Eddy-Current Testing For A Thick Sus Plate

Applications of Electromagnetic Phenomena in Electrical and Mechanical Systems
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EDDY-CURRENT TESTING FOR A THICK SUS PLATE

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Abstract

To improve the eddy-current testing (ECT) method for the non-destructive detection of defects in thick non-magnetic metal objects, we have examined using of the spin-valve type giant magnetic resistance (SV-GMR) sensor instead of a conventional pick-up coil, which cannot be used effectively at low frequency to obtain enough skin depth. The GMR sensor has high sensitivity and frequency-independent characteristics. The experimental detections of both deep notches and scratches on thick stainless steel (SUS) show that the GMR sensor can give high-sensitive inspection. It is confirmed that the ECT technology for detecting thick non-magnetic metal has much possibility by using GMR as a sensor.

1. INTRODUCTION

Eddy-current testing (ECT) is used in the non-destructive testing of thin non-magnetic metal objects such as pipes in a nuclear power plants, riveting points on the body of aircraft, and blades of turbines because of its high sensitivity [1]. On the other hand, Ultrasonic Testing (UT) is commonly used in the testing of thick objects as well as thin objects, but it is difficult for the method to specify the location of the defects, and the sensitivity to small scars existing on the surface of the object is not as high as ECT. Moreover, the system apparatus for UT is not as compact as for ECT, so UT is not suitable for testing objects that have complicated structure [2].

According to the configuration or temperature of the object being tested, some height of lift-off may be required to test the object. For example, in the SUS production a proper lift-off height is required to protect the probe from the severe temperature of the tested objects. But the greater the lift-off height, the more sensitive the ECT probe needs to be. Moreover, UT is commonly used in the testing of the shroud in a nuclear power plant, even though we expect testing with ECT to be more reliable. Such as object is too thick for the current ECT method with a conventional pick-up coil sensor. Therefore it is very desirable to make possible the use of ECT not only for thin objects, but also for thicker objects by using a high sensitivity sensor.

To test thick objects, it is necessary to apply low frequency magnetic fields in order to get enough skin depth. A conventional pick up coil cannot be used effectively at low frequencies because of its dependency on the frequency of the external magnetic field [3]. In order to solve the problem, we examine the adoption of the Giant-Magnetic Resistance (GMR) sensor instead of the conventional pick-up coil. As GMR is a kind of resistive sensor, the external magnetic fields vary the resistance of the GMR sensor, and the sensitivity to magnetic fields is independent from the frequency of the magnetic fields up to 100 MHz. Therefore, the GMR sensor has high potential in its performance in the testing of non-magnetic metal objects based on the ECT technique [4,5].

2. STRUCTURE OF ECT PROBE

2.1 GMR element and characteristics

The GMR varies its resistance value when magnetic fields are applied. So, it is widely used as a magnetic sensor in recent years. Fig. 1 shows the configuration of the GMR sensor, and Fig. 2 shows its AC characteristics at 1.0 kHz. The normal resistance value of the GMR is

627 Ω without a magnetic field. As shown in Fig. 2, the GMR sensor has the highest sensitivity to B_z and also a small sensitivity to B_x, but it has no sensitivity to B_y. Because of its high sensitivity to only the one direction, it is easy to pick up only necessary information by using the GMR sensor.

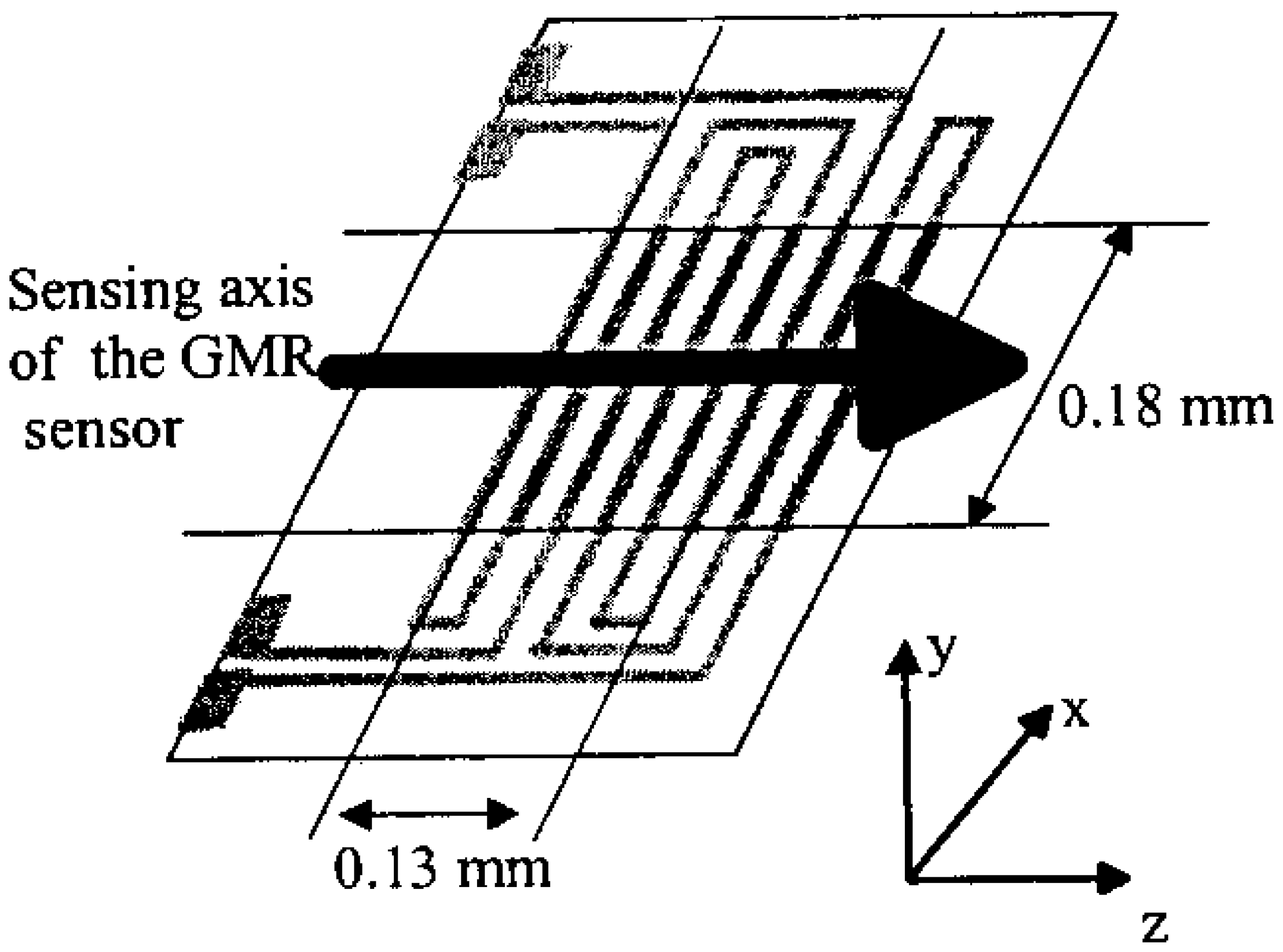


Fig. 1 Structure of SV-GMR sensor.

