



Low Frequency Eddy Current Testing of Insulators and Composites

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Abstract: Eddy current testing (ECT), a non-destructive testing method widely used to evaluate defects within conductive materials, is explored in this study as it applies to insulators and nonuniformly conductive materials. Previous work has shown that at high frequencies, differences in electric permittivity can be detected with ECT. In this study, a new design of an ECT sensor that employs two resonance-tuned coils is evaluated. Results show that material inconsistencies in insulators are detectable due to spatial variations in permittivity and magnetic permeability, and that detection is possible at lower frequencies than previously demonstrated. In addition to determining signal dependence on individual electromagnetic parameters, sensitivity for defect detection in a carbon fiber-reinforced polymer (CFRP) composite is qualitatively determined. Although low signal- to-noise ratio is observed with a small-diameter coil, by increasing the coil diameter, the signal to noise ratio is increased while preserving adequate spatial resolution to detect defects in the sample. This study expands on previous studies of the application of ECT to insulators, and demonstrates that defect detection is possible in CFRPs.

Key words: Composite materials, Defects, Eddy currents, Material properties, Magnetic materials





1. INTRODUCTION

Electromagnetic non-destructive testing (NDT) is widely used for the evaluation of conductive materials [1–3]. One common approach, eddy current testing (ECT), employs a system of coils that induces eddy currents in a conductive sample and subsequently monitors changes in the secondary magnetic field generated by the eddy currents [2, 4]. Defects in the sample distort the eddy currents, resulting in a change in the magnetic field detected by the coils. ECT has limi- tations, including shallow penetration depth, an inability to detect defects with interfaces parallel to the surface, and the requirement that the probe maintain minimal lift-off from the test material. Despite these limitations, ECT is widely used for NDT and inspection because of the advantages offered in terms of cost, portability and ease of interpretation of results. Currently, the practical utility of ECT is restricted to conductive materials. However, with the growing use of non- conductive materials in industrial applications that require non-destructive evaluation, there is a need for an approach for these materials with comparable advantages to ECT.

Recent work has explored the use of ECT on non- conductive materials. High frequency eddy current (HFEC) devices in the range of 1–500 MHz are capable of permittivity characterization of insulators [5, 6]. Gäbler et al. reported the theoretical influence of sample permittivity on the induced magnetic field and demonstrated experimentally that differ- ences in sample permittivity are detectable by a HFEC device [5]. In that study, exposed holes in a polymethyl methacrylate (PMMA) block are shown to be detectable when the coils are operated between 1.75 and 3.5 MHz, and sub-surface holes at varying depths are detectable when operated at 6 MHz. Mizukami et al. provided a theoretical





derivation of permit- tivity effects and experimental results in which holes in a glass fiber reinforced plastic (GFRP) were detectable by an eddy current device operated at 10 MHz [6].

In addition to insulators, there is a specific need for expanded NDT options for carbon fiber reinforced polymer (CFRP) composites, a material in which the conductive car- bon fibers are embedded in a non-conducting matrix. CFRPs are increasingly used in applications requiring materials with high strength-to-weight ratios. As the use of CFRPs con-tinues to expand, so will the demand for low-cost NDT techniques that are portable and capable of accessing struc- turally complex regions without the use of a coupling agent. ECT satisfies these requirements and has been shown to be successful in exploiting the conductivity of the carbon fibers to detect various CFRP features. Researchers have demon- strated that the following features of CFRPs are detectable by ECT operated at 1–500 MHz: fiber orientation, fiber frac- ture, fiber volume fraction, and artificial defects up to 8 mm deep [7–12].

1.1 Resonance-Tuned ECT

In the present work, we report an approach to NDT testing of insulators using an eddy current type device with transmit and receive coils that are tuned such that their respective res- onant frequencies are close in value and the quantity QVm is maximized, where Q (quality factor) is the ratio of reso- nant frequency to bandwidth, and V m is the maximum output voltage. This system has been shown to optimize sensitivity for flaw detections.



