Frequency considerations for a system using phase information to detect and image corrosion in steel rebars located at distances of 8-9 cm.

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Abstract

Professor Gaydecki’s group at The University of Manchester have imaged steel rebars using a system comprising of a square DC field generating coil with an array of sensors underneath, which produces an image without using a scanner. A square coil was used to generate an AC magnetic field allowing the skin depth principle to be used to detect corrosion. Also the receiver was placed in an orthogonal position instead of the original vertical position, enabling corrosion to be detected at deeper distances, particularly when using the phase information. When generating images of an area there is an optimum frequency range to enable the changes due to corrosion to be visualized.

1. Introduction

Reinforced concrete is used through the world in the construction industry to build offices, blocks of flats, bridges and large buildings, being cheap and easy to use. Because concrete has no physical strength on its own, it is reinforced with steel bars, called rebars. The steel embedded in the concrete can sometimes be subject to corrosion, which can be potentially disastrous if left to advance, leading to the collapse of the structure. If the corrosion is detected in the early stages, remedial work can be carried out on the structure to strengthen it. The rebars are embedded in the concrete up to a distance of 10 cm. Because the steel bars are embedded in the concrete it would be necessary to destroy the concrete to inspect them, which is undesirable. This has lead to the development of various non-destructive testing methods. The main non-destructive techniques are ultrasound, radar and microwave radiation, x and gamma rays and AC and DC magnetic field scanning. Concrete is essentially invisible to DC and AC magnetic fields, so these can be used to obtain information about the steel bars embedded in it. The disadvantage of using a DC magnetic field is that it can only detect cracks or loss of material in the steel bars, whereas AC magnetic fields induce currents in the surface of the bars due to the skin effect, enabling surface corrosion to be detected and producing both amplitude and phase information. Corrosion can be detected in a non-destructive manner using magnetic field imaging, the group at Manchester has in the past managed to image corrosion using eddy current techniques [1] and [2] and up to now detection has been successful using an AC magnetic field down to a depth of 4-6 cm [3], but since it is possible that the rebars may be located at a distance of 10 cm, the detection distance must be increased.

2. Background theory

The inductive scanning system comprises a driving coil, which generates a magnetic field, if a bar is present in the field, the time varying magnetic field induces eddy currents which in turn generate an opposite magnetic field. The characteristics of the reflected field, phase and amplitude, depend on the bar properties. The driving coil behaves in a similar way to a coil antenna operating in the near field region. One of the characteristics of the antenna near field
region is that the field decays as $1/r^3$, where $r$ is the distance from the coil. The driving coil can be optimized so that it generates the biggest field possible for the least amount of ampere-turns at the distance where the target bar is located.

3. Experimental Setup

A square coil measuring 30 x 30 cm with 18 turns was used. Quek et al showed that a square coil produced a more uniform field than a circular shape [4]. According to calculations 30 x 30 cm is the optimum coil measurement to generate a maximum field at 10 cm using the By component, the same should be true for the Bz component. The receiver sensor is a wound coil with a ferrite core. To measure Bz, this sensor is placed orthogonally with respect to the coil and because the value of Bz is zero in the plane of the coil it is placed as near as possible to the coil plane. Placing the sensor as near as possible to the plane minimises the pick up from the transmitting coil field as compared to the field from the bar. This sensor was positioned below the driving coil, in between the coil and the metal bar, the sensor then was moved around the area covered by the coil using a Labview controlled scanning system [5], stopping at specific x and y coordinates so as to cover the area in a manner similar to a grid. An amp meter is attached to the driving coil and then the driving voltage is adjusted to produce the required current, as the magnetic field is proportional to the current. An automated measurements setup using an oscilloscope and controlled via a Labview program was used to measure the amplitude and phase of the sensor at each point. Alternatively, the bar can be moved instead of moving the sensor, this enables the sensor to be placed in an optimum location beneath the square coil, the best location being the centre where the field, measured as a voltage, picked up by the coil was at its lowest, which was crucial to detect corrosion.

3. Results

Scans were carried out covering the whole area beneath the transmitter coil. Because of the skin effect, an AC current will circulate near the surface of a conductor and as the current frequency increases, the region where conduction occurs diminishes. As corrosion begins on the bar surface, higher frequencies should generate better results, with the limitation of the intensity of the magnetic field. As frequency increases so will the impedance of the coil, limiting the current circulating resulting in a lower magnetic field intensity. The bar used was a bar which had one half corroded and the other side intact, see figure 1.1. Scans were carried out at various frequencies and with the top of the bar at different distances to the sensor coil, at 3, 6, 8.8 and 10 cm. The current was set to 0.85 Amperes, except at the higher frequencies where it was lower due to the increase in inductance of the transmitting coil and the signal generator voltage limitation. The frequencies scanned were 600 Hz, 2,4,7,8,10,12,13,15, 20 and 30 kHz, above this frequency the current available is too low.