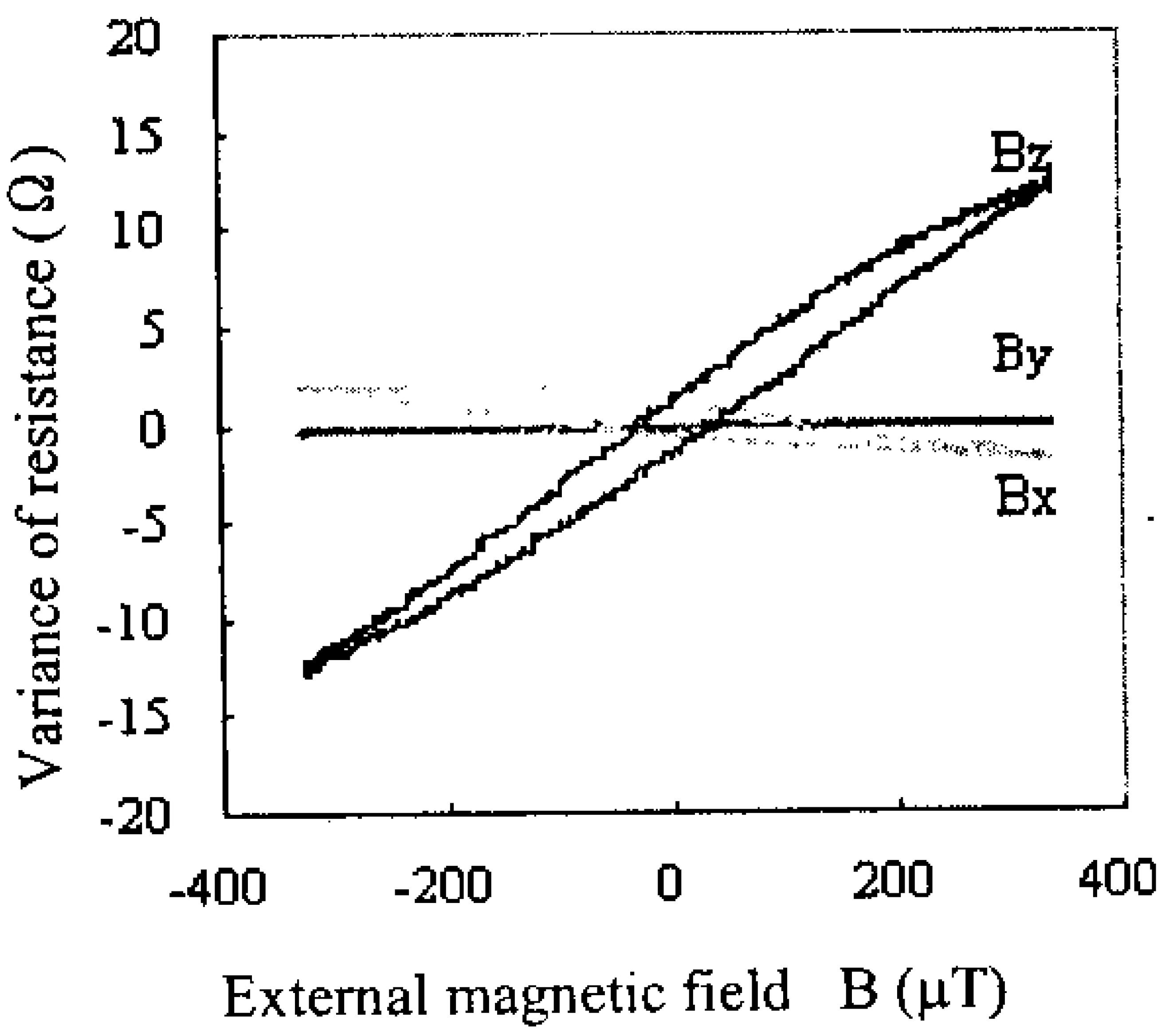


Fig. 2 Small-signal characteristics of GMR sensor at 1.0 kHz.

2.2 Probe structure and

2.2.1 Probe structure

Fig. 3 shows the structure of the ECT probe. The probe consists of an exciting coil and the GMR sensor. The pancake type coil has a rectangular shape (z = 40 mm by x=15 mm) with 100 turns, and the magnitude of the AC exciting current is 0.1 A. The GMR sensor is placed at the centre of the exciting coil. The sensitive axis of the GMR is directed to the z-axis in order to pick up B_Z. A DC current of 5.0 mA is applied to the GMR element and the voltage between the GMR electrodes is measured.

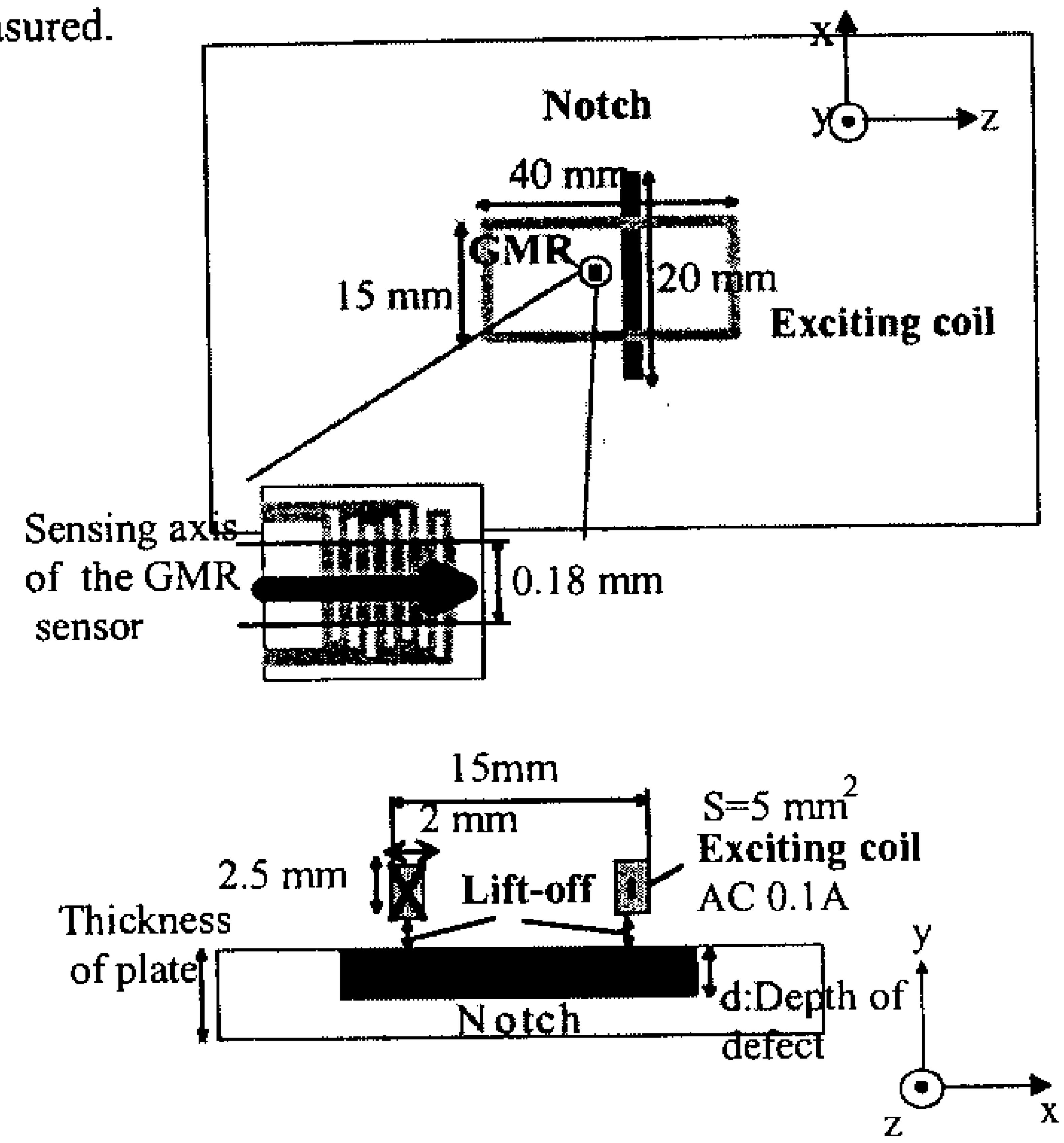


Fig. 3 Structure of the proposed ECT probe.

