PULSED EDDY CURRENT RESPONSE TO GENERAL CORROSION IN CONCRETE REBAR

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Overview of Presentation

- Motivation & Background
- Theory
- Experimental Setup
- Test Methods & Results
  - Varying Rebar Diameter
  - Varying Liftoff Distances
  - Varying Angle
  - Inspection of Junction Nodes
- Conclusions
- Future Work

Rebar Motivation

- Generally a carbon steel
- Used in structures to stabilize concrete and maintain structural integrity
- Usually layered and cross-hatched
- Steel can corrode over time, causing damage to concrete and degrading tensile strength
- Goal is to determine reduced diameter due to corrosion, when compared to original diameter, independent of rebar depth into concrete structure

[1] https://ridgeend.files.wordpress.com/2014/10/ridge-end-2-224a.jpg

Theory

Magnetic field diffusion equation is given by:

$$\nabla^2 \boldsymbol{B} = \mu\sigma \left(\frac{\partial \boldsymbol{B}}{\partial t}\right) \qquad (1)$$

where B is the magnetic field, μ is material permeability and σ is material electrical conductivity.

Equation (1) has general solution of [1],

$$\mathbf{B}(t) = f\left(e^{-t/\tau_D}\right)$$

where τ_D is the diffusion time.

Magnetic flux, Φ, through a coil loop is given by:

$$\Phi = \int B \cdot da$$

where ‘a’ is the cross-sectional area of the pickup coil.

Theory Continued

- Following Faraday's Law [2], where V is voltage generated, and N is the number of coil turns:

$$V = -N\left(\frac{\partial \Phi}{\partial t}\right)$$

- The diffusion time for cylindrical geometry of radius R is given by [3]

$$\tau_D \sim \mu\sigma R^2,$$

which leads to the following relationship in semi-log space:

$$\log(V) = \left(-\frac{M}{\tau_D}\right) * t + \log(C)$$

where 't' is time, 'M' and 'C' are constants dependent on probe parameters

Transient Response due to PEC

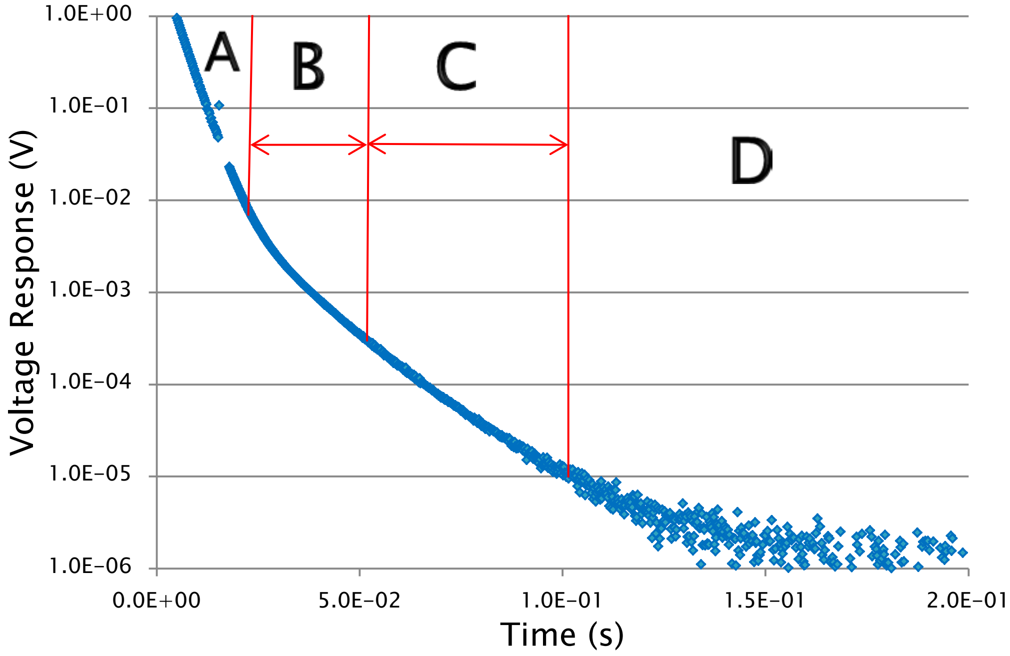


Figure 1 – Regions of the transient response worth note

- A: Decay of signal dominated by probe parameters
- B: The transition area where the response changes from exponential decay dominated by probe parameters to a decay dominated by sample parameters
- C: Useful long-time decay region that is analyzed
- D: Noise floor reached (1E-5V)