At 600Hz, the image generated using the phase information to compare the half corroded bar in the two different positions does not show any evidence of detecting corrosion. At higher frequencies corrosion detection improves which increases as the frequency rises. It would be expected that corrosion detection would be the best for the highest frequency for which the current was of a reasonable amount. This is certainly the case when the bar is moved beneath the sensor but it is not true when the sensor is moved about beneath the transmitter.

Figure 1.1 Half corroded steel bar used for scanning, the top half of the bar has been corroded.
corroded, the lower half is steel.

generating an image similar to an array of sensors. Figure 1.2 shows the profile of a steel bar, obtained from scanning the area under the coil, the bar is shown lengthwise along the y axis, at 6 cm the highest phase values are at higher frequencies, which show a much more peaky profile, the phase peaks appear at the same field points, y=-20 mm. This point must be a sensitive region in the field. Figure 1.3 shows a similar profile at 8.8 cm, in this case 4 kHz shows a high phase value for a low frequency which ties in with the fact that the half corroded bar difference was high at some of the low frequencies at 8.8 cm.

![Figure 1.2 Profile of a steel bar at different frequencies, the distance from the sensor to the top of the bar is 6 cm, the scan is an image obtained by subtracting the bar scan versus the coil scan without a bar.](image1)

![Figure 1.3 Profile of a steel bar at different frequencies, the distance from the sensor to the top of the bar is 8.8 cm, the scan is an image obtained by subtracting the bar scan versus the coil scan without a bar.](image2)
From the previous results, the best frequency to image the full area beneath the square coil and obtain an image of corrosion versus the coil appears to be around 10 kHz. Many scans were carried out at different frequencies and the only images which showed indication of corrosion versus the coil were found to be at frequencies around 10-12 kHz. At these frequencies, the phase shift is big enough and there is some skin effect but the profile has not become too peaky. The following figures, figures 1.4, figure 1.5 and 1.6 show the half corroded bar at 10 kHz, at this frequency it appears corrosion can be detected at a distance of 8.8 cm, both by comparing the half corroded and non-corroded sections of the half corroded bar and by comparing both positions of the half corroded bar against the coil, shown in figures 1.4 and 1.5. Figure 1.6 shows a metal bar without any corrosion versus the coil field, it showing a symmetrical image around the peak where the magnetic field is most sensitive to phase. These images have been enhanced by detecting the position of the bar and amplifying the data to improve visualization, to obtain a good image the bar must be located in the sensitive area of the field.

**Figure 1.4** Half corroded bar at 10 kHz, the distance from the sensor to the top of the bar is 8.8 cm, this image shows a bar with corrosion in the region of $y = 0$ mm to $y = -80$ mm, the scan is an image obtained by subtracting the bar scan versus the coil scan without a bar.
Figure 1.5 Half corroded bar at 10 kHz, the distance from the sensor to the top of the bar is 8.8 cm, this image shows a bar with corrosion in the region of \( y = 0 \) mm to \( y = 80 \) mm, the scan is an image obtained by subtracting the bar scan versus the coil scan without a bar.

Figure 1.6 Steel bar at 10 kHz, the distance from the sensor to the top of the bar is 8.8 cm, the scan is an image obtained by subtracting the bar scan versus the coil scan without a bar.
5. Conclusion
The orthogonal sensor enabled an area scan to produce images showing corrosion at deeper distances around 8-9 cm. Results obtained with a stationary sensor located in one position show that the highest frequencies are the best to detect corrosion. However if the sensor is used in different locations under the non uniform field generated by the transmitter, the optimum frequencies to visualize corrosion are in the range of 10-12 kHz as these produce a more uniform profile of the bar. Frequencies in this range should be ideal if the transmitter area is to be covered by an array of sensors.

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References
[1] P. Gaydecki, S. Quek, G. Miller, B.T. Fernandes, M Zaid. “Design and Evaluation of an Inductive Q-Detection Sensor Incorporating Digital Signal Processing for Imaging of Steel Reinforcing Bars in Concrete,” Meas. Sci. Technol., Vol. 13, 2002.

[2] G. Miller, P. Gaydecki, S. Quek, B. T. Fernandes, M. Zaid. “A Combined Q and Heterodyne Sensor Incorporating real Time DSP for Reinforcement Imaging, Corrosion Detection and Material Characterisation,” Sensors and Actuators A. Vol. 121. June 2005.

[3] G. Miller, P. Gaydecki, S. Quek, B.T. Fernandes, M. Zaid. “Detection and Imaging of Surface Corrosion on Steel Reinforcing Bars Using a Phase Sensitive Inductive sensor Intended for Use with Concrete,” NDT&E International 36, 2003.

[4] S. Quek, D. Benitez, P. Gaydecki, V. Torres. “Studies on Geometries for inducing Homogeneous Magnetic Fields in the Application of Real Time Imaging of Steel Reinforced Bars Embedded Within Pre-Stressed and Reinforced Concrete” Review of Quantitative Nondestructive Evaluation vol 25. 2006

[5] D. Benitez, S. Quek, P. Gaydecki, V. Torres. “A 1D solid state array system for real time magnetic field imaging of steel reinforcing bars embedded within reinforced concrete” IEEE Transactions on Instrumentation and Measurement. 2007.