2.2.2 Principle of inspection

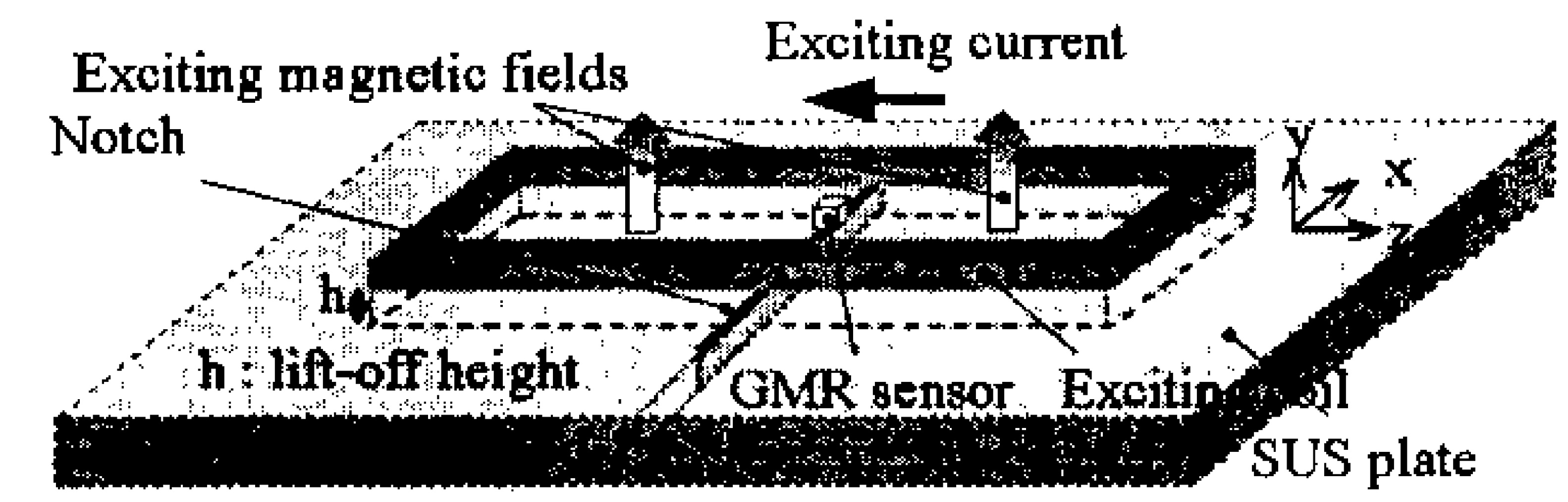
Fig. 4 (a) shows the model of the ECT probe and the plate being tested. The lift-off height is the distance between the probe and the plate. In the plate, eddy-currents are induced which make magnetic fields that are opposite to the exciting magnetic field, and the path of the eddy-currents is the same as the exciting current, but the opposite direction. But around a notch, the path of the eddy-currents is changed by the notch, and then eddy-currents in the x-axis are generated along the notch. Therefore, we placed the GMR sensor to measure B_Z, which accompanies the x-axis direction of the eddy-currents.

Figs. 4 (b), (c) and (d) show the eddy-current flows and induced magnetic fields when the exciting frequency changes. The relationship between skin depth and the depth of notch plays an important role. The skin depth is defined by,

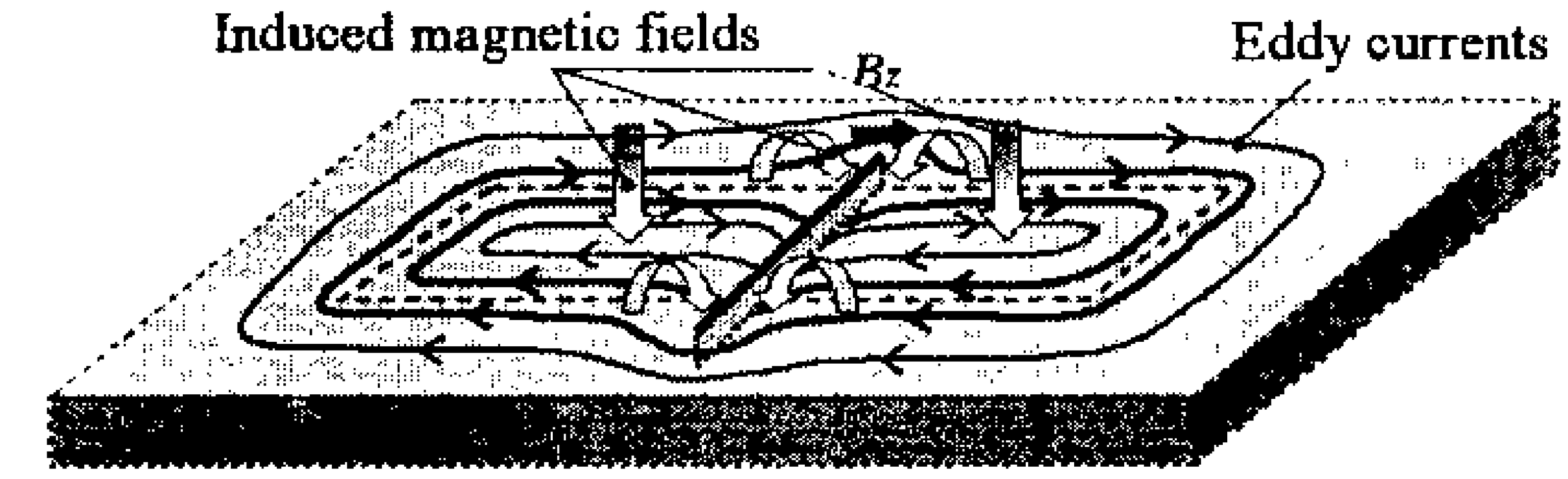
$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \qquad (1)$$

