voltage drop across the resistor, as a function of time, will represent the train of transient magnetic fields that are scattered back to the surface as a result of the square-wave current excitation (Giguère, 1999).

Most of the transient response gradient is caused by dispersion in the material and remains constant. It is therefore customary to ignore this gradient and subtract it by signal processing. This process is referred to as "balancing". One particular way to perform balancing is by subtracting a reference signal from the total transient response. As long as the transducer is moved over regions similar to that of the reference, a zero transient will be measured If the transducer is moved over a flaw or other geometric feature, the transient can be associated with that condition (Harrison, 1994). The transient response features can therefore be used to characterize the test object. In fact, the two features of the balanced transient (**Figure 1**) most often employed to quantify the defect are the peak amplitude and time-to-zero crossing (TZC).

There is a significant drawback to the balancing process. In order to identify the flaw transient, it is essential that the background parts of the transient remain constant throughout the duration of even the most extensive of measurements. Any changes to the background, such as lift-off, will be interpreted as changes to the flaw signal, thus leading to inaccurate results (Harrison, 1995). This restriction severely limits any "field" application of the pulsed eddy current technique for corrosion detection in aircraft structures since lift-off is caused by uneven rivets, pillowing between rivets, or simply by uneven paint thickness

EXPERIMENTAL PROCEDURE

The experimental set-up consists of an XY positioning robot and a data acquisition system, both interfaced to a PC computer. The software interface controls the motion and positioning of the robot as well as the data acquisition. The transient response captured during inspection is based on a technique initially developed by Moulder *et al.* (Moulder, 1995). It consists of a circuit where the detection coil is in series with a resistor, and the voltage drop across a resistor is fed into a low-noise amplifier, then digitized by a PC-based data acquisition board (Lepine, 1998) These signals contain the total information on both the incident and reflected fields.

The system can accommodate several probe-coil configurations; however, the best results were obtained with reflection probes, also referred to as concentric driver-pickup transducers. For these transducers, excitation and detection is

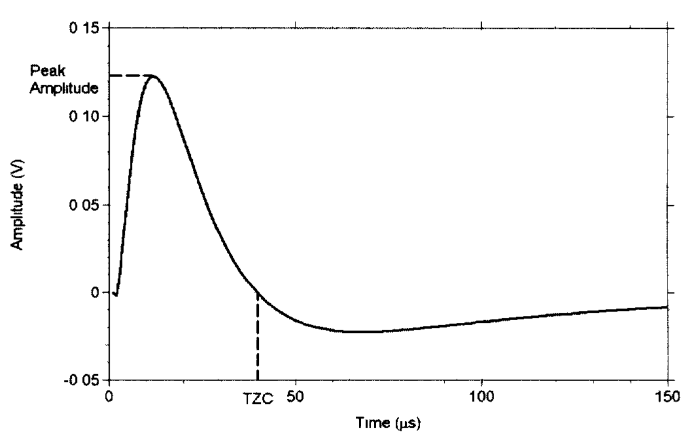

Figure 1.
Balanced transient response.

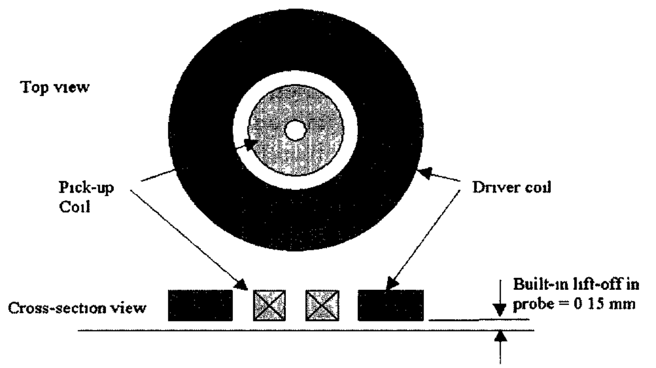

Figure 2.
Reflection probe configuration. Driver coil dimensions: ID = 6.6 mm; OD = 13.8 mm; Length = 0.65 mm; Turns = 400; Wire size = 41 AWG. Pick-up coil dimensions: ID = 1.59 mm; OD = 6.35 mm; length = 0.66 mm; Turns = 625, Wire size = 45 AWG.

carried out by two different coils having different characteristics. **Figure 2** shows a diagram of the transducer's right cylindrical coil with rectangular cross-section and details its parameters.