Experimental Setup

Figure 2 – Data acquisition setup

- As seen in Figure 2 on the left, the solenoid coil is within the upper half of the black rod
- The green button activates data acquisition
- Response from rebar samples, Figure 3 on right, was obtained at varying liftoff

Figure 3 – From left to right diameters (closest fractional inches): 1”, 3/4”, 5/8”, 2/5” (untouched rebar samples), 7/8” (lathed rebar), 1 ½” (smooth rod)

Permeability, μ, and Conductivity, σ

- Expression for diffusion time:
  $$\tau_D \sim \mu \sigma R^2$$
- Eddy-current indicated all samples had similar permeabilities.
- 4-point measurement used to determine conductivity

Table 1 – Parameters of rebar, including conductivity (green)

Label	Radius(mm)	Conductivity (S/m)	Error (S/m)
1 1/2"	19.0	6.90E+06	3E+04
1"	12.7	6.84E+06	3E+04
7/8"	11.1	6.84E+06	2E+04
3/4"	9.6	6.68E+06	2E+05
5/8"	7.8	5.92E+06	4E+05
2/5"	5.6	6.69E+06	3E+05

Varying Diameter

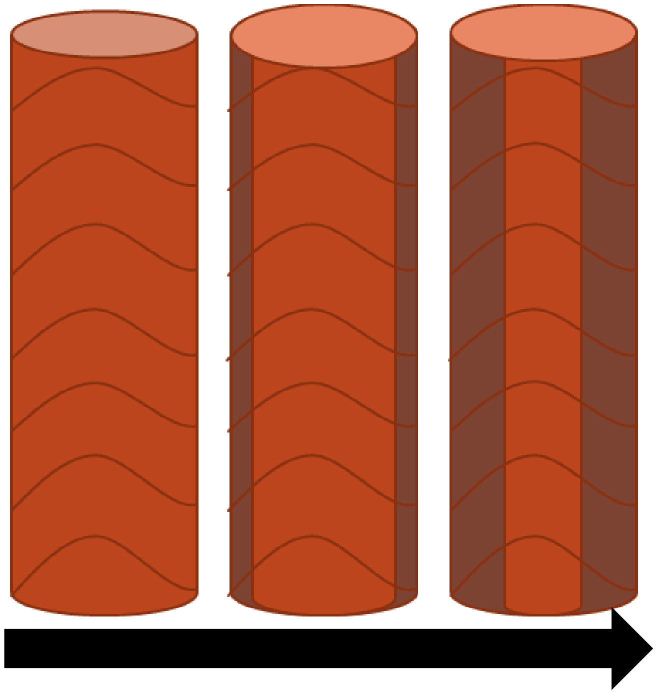


Figure 4 -Corrosion progression over time

- Ingress of water and salt into concrete may deteriorate rebar over time
- Effective strength relies on non-corroded areas
- Effective diameter picked up by PEC is the metallic middle unaffected by corrosion
- Fig 4 shows effective inner ferromagnetic diameter