ω: Angular frequency, μ: Permeability,
σ: Conductivity

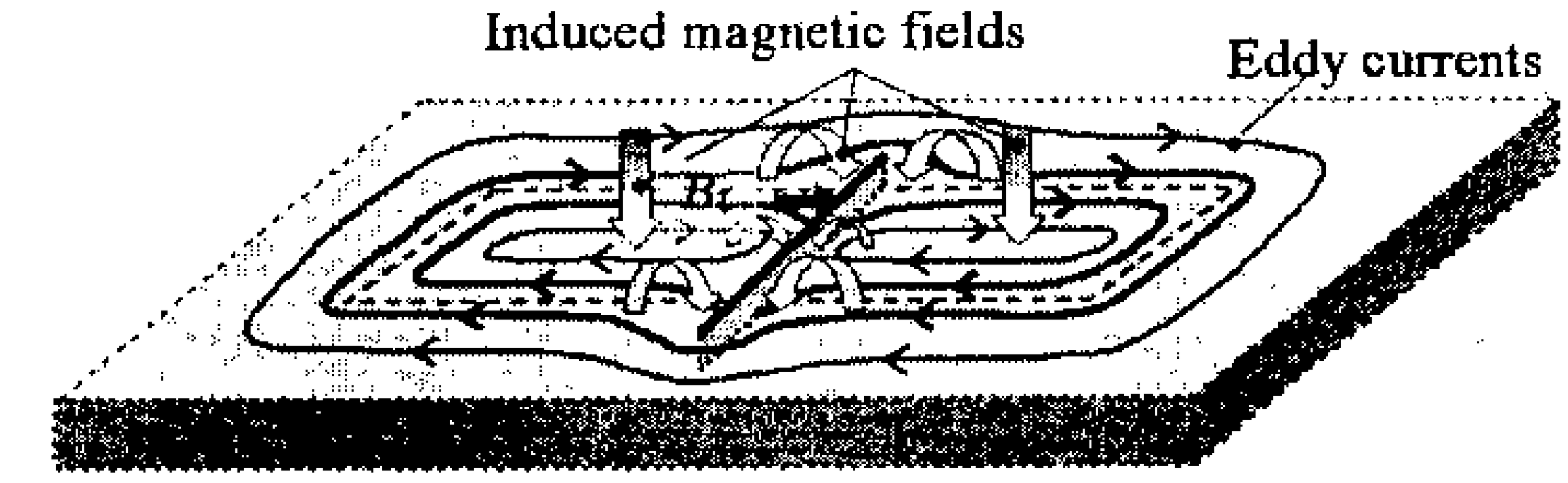
When the exciting frequency is very low, the depth of the notch, d, is shallow compared to the skin depth, δ. Most of the eddy currents flow beneath the notch without changing their flow direction after hitting the notch. Therefore, there are not many eddy-currents directed toward the x-axis that would make B_Z to be observable. The situation is shown in Fig. 4 (b). When the frequency is increased such that the depth of the notch is as deep as skin depth, some of the eddy currents flow beneath the notch, and the rest of the eddy currents change their direction along the notch and that makes B_Z observable as shown in Fig. 4 (c). Therefore, we can obtain a stronger signal from the notch than in Fig. 4 (b). When the exciting frequency is increased even more (δ<<d), most of the eddy currents change their flow direction to be along the notch, and that makes B_Z even more observable. Therefore, we can obtain the strongest signal from the notch as shown in Fig. 4 (d).



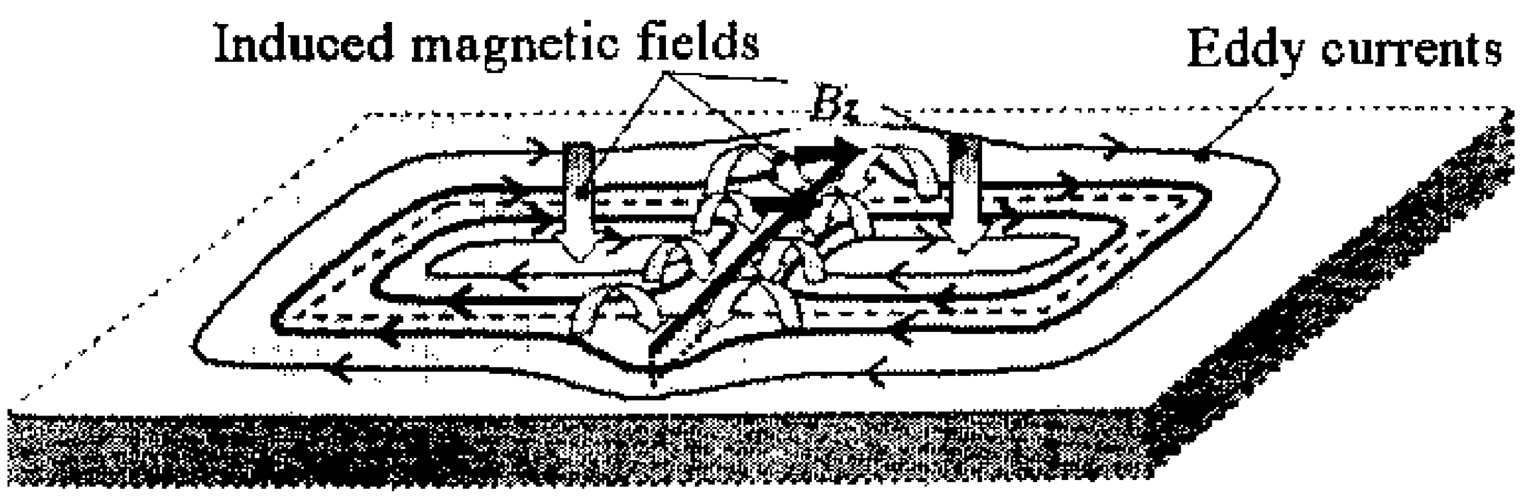
(a) Model of exciting coil and SUS plate with notch



(b) d (depth of notch) << δ (skin depth)



(c) d≈ δ



(d) d >> δ

Fig. 4 Principle of inspection

Fig. 5 shows a calculation of the induced eddy currents on the surface around a 6 mm deep notch at a frequency of 500 Hz. According to the calculation, there are few eddy currents along the notch, and this means most eddy-currents flow beneath the notch and are not displayed by the figure. Fig. 6 shows a calculation of the induced eddy currents on the surface around a 6 mm deep notch at 6 kHz. There are some eddy-currents flowing in the x-axis direction along the notch. However, eddy-currents along the notch are still smaller than the eddy-currents in other areas. This means some of the eddy-currents flow beneath the notch and they are not visible in the figure. Therefore, only the eddy currents in the x-axis direction are displayed along the notch.

