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Detecting the Diameter and the Depth of Steel Reinforcing Bar in Concrete Using Electromagnetic Method

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Abstract

When corrosion happens with the steel reinforcing bar (rebar) in concrete, the diameter of the steel rebar is reduced. It is possible to judge the corrosion of the steel rebar by measuring the diameter of the steel rebar nondestructively. We developed an electromagnetic method to detect the diameter and depth of the steel rebar in concrete simultaneously. In this method, the eddy current testing method with two probes was developed. To avoid the interference between the two probes, two excitation frequencies of 3.8 kHz and 4.2 kHz are used. With this system, it was possible to evaluate the depth and the diameter of the steel rebar and the resolution of better than 1 mm was obtained.

Keywords: steel reinforcing bar; electromagnetic method; concrete; nondestructive evaluation; corrosion.

1. Introduction

For the steel rebar in the concrete, due to the protection of the concrete cover and the high pH value of the fresh concrete, corrosion speed of steel rebar is very slow in the beginning. However, as time passes the above conditions tend to alter. Water, salt, O_2, CO_2, and industrial gases (if present) slowly begin penetrating the concrete. Both the pH value and the protective quality of concrete are reduced. The corrosion speed increases rapidly when chloride ions penetrate to the steel rebar through some cracks of the concrete. The big volumes of corrosion products also cause the damage of concrete. The corrosion of steel rebar reduces the strength of the concrete structures so the periodic inspection of the steel rebar in concrete is necessary and important. Knowing the conditions of the steel rebar, such as the location, the diameter, and the corrosion of steel rebar, is important for the safety evaluation of concrete structures.

DC field magnetic flux leakage method [1-3], AC field electromagnetic induction method [4-9], radio frequency microwave radar system [10-12], and eddy-current thermography technology [13-14] have been used to evaluate the break, the location, or the corrosion of the steel rebar in concrete.

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The DC field magnetic flux leakage (MFL) method uses a powerful magnet to magnetize the conductive material under test (usually steel). Where there are defects (corrosion or material loss) the magnetic field "leaks"

from the steel. MFL method is mainly used to detect breaks in prestressing steel of pretensioned and post-tensioned concrete structures.

The radio frequency microwave radar systems can be used to detect the position and the covering depth of the steel rebar. Due to the high frequency (usually hundreds of MHz or several GHz) used by radar system, the moisture in the concrete may influence the detection accuracy, and it is difficult to detect the second layer steel rebar for the concrete with steel rebar grid. Eddy current thermography technology is not suitable to detect the steel rebar with deep depth because of the worse thermal conductivity of concrete cover.

3D X-ray tomography [15] is used to get the 3D image of the corrosion products. The resolution is good, but the emitter and the detector of X-ray is often put on the opposite sides of the sample, which is difficult for field experiments. Ultrasonic method [16] is also used to evaluate the corrosion of the steel rebar, but the stones and small holes in the concrete produce noises and that reduces the signal-to-noise ratio of ultrasonic method.

Compared with other nondestructive evaluation methods, the low frequency electromagnetic induction method has the advantages of easy operation and low cost and easy operation. It can be used to detect the covering depth and diameter of the steel rebar. For the low frequency electromagnetic method, the moisture of concrete also has less influence to the detection results. However, for commercial electromagnetic system, the depth resolution or depth accuracy is not good enough to evaluate the diameter reduction of steel rebar due to corrosion.

We developed electromagnetic evaluation system with double probes to detect the depth and the diameter of steel rebar in concrete simultaneously, and the detection accuracy was also improved.

2. Experimental setup

Figure 1 shows the schematic diagram of the electromagnetic system to measure the diameter and the covering depth of steel rebar. The system was composed of two probes. Each probe had a detection coil, an excitation coil, a signal generator and a demodulator. An AC magnetic field was produced by the excitation coil when an AC current, produced by the signal generator, flow into the excitation coil. The detection coil was used to detect the magnetic fields induced by the steel rebar. The output signals of the detection coils were amplified by the amplifiers and the demodulators were used to get the amplitudes of the signals. Using the output signals of V1 and V2 of the two probes, the diameter and the covering depth of steel rebar could be obtained by data processing and calculation.

The experimental conditions were as following: Both the two excitation coils are 100 turns with the same diameter of about 70 mm. The two detection coils had the same diameter of 10 mm and 200 turns. The gains of the amplifiers were 20 dB. The distance between the two excitation coils was about 10 mm. To reduce the interference between the two probes, the two probes had different frequencies. One frequency was 3.8 kHz and another frequency was 4.2 kHz.