Varying Rebar Diameter Data

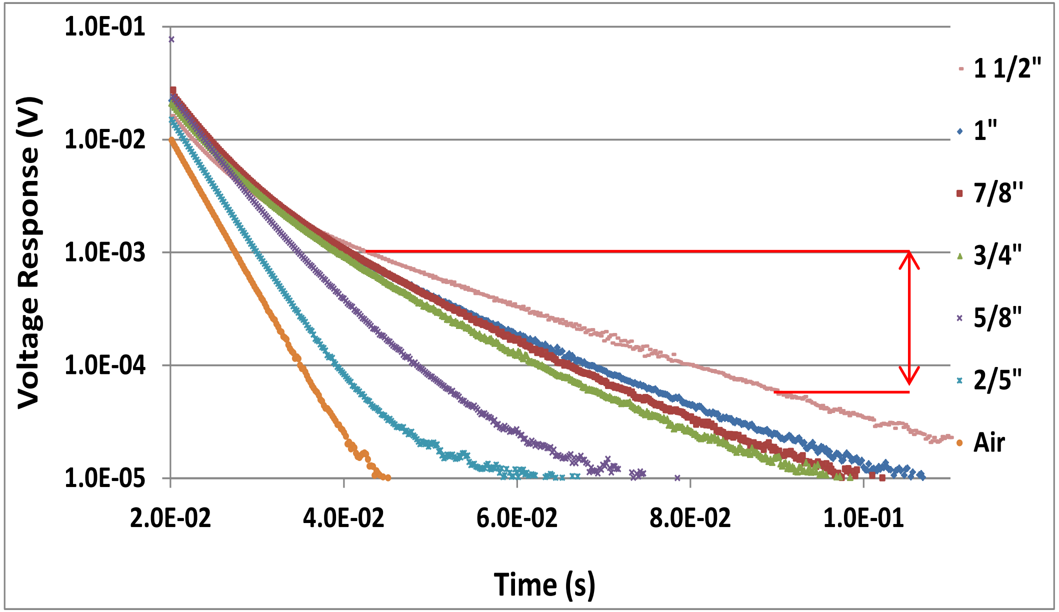


Figure 5 – The transient response to varying rebar diameters from a pulsed Eddy current solenoid coil.

- Noise floor reached at 1.00E-05V
- Solenoid used couples better with diameters close to 1” (~25 mm)
- For sake of initial data analysis, long term decay slopes were taken over the voltage response range of 1E-3 V to 7E-5 V.
- It is noted that the long-term decay transition is present for ½” & 5/8” at 0.048 s & 0.06 s, respectively, but approaches the noise floor.

Relationship Between Slope & Diameter(mm)

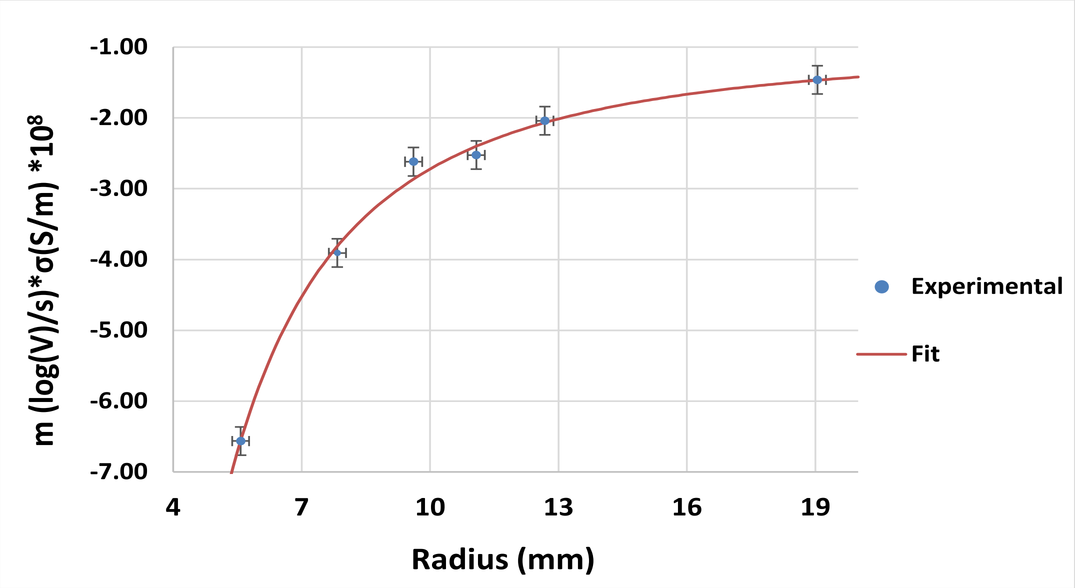


Figure 6 –Power law relationship between diameter of rebar and long time decay slope

- Values found through Matlab curve fitting tool
- y-axis values were graphed/fitted through $\log_{10}$ conversion
- Slope continues to increase in magnitude

- When slope is multiplied by conductivity, then relationship shows R^{-2} relationship
- Permeabilities were similar (except for carburized surface of 1" Sample)

$$m\sigma = (-173.2 * \boldsymbol{R}[mm]^{-2} - 0.9902)x10^8$$

Introducing Liftoff (Concrete Modeling)

- Signal strength is affected by distance of probe from rebar
- Noise floor is reached at ~1E-5 V with current system
- At what liftoffs can we still accurately collect data?
- What is the relationship between intercept of long-time decay and liftoff?