Experimental measurements were made for two types of test specimens. One type was used to develop the PEC technique. For this activity, the calibration test specimens were machined with material losses to simulate corrosion. The specimens were two-layer systems composed of 2024-T3 aluminum alloy, both layers nominally 1 mm (40 thou) thick. These plates could be assembled to simulate material losses at the bottom of the top plate (BoT), the top of the bottom plate (ToB) and the bottom of the bottom plate (BoB). The second type used for the experiments was a two-layer, riveted lap splice composed of plates 1 mm thick made of 2024-T3 aluminum. This assembly was placed in a corrosion chamber to initiate crevice corrosion. This specimen was considered representative of a lap splice since it exhibits the traditional surface deformation due to the corrosion products between the rivets. Hence, this specimen was used to validate the results obtained with the calibration test specimen.

RESULTS

The balanced transient is the traditional means for determining the presence, the amount, and the location of corrosion; however, an increase in the lift-off distance increases the balanced transient peak amplitude, advances its location, and advances the time to zero crossing (where applicable) to such an extent that defect size and location cannot be adequately determined by these traditional features. The effect of lift-off is clearly shown at **Figure 3**. The defects identified at **Figure 3a** are effectively undetected with the peak amplitude feature (**Figure 3b**). What is observed is simply the variation of the surface topography due to the surface warp that caused very slight probe tilt variations and reduced its coupling during the inspection. Fortunately, previous research (Giguère, 2000) has demonstrated that one particular feature, the Lift-off Point of Intersection (LOI), did not vary significantly with variation in coupling or increase in probe lift-off. The lift-off point of intersection C-scan (**Figure 3c**) clearly demonstrates the ability of this feature to detect material loss in the multi-layer structure. From this figure, it is also intuitively possible to quantify the material loss.

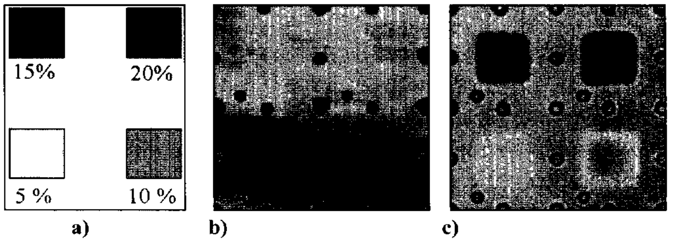

Figure 3.
Qualitative assessment of material loss:
(a) test specimen schematic,
(b) peak amplitude C-scan results,
(c) lift-off point of intersection C-scan results.

Through the use of calibration standards, it is then possible to determine the voltage value at the LOI for various defect sizes and generate a calibration curve as shown at **Figure 4**. This calibration curve can be applied to the inspection of the artificially corroded test specimen as shown at **Figure 5**. The

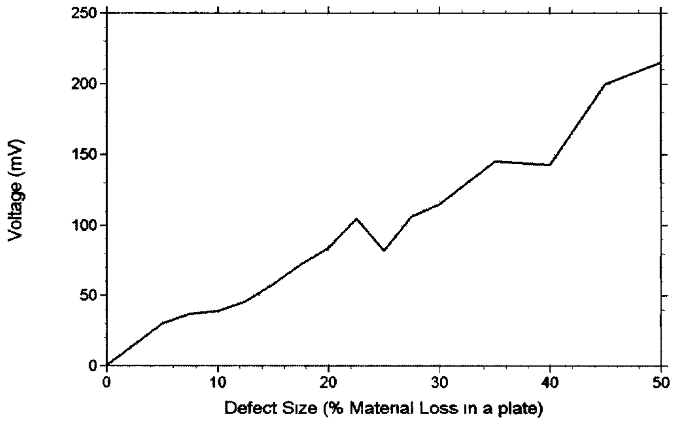

Figure 4.
Signal amplitude (mV) at the lift-off point of intersection as a function of the defect size (% of material loss in a plate).