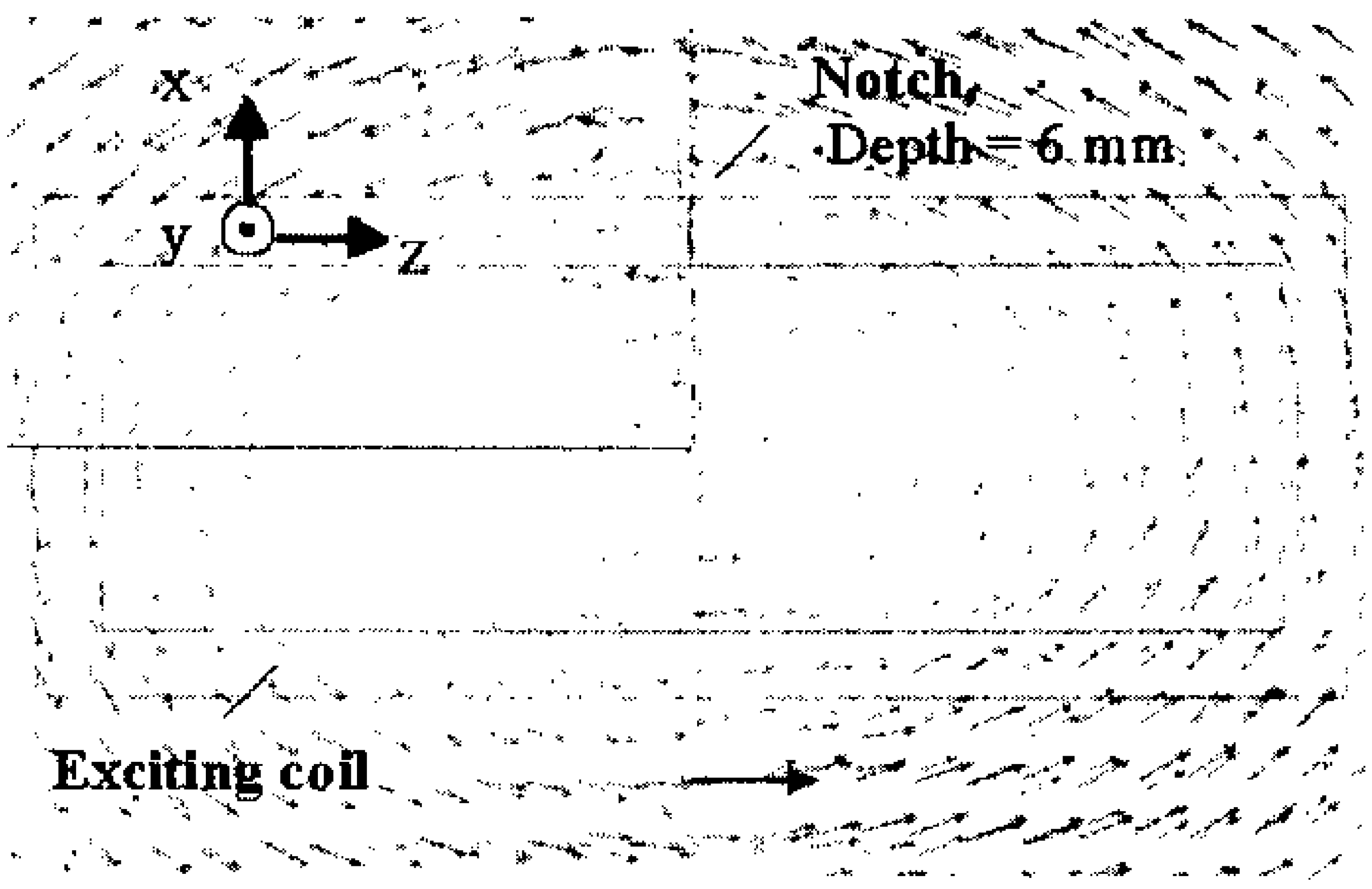


Fig. 5 Eddy-current distribution (d << δ).

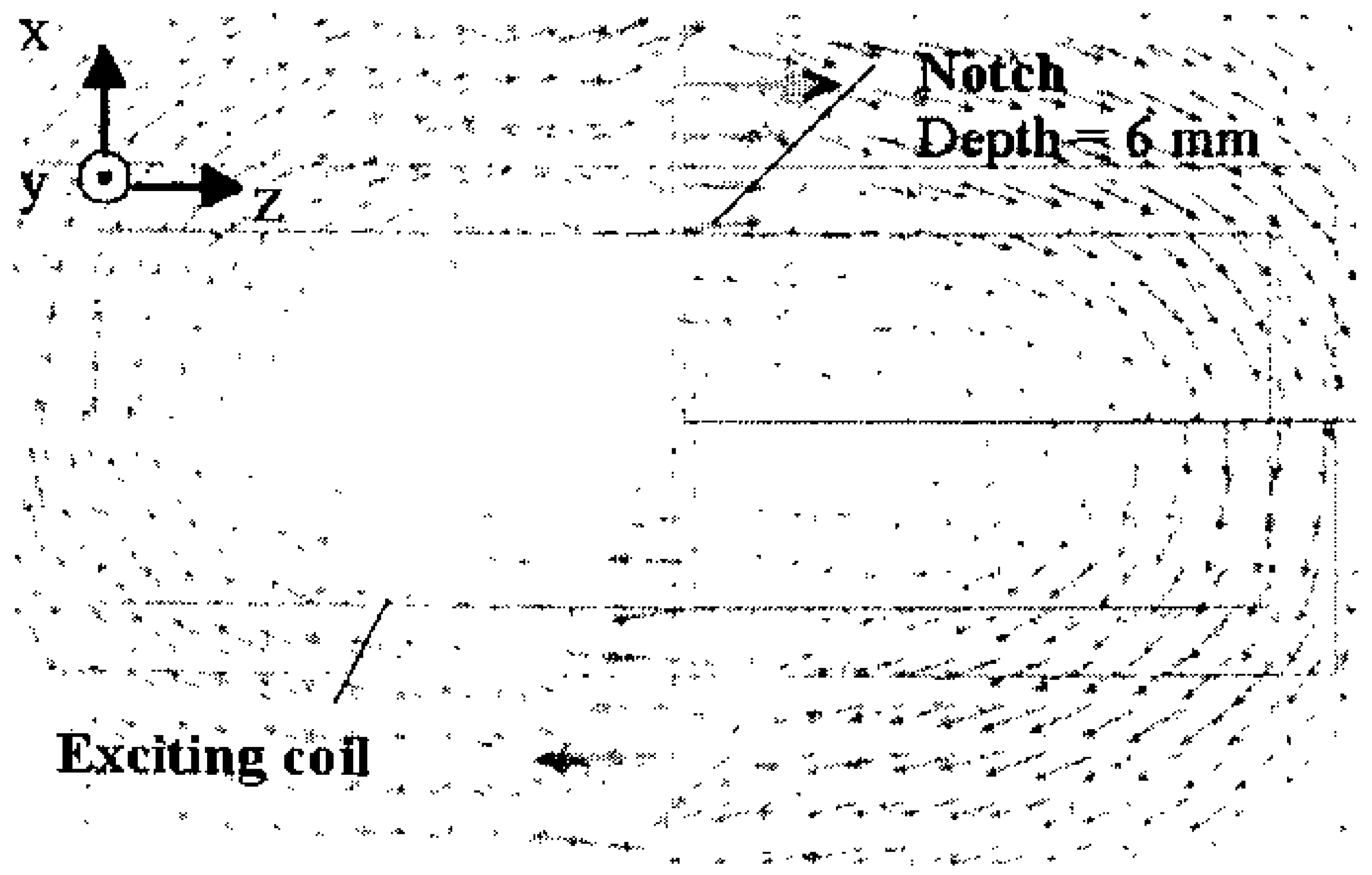


Fig. 6 Eddy-current distribution (d >> δ).

3. DETECTION OF NOTCH ON THICK SUS PLATE

3.1 Testing system

Fig. 7 shows the testing system. The constant current bias of the GMR is 5 mA DC, and the lock-in amplifier is used to measure the variance of the voltage across the GMR. The probe unit is moved along the z-axis to scan the notches.

3.2 Detection of deep notch on thick plate

To examine the performance of ECT with the GMR sensor at low frequency, we tested a thick plate with a thickness of 12 mm.