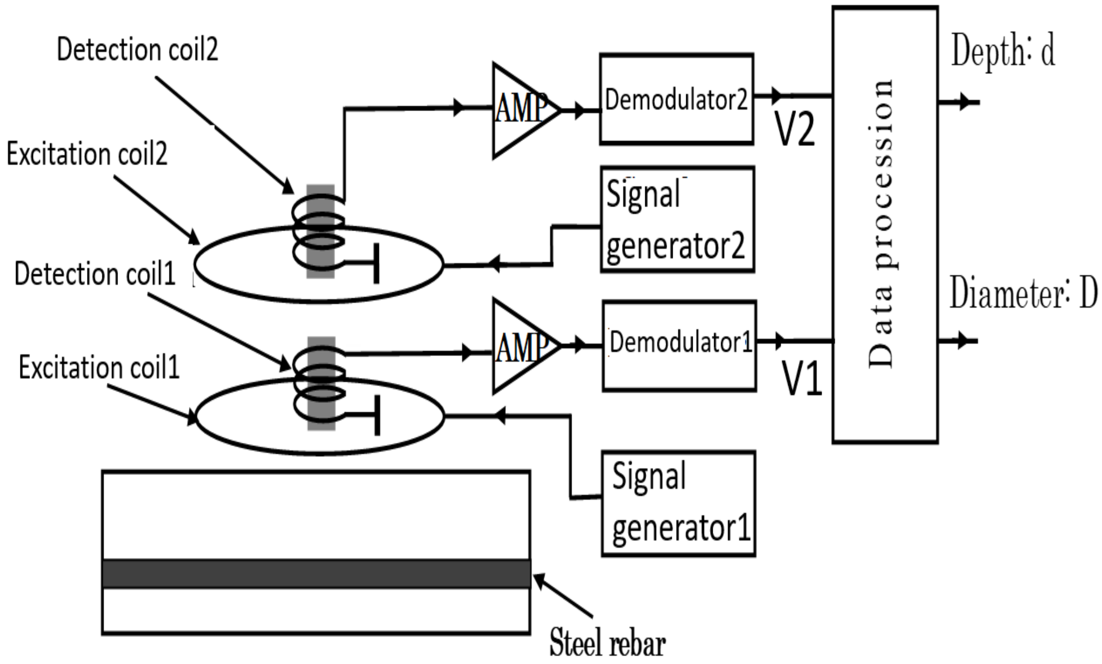

Figure 1: schematic diagram of the electromagnetic system for the detection of the diameter and depth of steel rebar in concrete.

Figure 2 shows the photo of the system. The two probes and electrical circuits were put in a small box with the size of 85 × 170 × 60 mm^3. The output signals were sent to an AD converter connected with a computer through a USB cable. The power of the probe was also from the same USB cable.