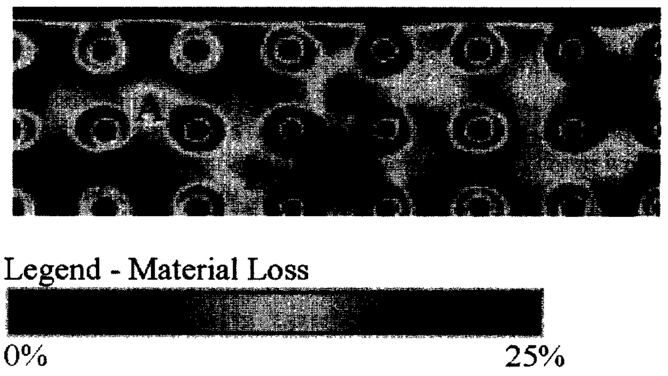

Figure 5.
Lift-off point of intersection C-scan results for the artificially corroded specimen with regions of interest.

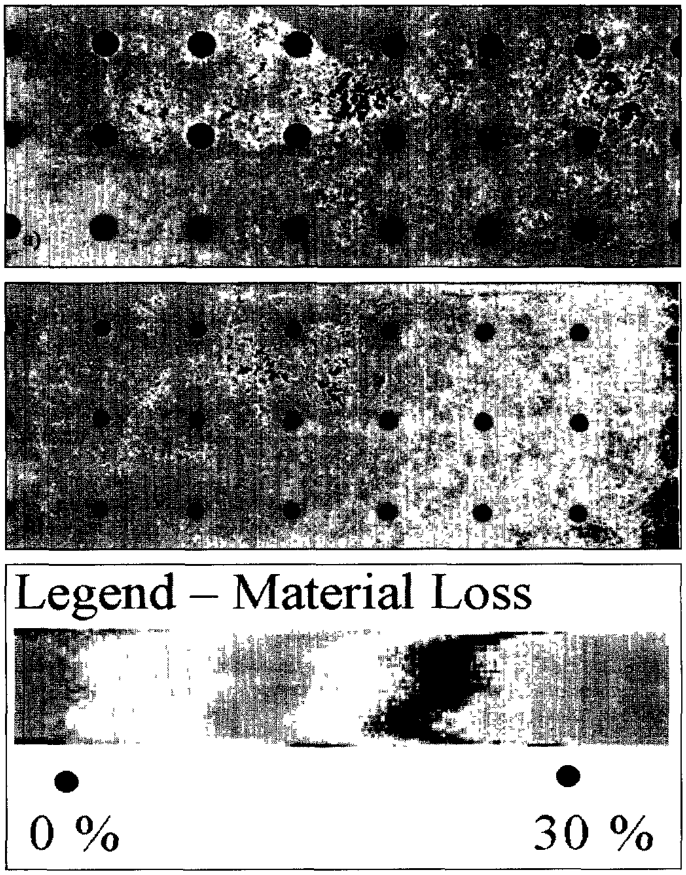

Figure 6.
Thickness mapping for (a) top plate, and (b) bottom plate of the two-layer artificially corroded specimen measured via digital X-ray thickness measurements.

accuracy of the LOI can be assessed by comparing the results obtained with PEC with those determined via digital X-ray thickness measurement after disassembly of the lap splice. The X-ray thickness measurement results are shown at **Figure 6**. By comparing the results in these two figures, it is found that there is some variation between the more precise material losses as determined by X-ray and the PEC results. It is believed that the PEC results are less than actual material losses because the probe averages the material loss over an area approximately 1 cm². In other cases, the PEC results may show a greater material loss due to the influence of variations in the gap *i.e.*, the distance between the two plates. This situation may cause an overestimation of the defect size. Notwithstanding these limitations, the blind test results obtained with the PEC technique provided a good assessment of the material losses for this artificially corroded multi-layer specimen as shown in **Table 1**

Thus far, researchers have relied on traditional time domain features such as the time to zero crossing. This particular feature is affected by lift-off and becomes inadequate for field inspection purposes. Reconsidering the fact that pulsed eddy current uses a broadband excitation, an alternative was found to locate defects in a multi-layer assembly. Specifically, the signal due to a defect near the surface arrives early while the corresponding signal from a deep defect arrives later and is characteristically broadened as a consequence of its longer path through the highly dispersive conductor. The effect is a decrease in the magnitude of the transient and a change in the shape which becomes much broader. This is consistent with the passage of a pulse through a highly dissipative medium (Harrison, 1994). Hence, the half-power transient response width should provide information pertaining to defect location. That is only true, however, when the lift-off distance remains constant, which is rarely the case during a field inspection. Hence, to use this feature, it is necessary to correct the signal for lift-off. The steps to accomplish the correction are to take the balanced transient response obtained during the inspection, subtract the transient response for the specific lift-off obtained during calibration, and normalize the resulting transient response to compensate for the loss in coupling associated with lift-off. The results obtained for the calibration specimen are presented at **Table 2**

Table 1.
Validation of PEC material loss estimation against the combined X-ray thickness measurement results for a square cm area.