- Can the 2 methods be combined to determine depth and remaining diameter of rebar?
- 1" Sample was examined, as it gave strongest response

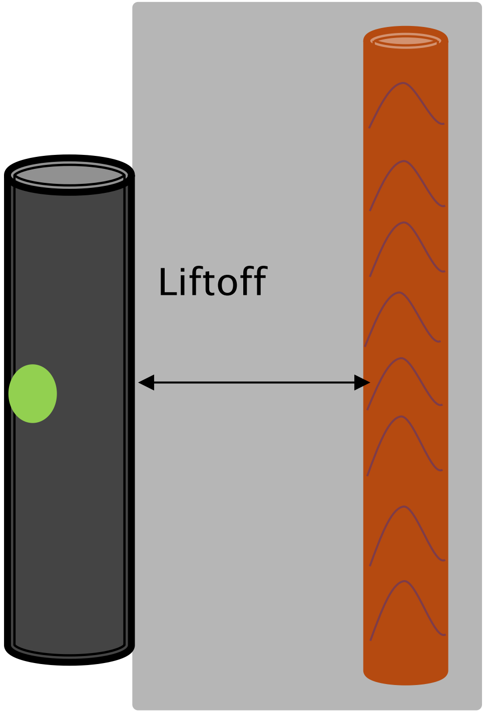


Figure 7 – General idea behind liftoff with rebar

Varying Liftoff for 1'' Rebar

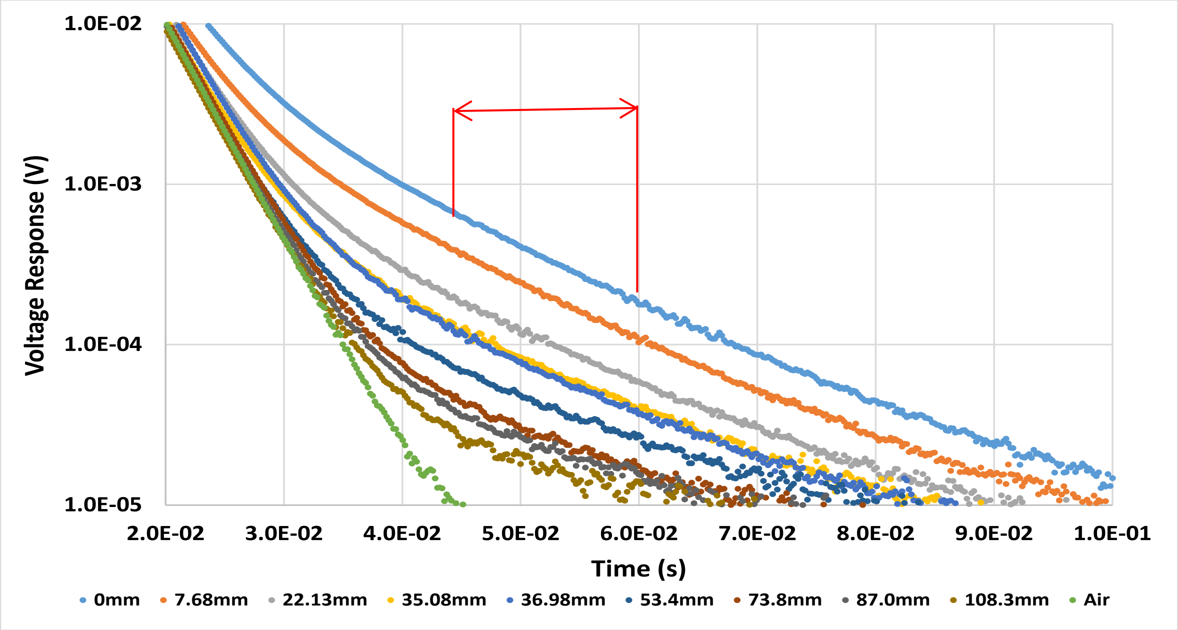


Figure 12 – Zoomed in area of the transient response on a semi-log graph for varying liftoff between solenoid probe and rebar. Response due to just air is also plotted.