Table 1 Coil dimensions



The sensor is capable of detecting defects based on per- mittivity, similar to those studied by Gäbler and Mizukami, but at lower frequencies (600–900 kHz) [5, 6]. In addition to demonstrating detection based on permittivity, we demon- strate the feasibility of using magnetic permeability as an additional parameter providing image contrast.

2. EXPERIMENTAL DETAILS

2.1. Sensor Configuration and Testing Method

Two sensors were used in this study, each consisting of a transmit coil (TC) and a receive coil (RC). Dimensions for each sensor are given in Table 1. In both sensors, the RC was placed inside the TC, such that their axes were paral- lel but offset by 4.3 and 11 mm, for the small diameter and large diameter sensors, respectively (Fig. 1). The TC was driven with a function generator (Hewlett Packard 33120A) operating from 940 to 980 kHz. Voltage from the RC was displayed on an oscilloscope (Tektronix TDS2014B), and data sets were processed with LabView Signal Express (National Instruments Tektronix Edition).

	Coil height (mm)	Coil radius (mm)	Number of turns	Wire gauge
Small diameter se	ensor			
Transmit coil	3.962	6.350	100	42
Receive coil	6.350	0.432	1000	47
Large diameter se	ensor			
Transmit coil	3.962	12.700	85	42
Receive coil	6.350	0.432	1000	47







Fig. 1 Schematic of the sensor consisting of an outer (transmit) coil, radius r_1 , and inner (receive) coil, radius r_2 . The coil axes are perpendicular to the sample surface offset laterally by a distance *d*. Lift-off, *h*, is the distance between the sensor face and the sample surface

For one-dimensional scans, the coil assembly was mechanically rastered across samples at variable lift-off (h = 0 - 4 mm) with a lab-developed pulley-based system. Scanning velocity was constant with the exception of start and stop points, which were distant from defect regions of inter- est (Fig. 1).

2.2. Materials

Defects were simulated in acetal resin (Delrin) blocks by drilling 12.7 mm diameter holes of varying depths. Scans were performed on either air-filled or fluid-filled gaps to examine the effects of electromagnetic properties in the defect. Tests involving air-filled gaps were performed on an acetal block with two holes, 24.75 mm and 25.5 mm deep, for the first and second hole respectively. For magnetic per- meability, a second acetal block with 19.5 mm deep holes was filled with four different ferrofluids with manufacturer- stated magnetic permeability values of 1.88, 4.57, 5.68, and 24.63 (×10–6 H/m2) (Ferrotec EMG 911, EFH 1, EFH 3, and EMG 900 respectively).





Carbon fiber epoxy prepreg was used to construct a composite defect sample. The prepreg material consisted of a toughened epoxy (Solvay, Inc. CYCOM 5320-1) and woven fabric of carbon fibers (Cytec Industries, Inc. T650-35 3 K 8HS Fabric). The 305 mm × 232 mm × 2.75 mm laminate consisted of eight prepreg plies in a [0/90]2s stacking sequence. Two types of plastic sheet were used to simu- late defects: vacuum bag (nylon, 0.06 mm thick—defects #1, #2, and #3) and prepreg backing film (polyethylene, 0.12 mm thick—defects #4, #5, and #6). Three square defects (25.4 mm× 25.4 mm) of each material were placed in the laminate, one at each of the following depths: shallow (below the first ply—defects #1 and #4), medium (in the middle—de- fects #2 and #5), and deep (above the last ply—defects #3 and #6). All six were evenly spaced along the length of the laminate. The laminate was oven cured according to the man- ufacturer recommended 3-h dwell at 121 °C and 1.5 °C/min ramp rate. Vacuum was applied during the cure to remove trapped air and consolidate the part.