Regions	PEC estimation % material loss	X-ray thickness measurement % material loss
A	13.8%	BoT 20%
B	15.1%	BoT 5% / ToB 15%
C	23.6%	BoT 25%
D	17.0%	BoT 25% / ToB 20%
E	23.7%	BoT 25%

Table 2.
Time ranges at "half-power" points for gap less than 12 thou.

Defects	Time Range (µs)
Gap Only	24.87 – 25.33
Bottom of Top Defects	25.98 – 30.21
Top of Bottom Defects	30.66 – 33.20
Bottom of Bottom Defects	35.48 – 41.21

The lift-off correction process was then applied to the artificially corroded specimen for the regions identified at **Figure 5**. **Table 3** provides a comparison between locations found from the X-ray thickness map and those based on the transient response half-power width. There is a very good correlation between the results. For regions having defects in both top plate and bottom plate, *i.e.*, regions B and D, the method adequately located the largest defect in the assembly.

Table 3.
Comparison between actual defect location and defect location predicted by the PEC half-power width method.

Regions	Location (X-ray thickness map)	Location (half-power width)
A	BoT	29.37 µs (BoT)
B	BoT / ToB	30.99 µs (ToB)
C	BoT	30.02 µs (BoT)
D	BoT / ToB	30.29 µs (BoT)
E	BoT	29.48 µs (BoT)

For example, the largest defect in region B is located at TOB (as shown in **Table 1**) and is classified as such in **Table 3**.

CONCLUSIONS

It was shown that PEC has the ability of quantifying material loss and determine the defect location in conductive multi-layered structures such as lap splices. Given its ability to detect and quantify material loss without negative impact from a major source of noise, *i.e* , lift-off, the PEC technique has now the ability to be accomplished under field conditions. In a two-layer assembly, the PEC techniques provides the means to detect and quantify assess material losses in a way far superior to that achievable with conventional eddy current techniques.

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REFERENCES

Ansley, G , *et al* (1992) "Current Nondestructive Methods for Aging Aircraft", DOT/FAA/CT-91/5

BDM Federal, Inc (1998) "Corrosion Detection Technologies, Sector Study, North American Technology and Industrial Base Organization"

Dubois, J M S , P R Roberge, S Giguère (2000) "Eddy Current Sliding Probe Technology for the Detection of Corrosion in Multi-Layered Aircraft Structures", *CORROSION/2000 Technical Symposia, NACE International*, paper 00296, 9 pgs

Giguère, S (1999) Pulsed Eddy-Currents for Corrosion Detection, M Eng Thesis, *Royal Military College of Canada*, Kingston, ON, 125 pgs

Giguère, S , J M S Dubois (2000) "Pulsed Eddy Current Finding Corrosion Independently of Transducer Lift-Off", *Review of Progress in Quantitative Nondestructive Evaluation*, D O Thomson, D E Chimenti eds , Vol 19, American Institute of Physics, pp 449-456

Harrison, D J (1994) "Detection of Corrosion in Layered Structure Using the Transient Eddy Currents", Defence Research Agency Farnborough, Hampshire, 53 pgs

Harrison, D J (1995) "Eddy-Current Inspection Using Hall Sensors and Transient Excitation", Defence Research Agency Farnborough, Hampshire, 43 pgs

Karpala, F , O L Hageniers (1994) "Characterization of Corrosion and Development of a Breadboard Model of a D-Sight Aircraft Inspection System – Phase I", DOT/FAA/DT-94/56

Lepine, B A (1998) "Pulsed Eddy Current Method Developments for Hidden Corrosion Detection in Aircraft Structures", *Proceeding of the 1st Pan-American Conference*, The Canadian Society for Nondestructive Testing Inc , Mississauga, ON, pp 107-117

Moulder, J C , *et al* (1995) "Pulsed Eddy Current Measurements of Corrosion Induced Metal Loss Theory and Experiment", *Review of Progress in Quantitative Nondestructive Evaluation*, D O Thomson, D E Chimenti eds , Vol 14, Kluwer Academic/Plenum Publishers, pp 2065-2072

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