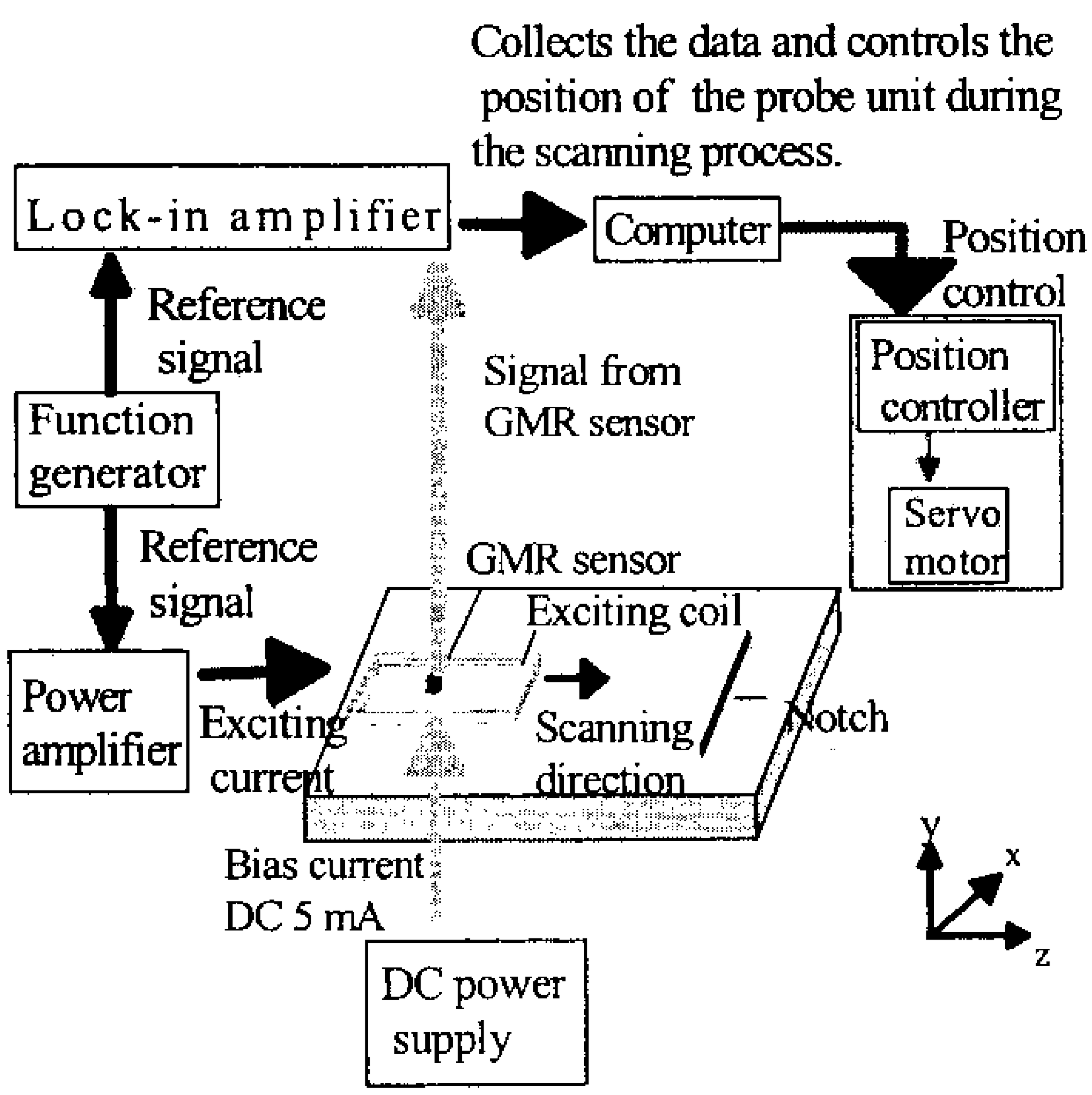


Fig. 7 The testing system.

3.2.1 Tested plate

The material of the tested plate is SUS304, and its conductivity σ is 1.0×10^{5} S/m, and its magnetic permeability μ is $4\pi\times10^{-7}$ H/m. The thickness of the SUS plate is 12 mm. As shown in Fig. 8, the plate has 4 notches made by electric discharge machining (EDM). The depth each notch is 8 mm, 6 mm, 4 mm, and 2 mm respectively, and the separation interval between notches is 40 mm.

Fig. 9 shows the relation between skin depth and frequency of the exciting current for the SUS plate. From the figure, we see that is necessary to reduce the frequency of the exciting current to less than 1.7 kHz in order to obtain enough skin depth.

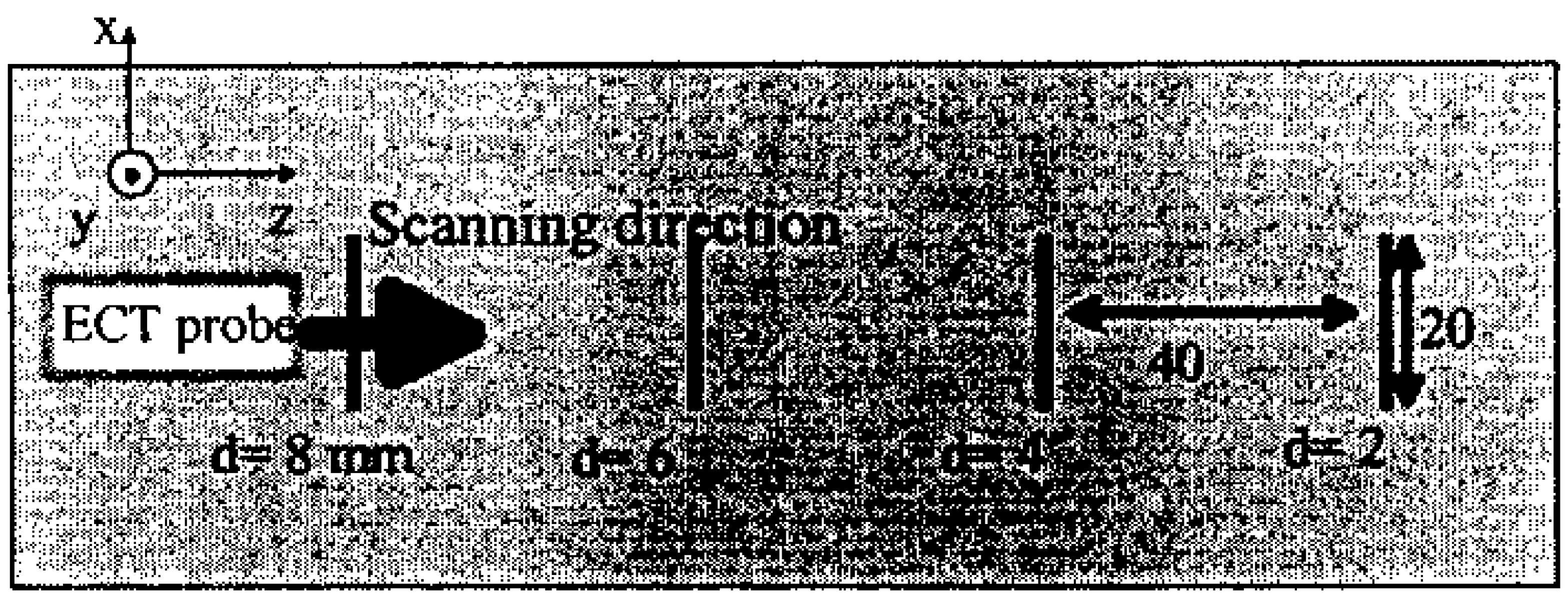


Fig. 8 Tested SUS plate with deep notches.