3. RESULTS AND DISCUSSION

3.1. Representative Scan

Figure 2 shows a representative scan of an acetal block con- taining two air-filled holes, which yielded signal deflections corresponding to sample and defect boundaries. Circuitry design of the RC circuit was such that constant magnetic flux in the RC resulted in zero voltage readings at the probes, and changes in magnetic flux in the RC due to electromagnetic property variations in the sample caused positive or negative voltage deflections. Alternating current in the RC was converted into direct current by a full wave rectifier. The direct current was subsequently fed to an operational Please cite the article as: L Hamill, J Emerson, K McGushion, and S Nutt, **"Low-frequency eddy current testing of insulators and composites"**, J Nondestructive Eval 37 [15] (2018) DOI: 10.1007/s10921-018-0513-1





amplifier, which allowed only transient signals induced by sample-dependent voltage changes in the RC to pass through. The resulting deflections of the signal from zero therefore were attributed to spatial variations in the electromagnetic properties of the inspected region. The scan displayed in Fig. 2 reveals six signal deflections corresponding to transi- tions from air to acetal and the reverse as the sensor rastered over the block. Signal deflections and amplitudes can be partly attributed to variations in lift-off distance caused by irregular surfaces. The effect of both sample-dependent and operating parameters on the output voltage of the RC circuit are discussed in the following sections.



Fig. 2 Receive coil output voltage as a function of traverse time and distance. Distance was estimated by correlating the dimensions of the block to location of peak signals. The dotted line indicates sensor path with signal time points corresponding to traverse distances to air/acetal and acetal/air interfaces

3.2. Effect of Operating Parameters on Detectability





3.2.1. Determining Resonant Frequency and Optimal Transmit Coil Frequency

Figure 3a shows the general relationship between the fre- quency of the alternating current in the TC (f) and the output voltage of the RC (V), with output voltage maximal at reso- nant frequency. Resonant frequency of the sensor is altered by the electromagnetic properties of materials near the sensor, thus resulting in a horizontal shift in the curve. To deter- mine the resonant frequency of the sensor in the presence of a particular sample, f was swept in 1-kHz increments. The amplitude of the resulting signal deflections as a function of f is shown in Fig. 3b. Signal deflections are positive when < f R, and negative when f > fR. Thus, resonant frequency can be determined by the point of inflection.



Fig. 3 a General relationship between output voltage of the receive coil and frequency of the alternating current going through the transmit coil. \mathbf{b} Signal deflection amplitude as a function of transmit coil fre-

quency. c Amplitude of signal deflection as a function of frequency for an acetal/air interface at a lift-off of 0.762 mm

With f held constant, sample-dependent shifts in f R (and thus, horizontal shifts in the frequency

response curve) resulted in a change in the output voltage, V, which caused signal deflections similar Please cite the article as: L Hamill, J Emerson, K McGushion, and S Nutt, **"Low-frequency eddy current testing of insulators and composites"**, J Nondestructive Eval 37 [15] (2018) DOI: 10.1007/s10921-018-0513-1





to those seen in Fig. 2. As shown in Fig. 3a, the slope of the frequency–response curve approaches zero as f approaches f R, and the slope increases as the operating frequency moves further from resonance.

Therefore, for a given shift in f R due to sample properties, the observed signal deflection is larger when the value of f is further from the initial resonance value. For defect detec- tion, the optimal TC frequency is one which results in signal deflections with the largest amplitude. To determine the opti- mal TC frequency for this sensor, signal deflection amplitude as a function of f for the acetal-air interface of an acetal block with holes was investigated using the small-diameter sensor. The resonant frequency of the sensor over acetal was determined to be 951 kHz \pm 1 kHz. Signal deflection ampli- tude at this interface was shown to be maximum at 960 kHz (Fig. 3c) or approximately 10 kHz above resonant frequency. The operating frequency for each scan was selected to max- imize signal accordingly.