- Slopes are all similar
- Voltage range of linear response in semi-log plot varies
- Slopes were at looked at over the range of 0.045s–0.06s

Relationship Between Intercept & Liftoff

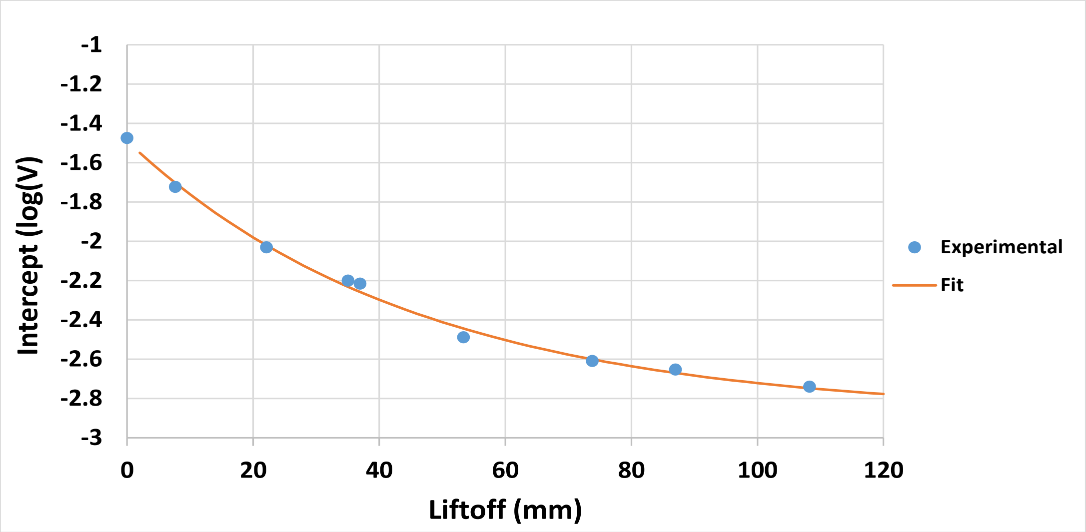


Figure 13 –Exponential decay relationship between liftoff from rebar and long time intercept

- As expected, slopes remain similar, while intercept values change.
- A discrete relationship between liftoff and intercept was found
- Exponential relationship present between intercept of the long time decay and the liftoff
- Decay term of 46 mm. The signal decreases by 39% every 46 mm.

$$b = 1.39 * e^{-LO/46} - 2.88$$

b – intercept value [log(V)]; LO – liftoff [mm]