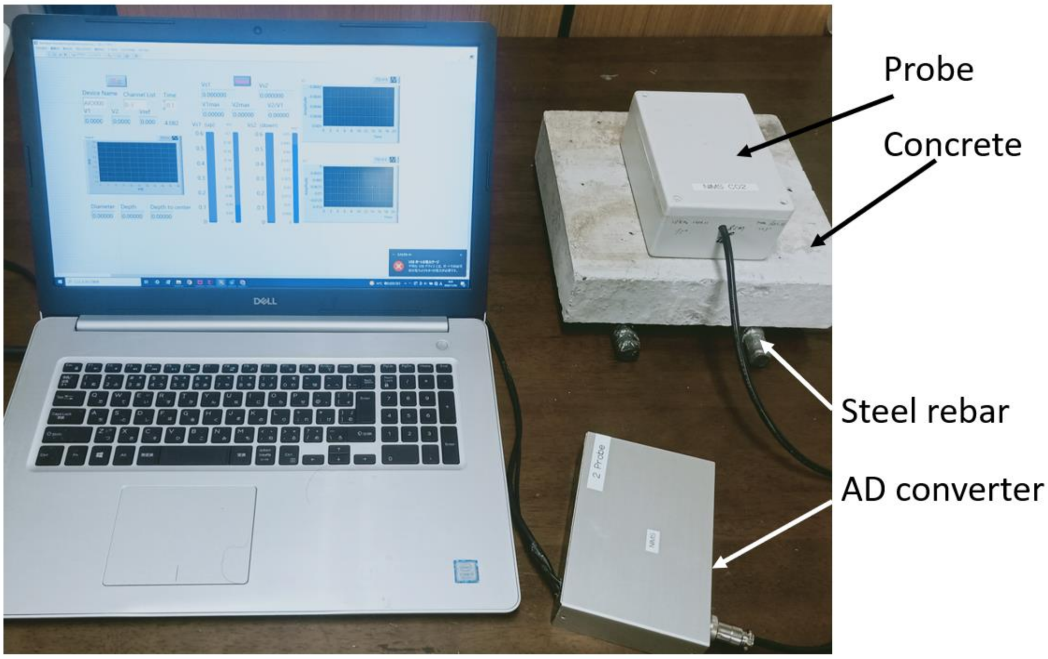

Figure 2: picture of the electromagnetic system for the diameter and the depth detection of steel rebar.

Figure 3 shows the interface of the Labiew program for the control and measurement. The diameter and the depth of the steel rebar can be real-time calculated and displayed.

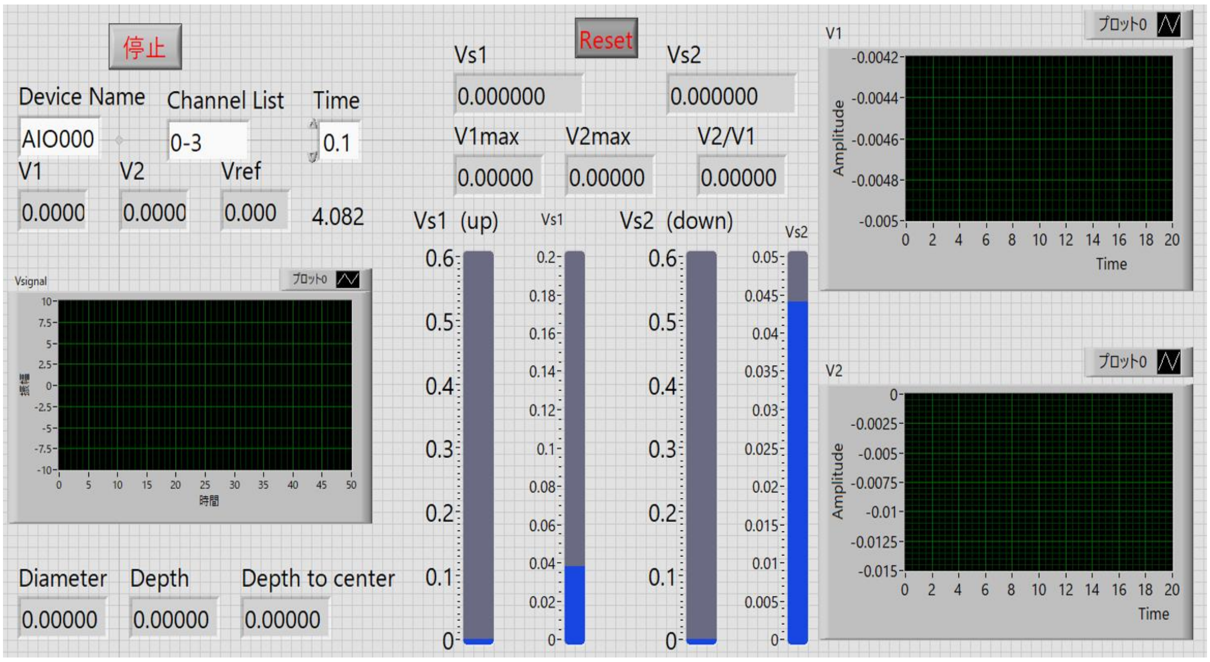

Figure 3: interface of the labview for the control and measurement.

3. Experimental results

We measured the outputs signals of probe1 and probe2 for the steel rabars with different diameters of 10 mm, 13 mm, 16 mm and 20 mm, and different depths of 20 mm, 30 mm, 40 mm, 50 mm, 60 mm, 70 mm, 80 mm, 90 mm and 100 mm. Table I shows the output signals of probe1. The unit of the data was Volt.

Table I: Output signal V1 of probe1 for the steel rebars with different diameters and depths.