3.2.2. Lift-Off

For a coil with windings parallel to the surface of a sample, magnetic field strength varies inversely with z, the distance along the axis perpendicular to the coil radius and through the center of the coil. An N-turn coil produces a magnetic field according to Eq. (1), where R is the radius of the coil, and $\mu 0$ is the permeability of free space. For z = 0, the magnetic field at the center of the coil is reduced to Eq. (2).



$$H = \frac{\mu_0 N R^2 I}{2(z^2 + R^2)^{3/2}}$$
(1)
$$H_0 = \frac{\mu_0 N I}{2R}$$
(2)

When z = R, $H \approx 0.35H0$. By Maxwell's equations, (Eq. 3–6) the induced electric field is proportional to the magnitude of the magnetic field from the coil. Thus, increased lift-off decreases the induced electric field, and for constant permeability, the secondary induced magnetic field. This in turn reduces the output voltage from the RC.

$$\nabla \cdot \boldsymbol{E} = \frac{\rho}{\varepsilon_0} \tag{3}$$

$$\nabla \cdot \boldsymbol{H} = 0 \tag{4}$$

$$\nabla \times \boldsymbol{E} = -\mu \frac{\partial \boldsymbol{H}}{\partial t}$$
(5)

$$\nabla \times \boldsymbol{H} = \varepsilon \frac{\partial \boldsymbol{E}}{\partial t} + \sigma \boldsymbol{E}$$
(6)

Signal dependence on lift-off for the acetal block with two air-filled holes is shown in Fig. 4. Values given represent the signal deflection amplitude at the leading acetal-air interface. The lowest value of lift-off tested (0.254 mm) resulted in a peak voltage of 0.208 V. Increasing the lift-off to 1.27 mm decreased the signal by 57.7% to 0.088 V. At a lift-off of 2.032 mm, the signal dropped 73.1% to 0.056 V. Signal-to- noise was sufficient to detect the interface at all lift-off values tested, resulting in a signal amplitude of 0.024 V at the largest lift-off of 3.81 mm.



Fig.4 Signal deflection amplitude as a function of lift-off for an air/acetal interface

Fig. 5 Signal deflection amplitude as a function of magnetic permeability for a ferrofluid/acetal interface

3.3. Effects of Permeability on Detectability

The two terms on the right hand side of Eq. 6 can be regarded as the current densities induced in the test material by the magnetic field of the TC. The first term is the dielectric cur- rent resulting from the time-dependent electric field induced by the changing magnetic field in the TC. The first term is proportional to the electric permittivity and the magnetic per- meability of the test material. The second term is the induced conduction current which is proportional to the conductivity of the test material. In conducting media such as CFRP com- posites, the second term usually dominates (except for very high frequencies), while in insulators, the first term is the only contributor. These time-dependent currents are the source of the magnetic field which is detected by the RC.

Note that the dielectric currents are proportional to the frequency of the inducing field from the TC. Thus, in previous work with insulators, higher frequencies have been used than in the current work.





We have found that by use of a resonant circuit with the RC, it is possible to detect the magnetic field from the induced dielectric currents

From Eq. 5, permeability (μ) affects the electric field induced by an alternating magnetic field, and hence spatial variations in μ affect output in the RC. Variability in perme- ability was simulated with ferrofluid-filled holes in an acetal block. Scans performed with the small-diameter coil operat- ing at a frequency of 961 kHz and a lift-off of 0.762 mm are shown in Fig. 5. The signal obtained increases with increasing permeability values of the fluid. A non-linear effect would be expected, as we have shown signal-to-noise depends on the difference between operating frequency and resonance frequency, which in turn is affected by the large differences in permeability values of the samples.

3.4. Applicability to CFRP

In addition to applications for the inspection of insulating materials, this technique is potentially applicable to NDT of CFRPs. The composite defect sample described above was scanned using the small-diameter coil at a constant lift-off of 0.762 mm along two trajectories—one directly over the line of defects, and one along a control path that excluded defects from the sensor field of view. The resonant frequency for the composite sample was 943 kHz \pm 1 kHz, and the operational frequency was set to 953 kHz. Scan results are displayed in Fig. 6a. With this sensor, maximum signals reached approx- imately 15 V, much stronger than the values obtained on insulator samples, which did not exceed 1.5 V. As expected, stronger signals were obtained in the setting of conductive fibers than in the setting of permittivity or permeability vari- ability alone [7–12]. Signal peaks were strongest

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when the sensor entered and exited the sample, and the peaks were smaller during the time that the sensor was above the sam- ple. Because signal peaks represent the change in voltage, the peak magnitude is expected to be the greatest at the sam- ple boundary, where the sensor transitioned from air (low conductivity) to CFRP (high conductivity) and vice versa.