Variance of Coupling Angle

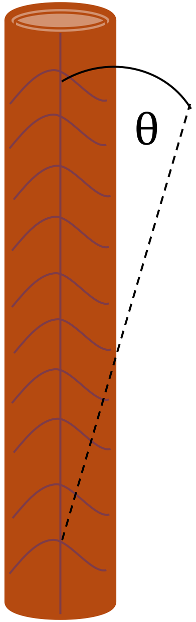


Figure 14 – Diagram of coupling angle

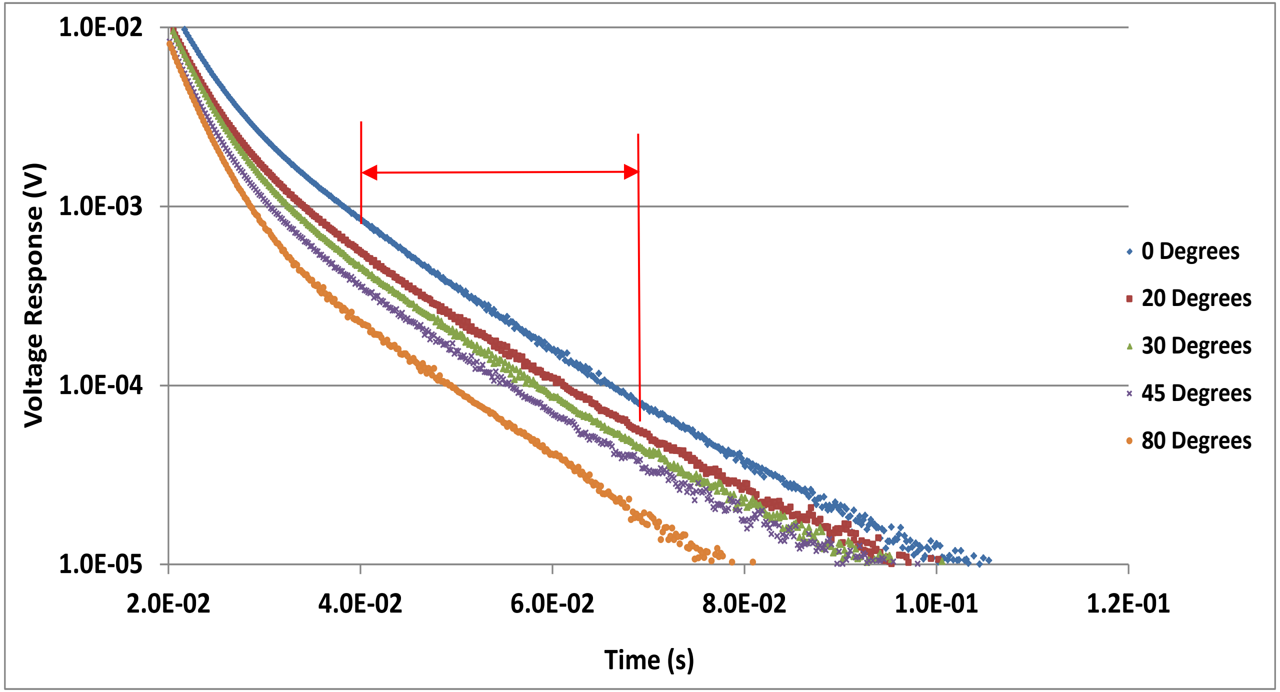
Coupling Angle

- Solenoid coil is being used to collect data
- Expected to have a stronger response when rod is inline with rebar (θ=0°)

Experimental Method

- 1” rebar was used
- Zero liftoff (in contact)
- Collected data at angles of 0°, 20°, 30°, 45° and 80°
- As θ increased, the slope of the long-term decay barely changed, while the response decreased

Coupling Angle Response



- Long time decay section reached at ~0.03 s for all measurements
- Range up to 80° tested

Figure 15- Transient response on a semi-log graph at varying angles between solenoid coil and rebar

Coupling Angle Results

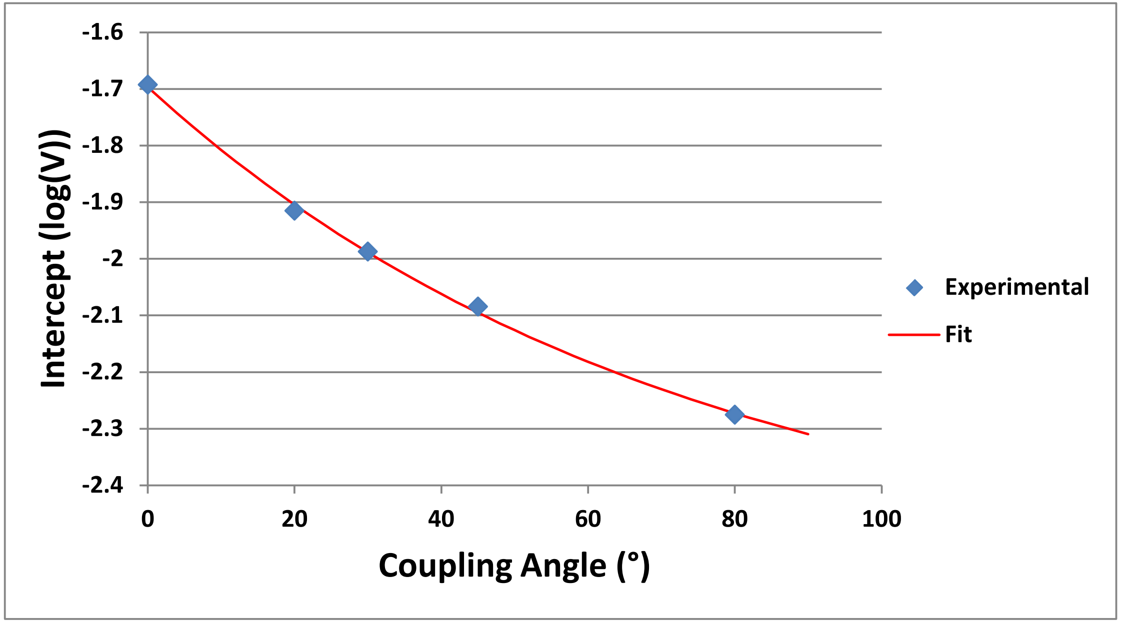


Fig 16 – Exponential decay relationship for coupling angle

$$b = 0.86e^{-\theta/71} - 2.56$$

Slopes remain similar, intercept decreases with increased θ

- Shows exponential decay relationship
- With a L/2*sinθ conversion, decay constants are similar