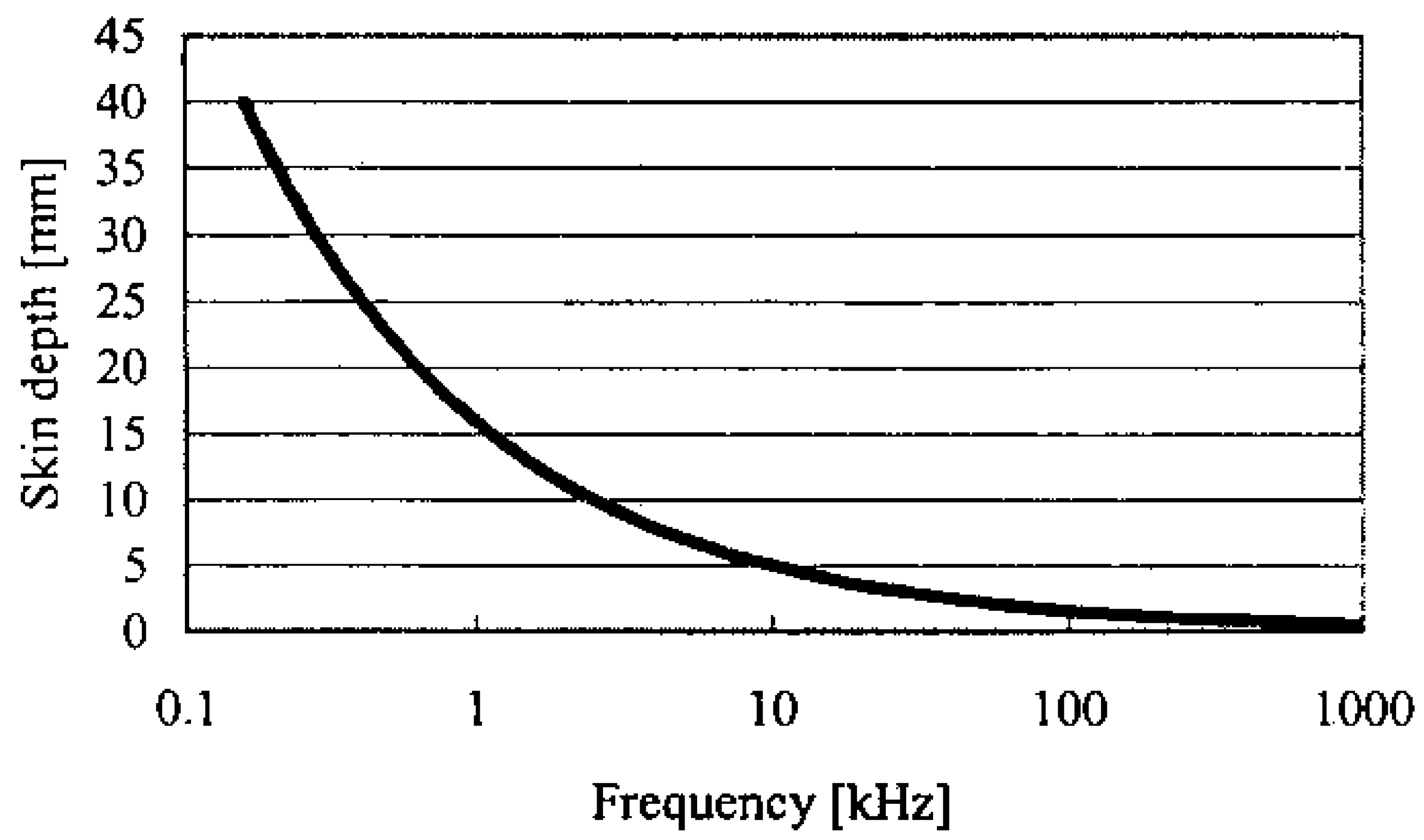


Fig. 9 Skin depth vs. frequency for the tested SUS plate.

3.2.2 Detection of deep notch

In order to induce enough skin depth of eddy-currents to the tested SUS plate, low exciting current frequencies (0.1A, 600 Hz -10 kHz) were applied to the exciting coil. The lift-off height is 260 µm. The probe unit is moved along the z-axis to scan all the notches.

Fig. 10 shows the output voltage across the GMR sensor when the probe is scanned along the z-axis at 1.7 kHz. Fig. 11 confirms that the amplitude of the signal of each defect increases when the depth of the notch gets deeper.

Fig. 12 shows the change of the signal amplitude in the testing of the 8 mm depth of notch, when the frequency of the exciting current is changed. It is seen that when the frequency is increased, the amplitude also increases.

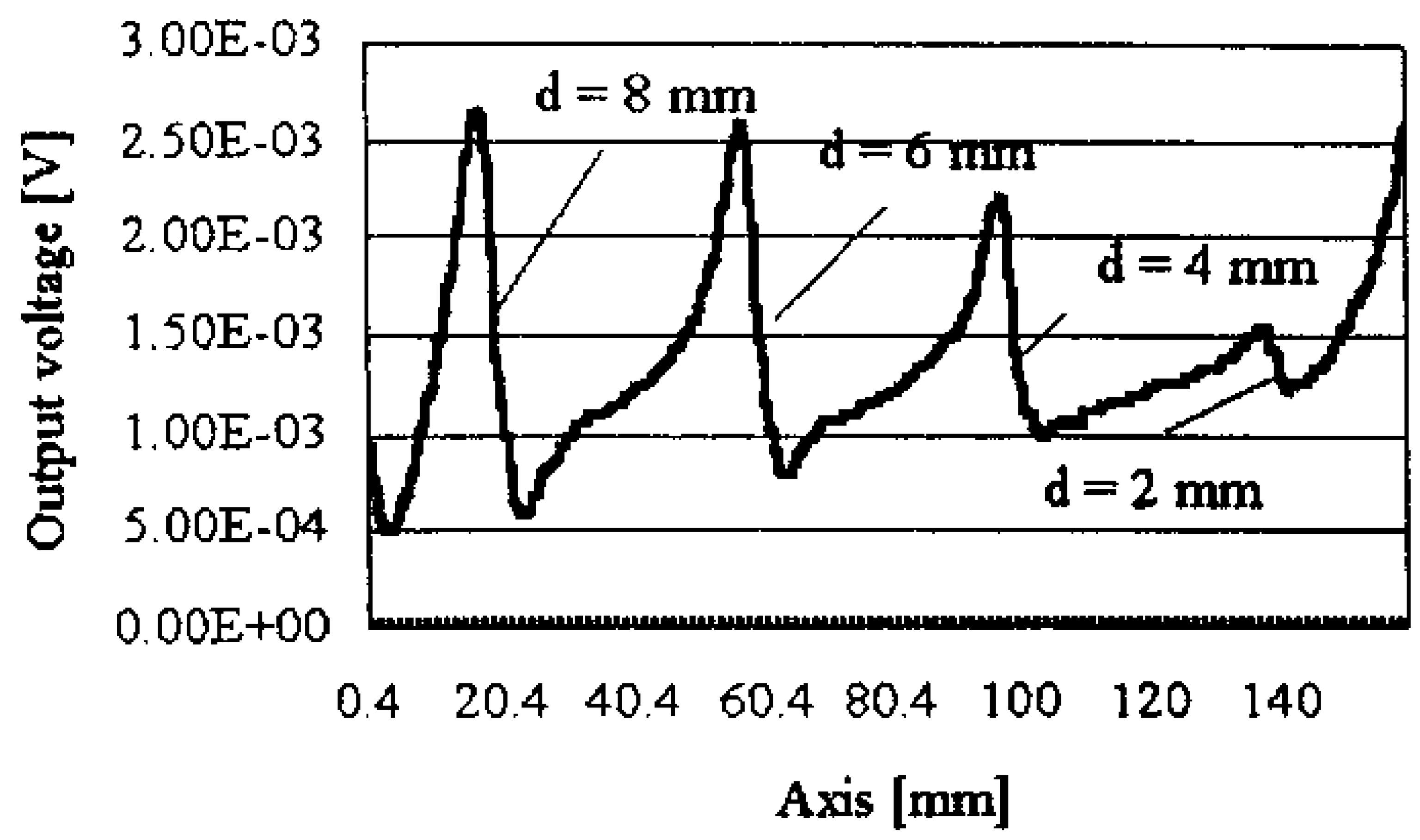


Fig. 10 Output voltage across the GMR sensor at 1.7 kHz.