Depth	Diameter (20mm)	Diameter (16mm)	Diameter (13mm)	Diameter (10mm)
20 mm	1.0314	0.8542	0.6114	0.3710
30 mm	0.2867	0.2322	0.1742	0.1076
40 mm	0.1011	0.0837	0.0635	0.0402
50 mm	0.0428	0.0349	0.0273	0.0171
60 mm	0.0200	0.0164	0.0128	0.0085
70 mm	0.0101	0.0084	0.0065	0.0042
80 mm	0.0056	0.0045	0.0036	0.0023
90 mm	0.0031	0.0026	0.0020	0.0014
100 mm	0.0019	0.0016	0.0013	0.0010

Figure 4(a) show the output signal V1 of probe1 changed with the depths for different diameters of the steel rebars; and Figure 4(b) shows the output signal V1 changed with the diameters for the steel rebars with different depths. From Figure 4(a), the signal amplitude decreased exponentially with the depth of the steel rebar. From Figure 4(b), the signal amplitude increased almost linearly with the diameter of the steel rebar.

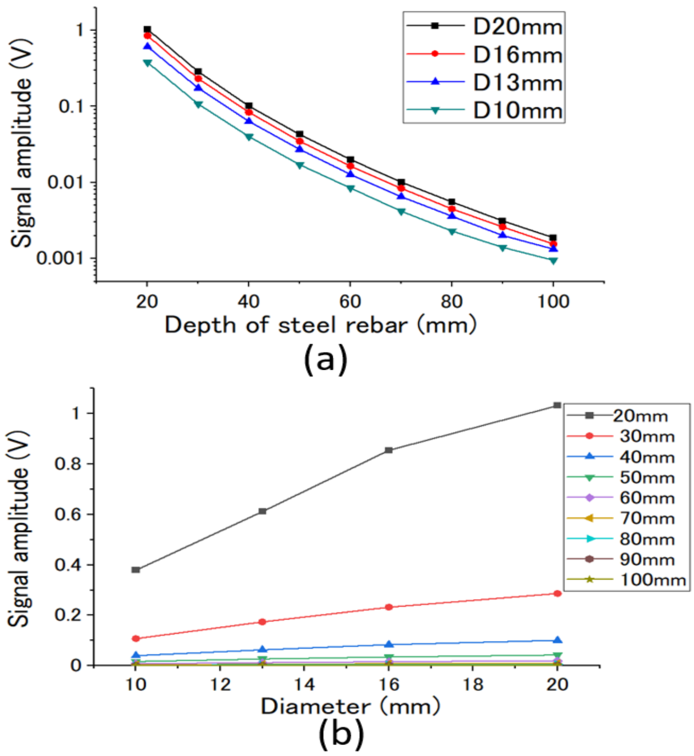

Figure 4: (a). Output signal V1 of probe1 changing with the depth of steel rebar for different diameters of steel rebar. (b). Output signa V1 changing with the diameter of steel rebar for different depths of steel rebar.

According to the data of Table I and Figure 4, we can use a fitting formula to express the signal amplitudes changing with the diameter and the depth of steel rebar.

$$V1 = kD \cdot e^{\left(-\beta d + \frac{\gamma}{\delta + d}\right)} \qquad (1)$$

Where, V1 was the output signal of probe1, D was the diameter of the steel rebar, d was the depth of the steel rebar. The k, β, δ and γ were constants. If the distance between the probe1 and the probe2 was L, the depth of steel rebar relative to the probe2 was (d+L), then we had following formula for the output signal V2 of probe2:

$$V2 = kD \cdot e^{\left(-\beta (d+L) + \frac{\gamma}{\delta + d + L}\right)} \qquad (2)$$

From formula (1) and formula (2), we can get:

$$\frac{V1}{V2} = e^{\beta L} \cdot e^{\left(\frac{\gamma}{\delta + d} - \frac{\gamma}{\delta + d + L}\right)} = e^{\beta L} \cdot e^{\frac{\gamma L}{(\delta + d)\cdot(\delta + d + L)}} \qquad (3)$$

From formula (3), V1/V2 was mainly determined by the covering depth d of steel rebar and it had less relation with the diameter of steel rebar. Table II shows V1/V2 for different diameters and different depths of the steel rebar. We can see the depth of the steel rebar had big influence to the value of V1/V2 and the diameter of the steel rebar had less influence to the value of V1/V2.

Table II: The values of V1/V2 for the steel rebar with different diameters and depths.

Depth	Diameter (20mm)	Diameter (16mm)	Diameter (13mm)	Diameter (10mm)
20 mm	1.526	1.532	1.528	1.521
30 mm	1.238	1.253	1.256	1.236
40 mm	1.058	1.074	1.081	1.057
50 mm	0.976	0.958	0.968	0.933
60 mm	0.849	0.874	0.910	0.910
70 mm	0.801	0.819	0.826	0.803
80 mm	0.768	0.762	0.777	0.761
90 mm	0.708	0.739	0.728	0.729
100 mm	0.655	0.672	0.693	0.681

For any steel rebar with unknown depth and diameter, the output signal amplitude V1 and V2 of the probe1 and probe2 were first measured, then the value of V1/V2 was calculated. The covering depth d of the steel rebar can be calculated using the value of V1/V2 and formula (3); then, the diameter D of the steel rebar can be calculated using formula (1) or formula (2).

