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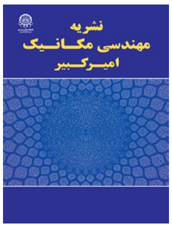

Experimental and Numerical Investigation on the Reinforcement Cover to Concrete Surface Using Eddy Current

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ABSTRACT: Non-destructive testing is one of the techniques which is used to ensure the health in concrete structures. To reinforce a concrete column, it is necessary to know the number of embedded reinforcements in the concrete and the reinforcement cover to the concrete surface. In the present paper, the finite element method was employed to obtain the reinforcement cover to the concrete surface in a concrete column using Maxwell commercial software. Then, a measuring probe was designed and fabricated. In the presence of a coil with a ferrite core, the conductive reinforcement interacts with low-frequency electromagnetic waves. The location of the reinforcement could be estimated measuring effects of these waves on the concrete surface. The designed probe was investigated in different distances and frequencies. The reinforcement cover to the concrete surface could be estimated through variations of inductance and ohmic resistance of a coil in a constant frequency and voltage. The full factorial design of experiments method was applied to investigate influences of the reinforcement cover to concrete surface and frequency on ohmic resistance and inductance of the measurement probe and a regression model was proposed for effective parameters. Finally, a neural network was used to estimate the reinforcement cover to concrete surface based on the frequency and ohmic resistance of the measuring probe.

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1- Introduction

Non-destructive testing plays an important role in investigating concrete structures. These techniques are used to evaluate the structure, quality, and embedded substrates [1]. The cover meter is a device which is used to estimate the location of the reinforcement and the cover to the concrete surface [2]. Eddy current test with a low-frequency magnetic field is a well-known non-destructive testing technique which is featured well by authors [3, 4]. Using an eddy current probe and measuring ohmic resistance and inductance in a given frequency, reinforcement corrosion was evaluated in addition to the determination of reinforcement cover to the concrete surface [5]. A neural network could be used to obtain the depth and thickness of reinforcements embedded in the concrete. A wide range of reinforcement cover to concrete distance and also various reinforcement diameters were determined using neural networks [6].

2- Theory

The influence of eddy currents which are induced by the magnetic field on impedance and ohmic resistance of measuring probe could be calculated using Maxwell equations [7, 8].

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{1}$$

$$\nabla \times H = J + \frac{\partial B}{\partial t} \tag{2}$$

$$\nabla \cdot \mathrm{D} = \rho \tag{3}$$

$$\nabla \cdot \mathrm{B} = 0 \tag{4}$$

where E is the electric field intensity (V/m), H is the magnetic field intensity (A/m), D is the electric flux density (C/m^2), B is the magnetic flux density (Wb/m^2 or T), J is the electric current density (A/m^2), ρ is the electrical charge density (C/m^3).

3- Finite Element Simulation of the Magnetic Field

In the present study, the eddy current package of the Maxwell software was used to obtain ohmic resistances and inductances of measuring probes in different reinforcement covers to the concrete surface. To simulate the experimental procedure using dominant equations of eddy current, the experiment geometry, material, and boundary condition applied to the software.

4- Experiments

Devices which were used in this study to measure reinforcement cover to the concrete surface include reinforced concrete samples, measuring probe, and electronic devices such as wave generator, digital multi-meter, oscilloscope, and LC-meter.

5- Design of Experiments

To evaluate the influences of distance and frequency on ohmic resistance and inductance of the measuring probe the full

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Table 1. Design of experiments

Parameters	Level 1	Level 2	Level 3	Level 4
Frequency (Hz)	5000	20000	50000	-
Distance (cm)	1	2	3	4

Table 2. Influences of frequency and distance on ohmic resistance of the measuring probe

Source	Sum of squares	Freedom degree	Mean of squares	Fischer number	*P*-value
Frequency	206224880	2	103112440	2784367.10	0.000
Distance	1218226	3	406075	10965.34	0.000
Frequency × Distance	1640182	6	273364	7381.70	0.000
Error	24	889	37		
Total	35	209084178			

factorial design of experiments with three replications was used which is presented in Table 1.

6- Results and Discussion

The influences of frequency and distance (reinforcement cover to the concrete surface) were evaluated. Considering these two parameters and also the design of experiments and replications, 36 tests were carried out in total. The outputs are ohmic resistance and inductance. It was determined that distance and frequency are not significant corresponding to the measuring probe inductance. However, considering that the P-value is lower than the significance level according to Table 2, all main effects and interactions of frequency and distance are significant corresponding to the ohmic resistance of the measuring probe.

Because the clearer results were obtained for ohmic resistance corresponding to the various distances in the frequency of 50 kHz, a quadratic regression equation with the correlation factor, R2, of 0.97 was proposed to estimate ohmic resistance of the measuring probe in 1, 2, 3, and 4 cm distances as follows.

$$R = 7112 - 1372d + 202.7d^2 \tag{5}$$

Where R is the ohmic resistance of the measuring probe in Ohm and d is the distance (reinforcement cover to the concrete surface).

7- Determination of Reinforcement Cover to the Concrete Surface

Evaluation of ohmic resistance of the measuring probe in different frequencies and distances which is done to predict reinforcement cover from concrete distance was simulated numerically. Various experiments were carried out and the corresponding data were recorded which were then used to train the neural network. Totally, 140 tests were carried out using different frequencies and distance levels and the corresponding ohmic resistances of the measuring probe were recorded. The neural network structure consists of two inputs including distance and frequency and one output which was ohmic resistance of the measuring probe. The number of neurons was considered to be 1 to 30. The neural network was trained ten times for each neuron. Five experiments using various frequency and distance levels were carried out to validate the simulation. Table 3 presents some examples of the experimental data using different frequencies and distance levels and also what are get using the Artificial Neural Network (ANN) and also corresponding errors. The evaluation of errors suggests that the minimum error occurs in the case of a frequency of 50 kHz.

Table 3. The evaluation of the neural network

Frequency (Hz)	Distance (cm)	Experimental ohmic resistance (Ohm)	ANN results for ohmic resistance (Ohm)	Error percentage (%)
500	1.5	6.2	6.42	0.22
750	3.5	4.6	4.97	0.37
1000	2.5	6	5.89	0.12
3000	4.5	8.2	8.86	0.66
10000	4.5	47	47.16	0.16
50000	3.5	4837	4836.98	0.02

8- Conclusions

Various non-destructive testing methods were evaluated to investigate the reinforcement cover to the concrete surface. The Maxwell commercial software was used to simulate the measuring probe and to investigate the influences of the magnetic field which is created in the result of the presence of reinforcement in the concrete in various frequencies and distances. A measuring probe was designed and fabricated using the data obtained from this simulation. The manufactured probe was tested using eddy currents in different frequencies and distances and then, the best frequency was determined.

Frequency, distance, ohmic resistance, and inductance were optimized using the design of experiments. The results suggest that the effects of frequency and distance are not significant corresponding to the inductance while they are significant in the case of ohmic resistance of the measuring probe. In the frequency of 50 kHz, the ohmic resistance was clearer for various reinforcement covers to the concrete surface. A regression model was also proposed to estimate ohmic resistance of the measuring probe properly in different reinforcement covers to the concrete surface. The proposed model suggests that any increase in distance results in a decrease in ohmic resistance in a constant frequency. A neural network was also proposed to predict interval values of reinforcement cover to concrete surface based on frequency, ohmic resistance, and distance parameters. Comparing experimental and ANN results suggests that the minimum error percentage occurs when the frequency of 50 kHz is used.

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