Likewise, as the sensor moved across the sample, it traveled across a region of the material that was relatively uniform in terms of conductivity magnitude, which resulted in smaller peaks.

Unlike a monolithic metal, CFRP is characterized by anisotropic conductivity, since the conductive fibers in CFRP laminates can be aligned in any direction. The composite defect sample contained fibers aligned in two (orthogonal) directions, and fibers were non-uniformly distributed in three dimensions, thus making flaw detection difficult. As shown in Fig. 6a, defects in the CFRP were indistinguishable from the noise from the carbon fibers with the small diameter coil.

Modifying coil diameter, and thus the effective region over which the signal is averaged, enhanced flaw detection. At the expense of spatial resolution, a larger-diameter coil increased signal-to-noise [13, 14]. Figure 6b demonstrates improved detectability of the defects in a CFRP composite. With con- stant raster velocity, scan distance varies linearly with time. A scaled outline of the defect side of the composite part is shown in Fig. 6b; the front and back edges of the outlined part line up with the base of the corresponding signal deflections, as shown by the dotted lines. The leading signal deflection was both large in amplitude and broad, obscuring any sig- nals that might have resulted from defects labeled #1 and #2. The three signal deflections observed in the middle of the scan correspond to the leading composite/defect interface for defects labeled #3, #4, and #5. No signal





corresponding to defect #6 was observable, indicating that it was either obscured by the large signal deflection from the back edge, or that the material type at that depth was undetectable.





Fig. 6 Output voltage of the receive coil as a function of time and distance, resulting from a scan across a CFRP sample containing defects labeled 1 through 6. Distance was estimated by corresponding the dimensions of the block to location of peak signals. Scans of the defect

side and the control (no defects) side are shown for the (a) small diameter and (b) large diameter sensor. A scaled outline of the part and defects is placed above the scans in (b)

4. CONCLUSIONS

The results in this study demonstrated expanded capabilities of ECT as it applies to insulators and CFRP composites. The use of ECT on insulators has been experimentally demon- strated at high frequencies, because the contribution from permittivity is greater with increasing frequency. Here we investigated a new approach for designing an ECT sensor in which the resonant frequency of the transmit and receive coils are specifically tuned to maximize signal output from the RC, resulting in a highly sensitive sensor capable of detect- ing defects in insulators at lower frequencies than previously reported. In addition, the dependence on magnetic perme- ability was demonstrated and confirmed to be a contributing factor in ECT.





As the composites industry continues to grow, new NDT methods will be required to meet evolving needs that are not addressable by current methods. Improvements in ECT techniques can extend applications to complex geometries, to those situations which prohibit the use of coupling agents, and to materials with variable electromagnetic parameters, including conductivity, permittivity and permeability. Not only can ECT be applied to cured CFRP composites with complex geometries, but in principle, it can be used to evaluate uncured CFRP prepreg, a specific application that requires the absence of a coupling agent. Valuable time and cost savings could be realized if uncured prepreg laminates could be evaluated for defects prior to cure. The under- standing of ECT as it applies to non-uniformly conductive materials was expanded by the results of this study, demon- strating increased versatility of this type of NDT method.

<u>Acknowledgements</u>: This research was supported by Northrop–Grum- man Corporation. The sensors were designed and supplied by Exel Orbital Systems Inc. Solvay Inc. and Airtech International donated prepreg and consumable materials, respectively. Experimental assis- tance on the project was provided by Ellen Emerson. David B. Chang, PhD, provided assistance in the discussion of physical concepts.

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