We can also use a recursion calculation method to calculate the depth d and the diameter D of the steel rebar. Figure 5 shows the program flow chart. of the recursion calculation method to get the depth and the diameter of the steel rebar.

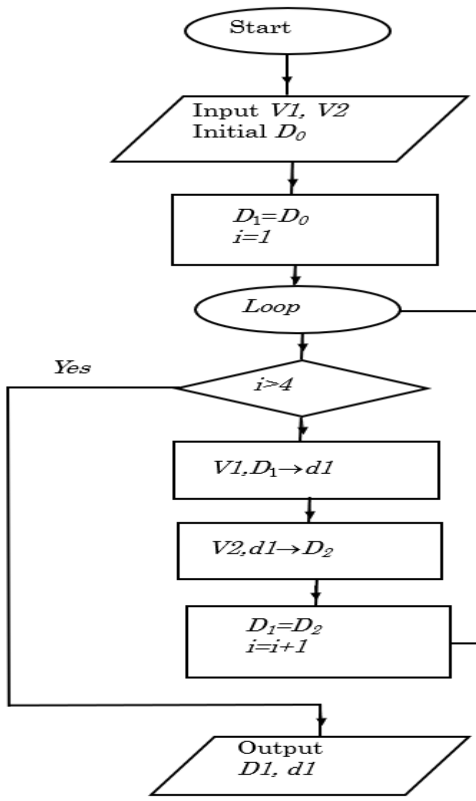

Figure 5: flow chart of the recursion calculation program to get the depth and the diameter of the steel rebar.

In the chart, d was the depth of the steel rebar and D was the diameter of the steel rebar. First, set the diameter

D1 to be equal to the initial value of D0. Then, used V1, D1, the output data of probe1 and the interpolation method to calculate the depth of d1; and used V2, d1, the output data of probe2 and the interpolation method to calculate D2; then repeated the calculation. The recursion calculation ended after four-time calculation. Finally, the values of depth d1 and the diameter D1 were obtained. The result using the recursion calculation method and the results calculated using formula (1), (2) and (3) were similar.

Table III shows the real values and the measured values of the depth and diameter of steel rebar using the recursion calculation method. For the steel rebar with the depth of about 50 mm, the error of the depth measurement was about 0.5 mm and error of the diameter measurement was about 1 mm.

Table III: real values and measured values of the depth and diameter of steel rebar.

Real diameter (mm)	Real depth (mm)	Measured diameter (mm)	Measured depth (mm)
10	20	10.73	20.45
	30	10.30	30.35
	40	09.73	39.60
	50	09.65	49.50
	60	09.02	58.20
13	17	13.35	17.33
	27	12:48	28.83
	37	12.01	36.55
	47	12.16	46.58
	57	12.14	56.50
	67	11.50	65.45
16	14	15.11	14.24
	24	15.35	23.60
	34	15.12	33.65
	44	16.80	44.45
	54	15.05	53.60
	64	16.63	62.97
20	10	19.91	10.55
	20	20.67	19.85
	30	19.67	29.82
	40	20.09	39.80
	50	19.05	49.50
	60	19.24	60.75

4. Conclusion and discussion

We developed electromagnetic methods with two probes to evaluate the depth and the diameter of steel rebar in concrete. The two probes had different frequencies of 3.8 kHz and 4.2 kHz to reduce the interference between the two probes. A recursion calculation method was developed. The depth and the diameter of steel rebar can be real-time calculated and displayed.

There are several limitations for this technology. The first limitation is the influence of the neighbor steel rebar. If the distance between the steel rebars is too small, the accuracy of the depth and diameter detection will be influenced. That distance is determined by the size of the excitation coil and the thickness of the concrete cover. According to our experiments, if the diameter of the excitation coil is 70 mm, and the thickness of the concrete is 50 mm, the detection accuracy becomes worse when the distance between the steel rebar is less than 10 cm. It is possible to reduce the influence by data procession. The second limitation is the influence of the surface roughness of the concrete structure. The problem can be solved by covering the concrete using a flat non-metal plate.

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