46th Annual Review of Progress
in Quantitative Nondestructive Evaluation
QNDE2019
July 14-19, 2019, Portland, OR, USA

QNDE2019-7001

PULSED EDDY CURRENT RESPONSE TO GENERAL CORROSION IN CONCRETE REBAR

I. Eddy, P.R. Underhill, T.W. Krause
Royal Military College of Canada
Kingston, ON

J. Morelli
Queens University
Kingston, ON

ABSTRACT

Corrosion of carbon steel rebar in concrete structures, such as highway bridges and buildings, has a direct impact on their structural integrity, since the rebar provides the tensile strength within the structure. Rebar strength depends on the remaining effective radius of a given rod. Examination of long-time decay, up to 0.1 s, in the transient response of Pulsed Eddy Current (PEC), was examined as a potential method to quantify general corrosion in ferromagnetic rebar. The transient response of a coaxial solenoidal drive-receive coil pair, oriented parallel to the rebar axis, was analyzed over a range of distances into the concrete (liftoff) and rebar radii. At long times, the single exponential decay constant was largely independent of lift-off. A power law relationship for the characteristic decay time, consistent with long-time diffusion of electromagnetic fields into a rod, was observed. The intercept of a best-fit line to measured voltage decay, decreased exponentially with lift-off, and maintained a measurable response up to 110 mm distance for a 25 mm (1 in) diameter rebar. Reported results demonstrate potential for PEC to quantify remaining cross-sectional area of rebar in concrete structures, accounting for distance of rebar within concrete.

Keywords: Concrete Rebar Inspection, General Rebar Corrosion, Pulsed Eddy Current, Electromagnetic Testing

1. INTRODUCTION

Rebar, or reinforcing bar, is placed within concrete structures to provide tensile support. Bridges, buildings and other structures can all undergo cycling stress loads. Concrete on its own provides significant compressive support, but the addition of rebar allows for stability under tensile stress conditions. The condition of the rebar is important for maintaining the structural integrity of buildings, bridges, pylons and other concrete structures.

Rebar is typically made of ferromagnetic carbon steel and is forged into specified lengths and sizes needed for a given application. This production process can result in varying microstructure between rebar samples as the grade of carbon steel and any machining effects can all change the material properties. There is a solid inner metal rod that has ribs protruding around the outer edge running the length of the material in order to mechanically fix it within the concrete. The ribs modify the effective metal diameter of any given rod.

Presence of water and migration of corrosive elements, such as chloride in concrete, may result in rebar corrosion and its conversion to rust. The rust occupies a greater volume than the original steel rod, resulting in expansion that can lead to cracking and deterioration of the concrete.

A number of NDT techniques have been investigated to evaluate concrete integrity [1]. While rebar in concrete can be detected by metal detectors, microwave technology or radiography, capability to determine metal loss, which can be used to determine remaining structural strength, is limited [1].

PEC utilizes a square voltage pulse excitation as opposed to the continuous sinusoidal excitation used in conventional eddy current [2]. The approach to a constant field in the pulse provides magnetization of ferromagnetic materials, enhancing pickup coil responses [3]. PEC has also demonstrated greater sensitivity at high liftoff when compared to conventional eddy current methods [4][5]. The long time decay of the transient voltage response in rods has the general form [6][7][8]:

$$V(t) = Ae^{-t/\tau_D}, \tag{1}$$

where A is a constant and t is the time. τ_D is the characteristic diffusion time, which has the general form [8]

$$\tau_D \sim \mu\, \sigma\, \ell^2 \tag{2}$$

where σ is the conductivity, μ the permeability of the material, and ℓ is a characteristic length, which in the case of a rod is its radius [6].

This work examines the novel application of pulsed eddy current (PEC) for identification of rebar diameter and measurement of remaining material at lift-offs up to 100 mm from a concrete surface.

2. MATERIALS AND METHODS

The experiment investigated 5 rebar samples with varying diameters as shown in Table 1. Four of the samples were original rods, while one was machined from a 25 mm (1”) diameter rod to produce a reduced (7/8”) radius. Nominal diameters were taken as the smallest diameter, as the ridges that surrounded the rebar increased the local radius by up to 1 mm (~0.04”). Rebar samples were labeled according to the fraction of an inch nearest the minimum diameter, which in all cases corresponded to standard rebar sizes except for the smallest diameter (2/5”) sample.

Conductivity measurements were performed on each of the rebar samples in order to compensate for potential variations in this parameter, which is a component of the characteristic diffusion time τ_D as expressed in equation (2). The 4-point method was used to collect the data. A current of 100 mA was driven between the rod ends using a Keithley 6221 DC and AC current source. Voltage was measured over a fixed length on the rod, a minimum distance of two rod diameters from either of the ends. Voltage was recorded using a Keithley 2182A Nanovoltmeter and collected via a LabView program. The voltage, current and cross-sectional area (found using mass measurements and a constant density) was used to calculate the conductivity. Table 1 also indicates the conductivity of each of the rebar samples.