Rebar Junctions

- Potential issues arise when junctions are considered
- Due to nature of the size of rebar available for testing and lack of repeatable sizes 1'' & ¾'' rebar were used
- It is expected that superposition of the individual signals will occur

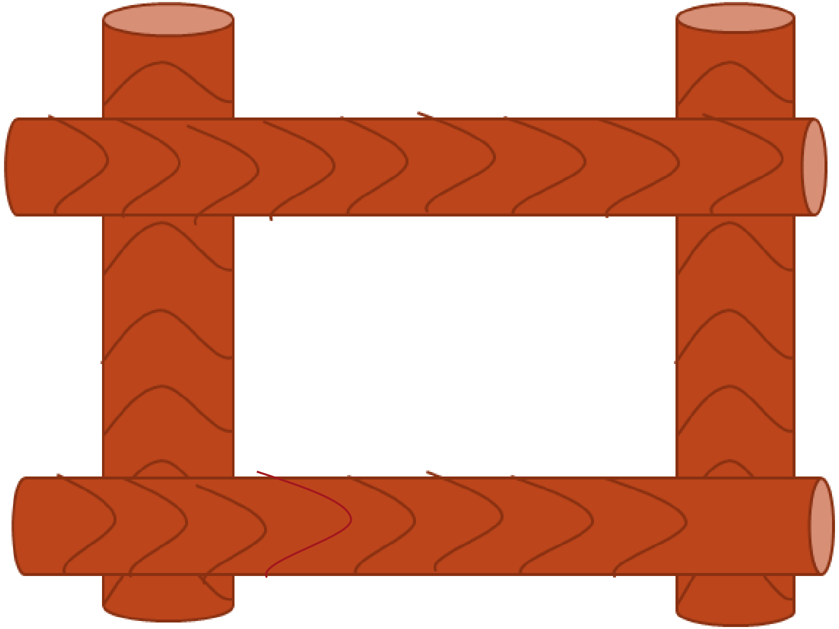


Figure 16- Crossed rebar area that will also affect signal

Junction Configuration Examined

- Example configuration:
  - 1” Rebar in front of ¾” Rebar
  - Probe is parallel to ¾” Rebar