TABLE 1: MINIMUM (NOMINAL) AND MAXIMUM (INCLUDING RIDGE) REBAR DIAMETERS LABELED ACCORDING TO STANDARD DESIGNATIONS IN FRACTIONS OF AN INCH

Sample Fraction Identifier	Minimum Diameter (mm)	Maximum Diameter (mm)	Conductivity (S/m)
1”	24.9	26.3	6.8×10^6
7/8”	22.2	22.2	6.8×10^6
3/4”	18.6	20.4	6.7×10^6
5/8”	15.0	15.8	5.9×10^6
2/5”	10.2	11.2	6.7×10^6

Pulsed eddy current measurements were performed using a Nexum pulser that excited a coaxial solenoidal probe (solenoid pickup coil within a 100 mm long solenoid). A LabView based data acquisition system, operated from a personal laptop computer, was used to record the data. The probe axis was oriented parallel with each of the rebar samples, while distance (liftoff) between the aligned rebar and probe was varied.

3. RESULTS AND DISCUSSION

Figure 1 shows the long-time decay of the transient response obtained from the rebar samples with varying diameter at 0 mm lift-off. Voltage range over which slope is measured, and which is inversely proportional to τ_D as obtained from equations (1) and (2), is between the two red lines. Above the upper red line, voltage is attributed to additional decay times including probe characteristics [3]. The lower red line is a conservative estimate of the noise floor, below which natural log of signal response is no longer linear with time. The observed trend is a decreasing slope and longer time-decay with increasing rebar diameter, in agreement with equation (2).

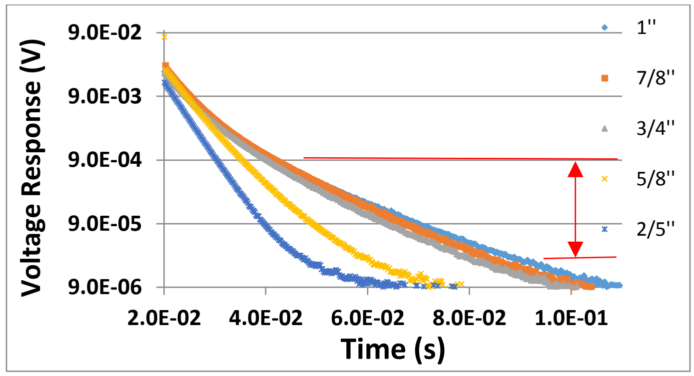

FIGURE 1: SEMI-LOG PLOT OF TRANSIENT RESPONSE AT LONG-TIME DECAY FOR VARYING REBAR DIAMETER. SLOPE OF BEST FIT-LINE IS MEASURED BETWEEN RED LINES

Figure 2 shows an inversed squared power law fit of slopes in Figure 1, multiplied by conductivity (see equations (1) and (2)) plotted as a function of rebar radius. Permeability is assumed to be constant. Error bars incorporate uncertainties in conductivity, permeability and radius. The data shows good agreement with the theory.

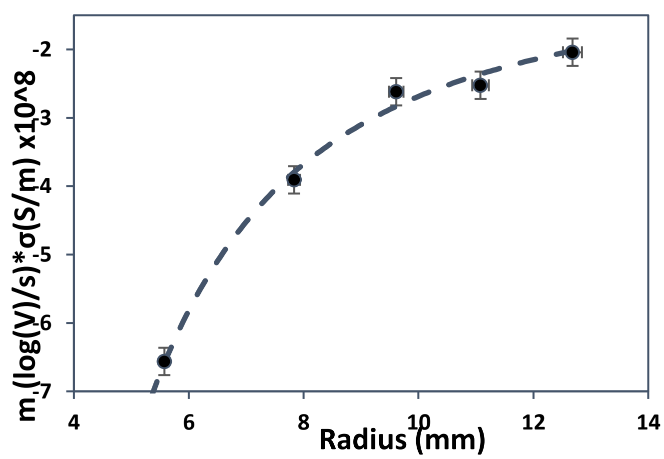

FIGURE 2: SLOPE OF BEST LINE FIT TO DATA IN FIGURE 1 MULTIPLIED BY CONDUCTIVITY AS A FUNCTION OF REBAR RADIUS. DASHED CURVE IS AN INVERSE SQUARED POWER LAW FIT TO THE DATA

Figure 3 shows semi-log plot of transient responses at long-time decay for 1” (25 mm diameter) rebar for various lift-off distances. Slope of lines remains relatively constant up to 100 mm lift-off, beyond which signals fall below the noise floor.

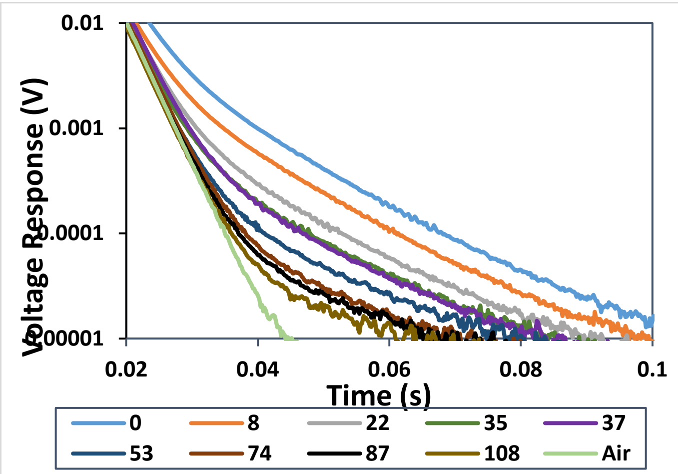

FIGURE 3: SEMI-LOG PLOT OF TRANSIENT RESPONSE AT LONG-TIME DECAY FOR 1” REBAR AT VARYING LIFT-OFFS

Figure 4 shows the intercepts of best-fit lines to data in Figure 3 as a function of lift-off. Data has been fit with an exponential. The curve permits determination of the distance of the probe from the rebar, independent of rebar diameter.

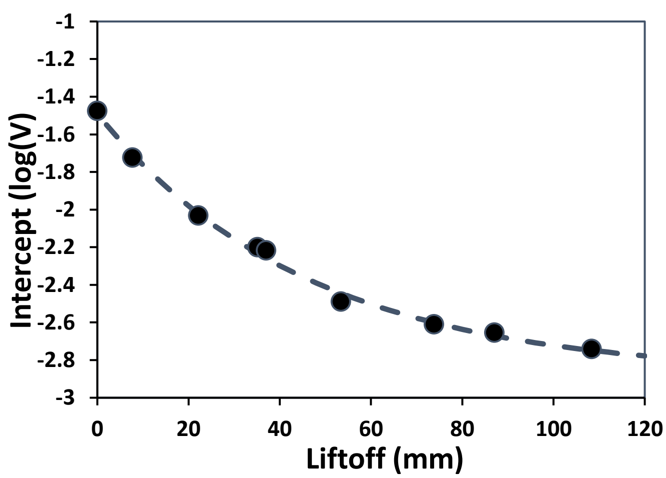

FIGURE 4: INTERCEPTS OF BEST-FIT LINES TO DATA IN FIGURE 3 AS A FUNCTION OF LIFT-OFF. SOLID CURVE IS AN EXPONENTIAL FIT TO THE DATA

The presented results demonstrate the potential application of PEC for determination rebar diameter and distance within concrete, with the prospective of quantifying general corrosion of rebar within concrete. Remaining challenges for technique implementation include increasing the range of detection, by reducing the instrument’s noise floor, taking account of conductivity and magnetic permeability variations, which cannot be easily discernable for concrete-imbedded rebar, accounting for varying ridge sizes and rebar surface preparation, which can modify surface magnetic permeability, presence of rebar sections that pass orthogonally across target rebar and potential interference by neighboring rebars.

4. CONCLUSION

In this paper, PEC response to rebar using a coaxial solenoidal probe was investigated by varying different parameters that could change signal response in the field. The variation of long-time PEC voltage response demonstrated an exponential dependence with a diffusion time that varied as a squared power law with rebar radius in agreement with theory. Diffusion time was largely independent of distance (lift-off) of the probe from the rebar up to 100 mm. The intercept of the linear response in semi-log space, varied exponentially with distance, permitting an independent lift-off determination to be made. This investigation indicates a potential for using PEC to detect and quantify general corrosion of rebar in concrete structures.

ACKNOWLEDGEMENTS

This work was sponsored by Groupe Mequaltech Inc. and Natural Sciences and Engineering Research Council (NSERC) through a collaborative research development grant.

REFERENCES

[1] Ha-Won Song and Velu Saraswathy, “Corrosion Monitoring of Reinforced Concrete Structures - A Review,” *Int. J. Electrochem. Sci.*, vol. 2, no. June, pp. 1–27, 2007.

[2] D. P. R. Desjardins, T. W. Krause, and N. Gauthier, “Analytical modeling of the transient response of a coil encircling a ferromagnetic conducting rod in pulsed eddy current testing,” *NDT E Int.*, vol. 60, Aug. 2013.

[3] J. A. Buck *et al.*, “Pulsed Eddy Current Inspection of Support Structures in Steam Generators,” *IEEE Sens. J.*, vol. 15, no. 8, pp. 4305–4312, Aug. 2015.

[4] T. W. Krause, R. J. McGregor, A. Tetervak, and P. R. Underhill, “Pulsed eddy current sensor for precision measurement at-large lift-offs on metallic surfaces,” Patent No.9;091;664 B2, 2015.

[5] P. F. Lara, “Transient Electromagnetic Method for Detecting Corrosion on Conductive Containers Having Variations in Jacket Thickness,” Patent No. 4,843,319.

[6] B. Von Wwedensky, “Concerning the Eddy Currents Generated by a Spontaneous Change of Magnetization,” *Ann. Phys.*, vol. 64, pp. 609–620, 1921.

[7] L. B. Bean, C. P. DeBlois, R. W. Nesbitt, “Eddy-Current Method for Measuring the Resistivity of Metals,” *J. Appl. Phys.*, vol. 30, no. 12, pp. 1976–1980, 1959.

[8] H. C. Ohanian, “On the approach to electro-and magneto-static equilibrium,” *Am. J. Phys.*, vol. 51, no. 11, pp. 1020–1022, 1983.