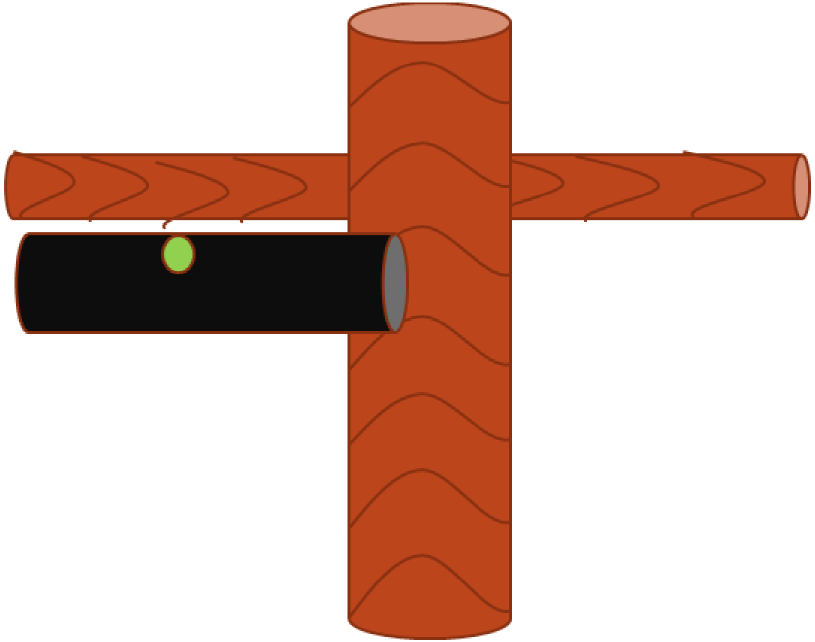


Figure 17- Measured configuration

Junction Response

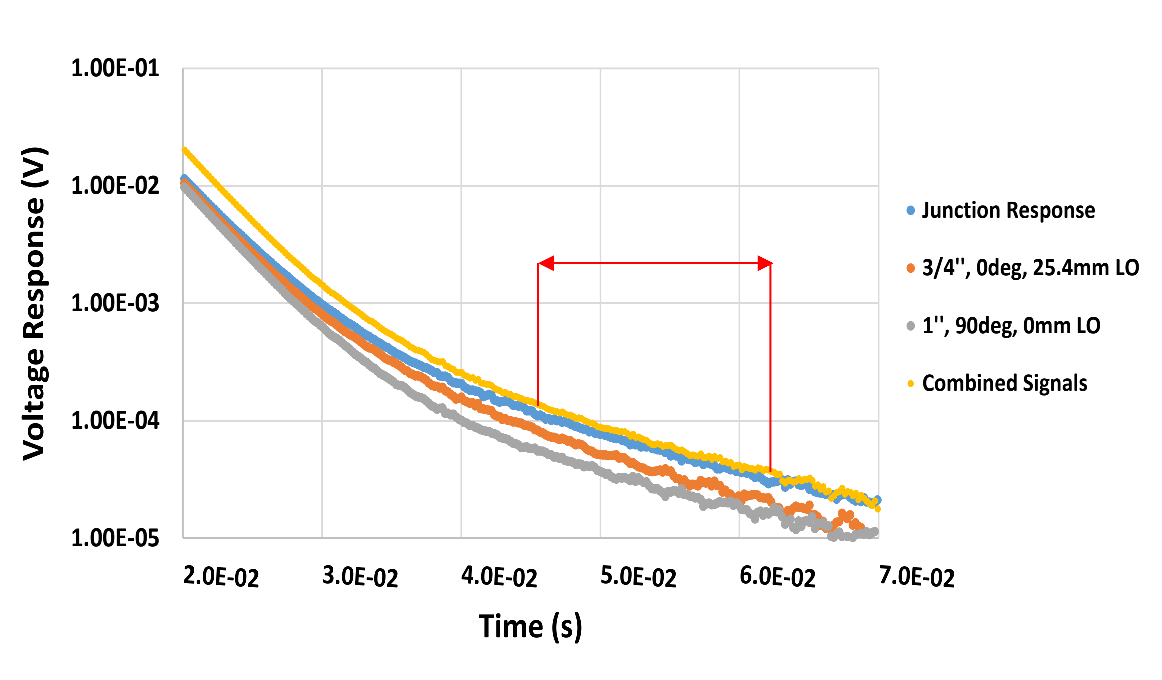


Figure 18- Transient response on a semi-log graph, while looking at example where 1’’ rebar is in front of ¾ ’’ rebar and probe is aligned with the ¾’’ rebar.

- Demonstrates superposition principle
- Signal response similar to addition of two individual signals
- Good agreement between superposed response (yellow) & experimental (blue) over sampling range

Conclusions

- Varying diameter of rebar changes slope of long-time decay in a semi-log plot. Inverse of the slope varies as radius squared, in agreement with theory
- For increasing liftoff, slopes remain similar, but intercept decays exponentially
- Varying coupling angle also changes transition voltage and response is similar to liftoff
- In the case of junctions signal response is dominated by the rebar that the probe is parallel to
- Effect of signal superposition is observed in this case

Future Work

- Optimize coil diameter for target rebar diameter
- Examine junctions with same sized rebar
- Perform field trials on rebar embedded in concrete

Acknowledgements

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Questions?

References

[1] J. D. Jackson, "Magnetostatics, Faraday's Law, Quasi-Static Fields," in *Classical Electrodynamics*, Hoboken: John Wiley and Sons, 1999, p. 17423.

[2] R. Nave, "Faraday's Law," *Hyper Physics*. [Online]. Available: http://hyperphysics.phy-astr.gsu.edu/hbase/electric/farlaw.html.

[3] B. Von Wedensky, "Concerning the Eddy Currents Generated by a Spontaneous Change of Magnetization (Translated - Jan. 2008)," *Ann. Phys.*, vol. 64, 1921.