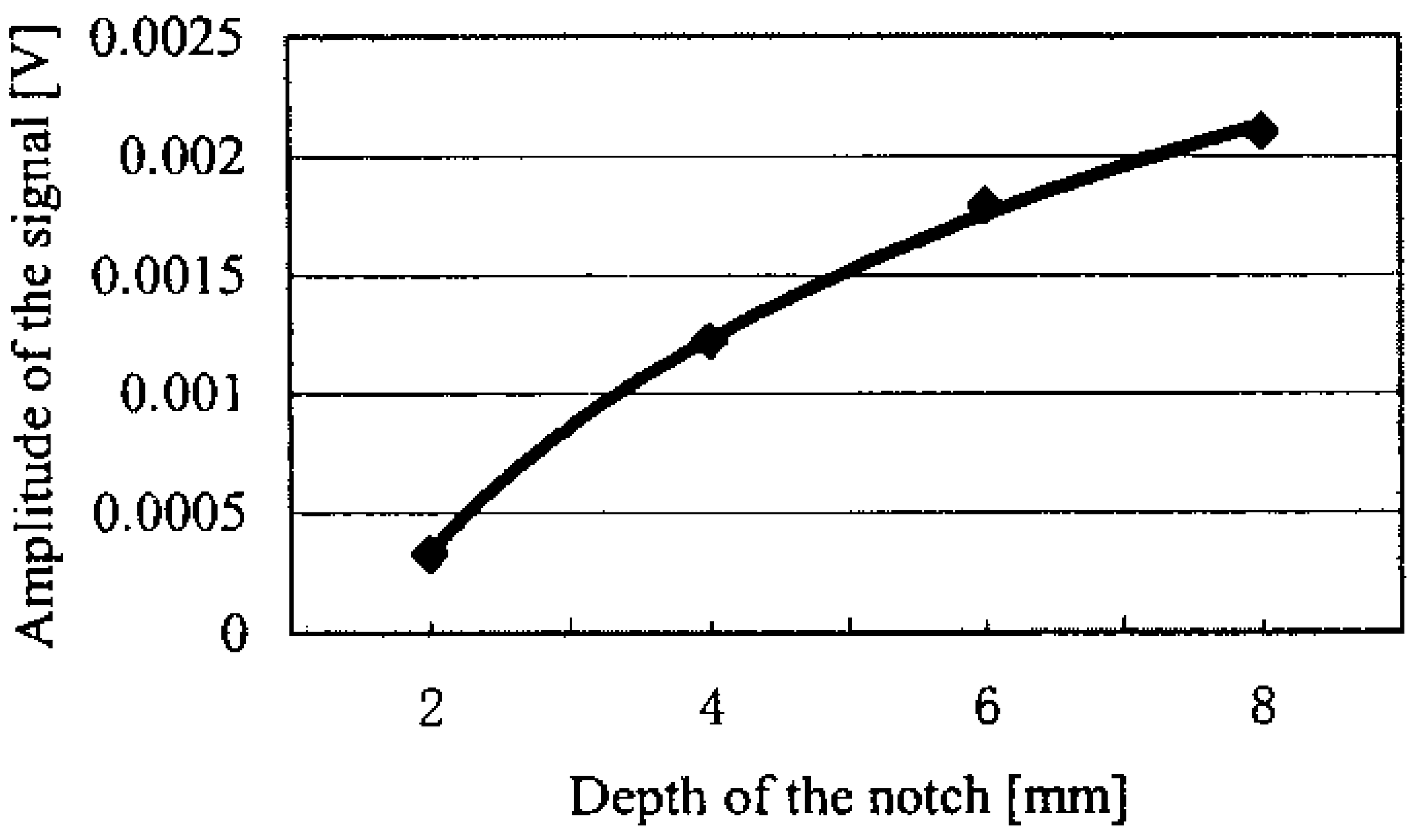


Fig. 11 Relation between amplitude of signal and depth of notch at 1.7 kHz.

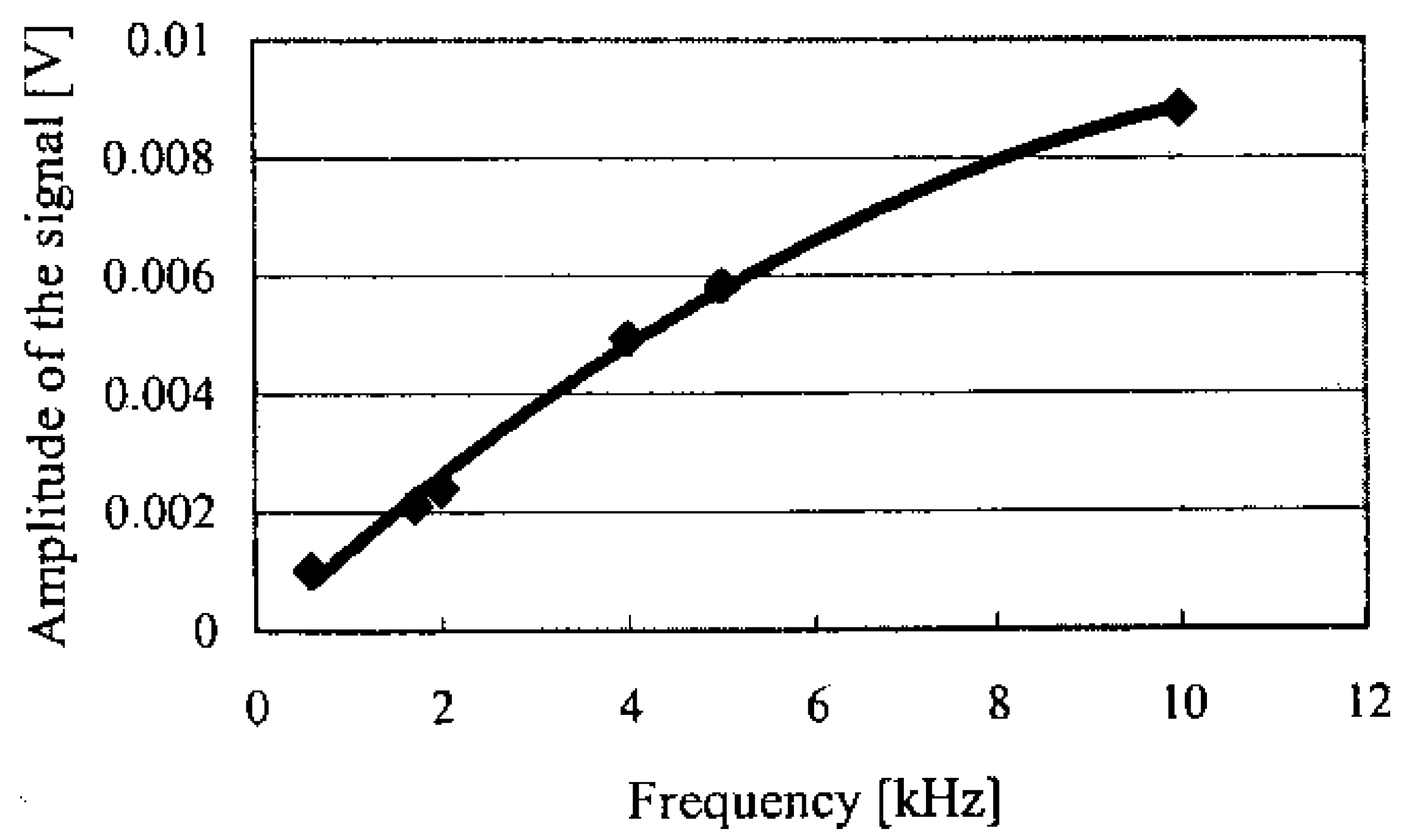


Fig. 12 Relation between amplitude of signal and frequency of the exciting current.

3.2.3 Detection from the opposite surface

We next examined the performance of ECT with the GMR sensor in the testing of notches on the opposite surface of the plate. The tested object was turned over, and the testing probe was again scanned along the z-axis. In order to induce enough skin depth of eddy-current to the tested SUS plate, low exciting current frequencies (0.1A, 600 Hz - 20 kHz) were applied to the exciting coil. The lift-off height is 260 mm

Figs. 13, 14 and 15 show the output voltage across the GMR sensor when the probe is scanned along the z-axis at 2, 5 and 20 kHz. In the testing at 2 kHz, although notches with the depth of 8, 6 and 4 mm are detected, the signal is not clear. In the testing result at 5 kHz, the notches with the depth of 8, 6 and 4 mm are clearly detected, however the notch with the depth of 2 mm is not sensed. This is because the skin depth is not deep enough and cannot induce eddy currents around the notch. In the testing result at 20 kHz, only the notch with the depth of 8 mm is detected very clearly, and the other notches are not detected. This is also because the skin depth is not deep enough, and eddy currents are not induced around the notches of 6, 4 and 2 mm depth.

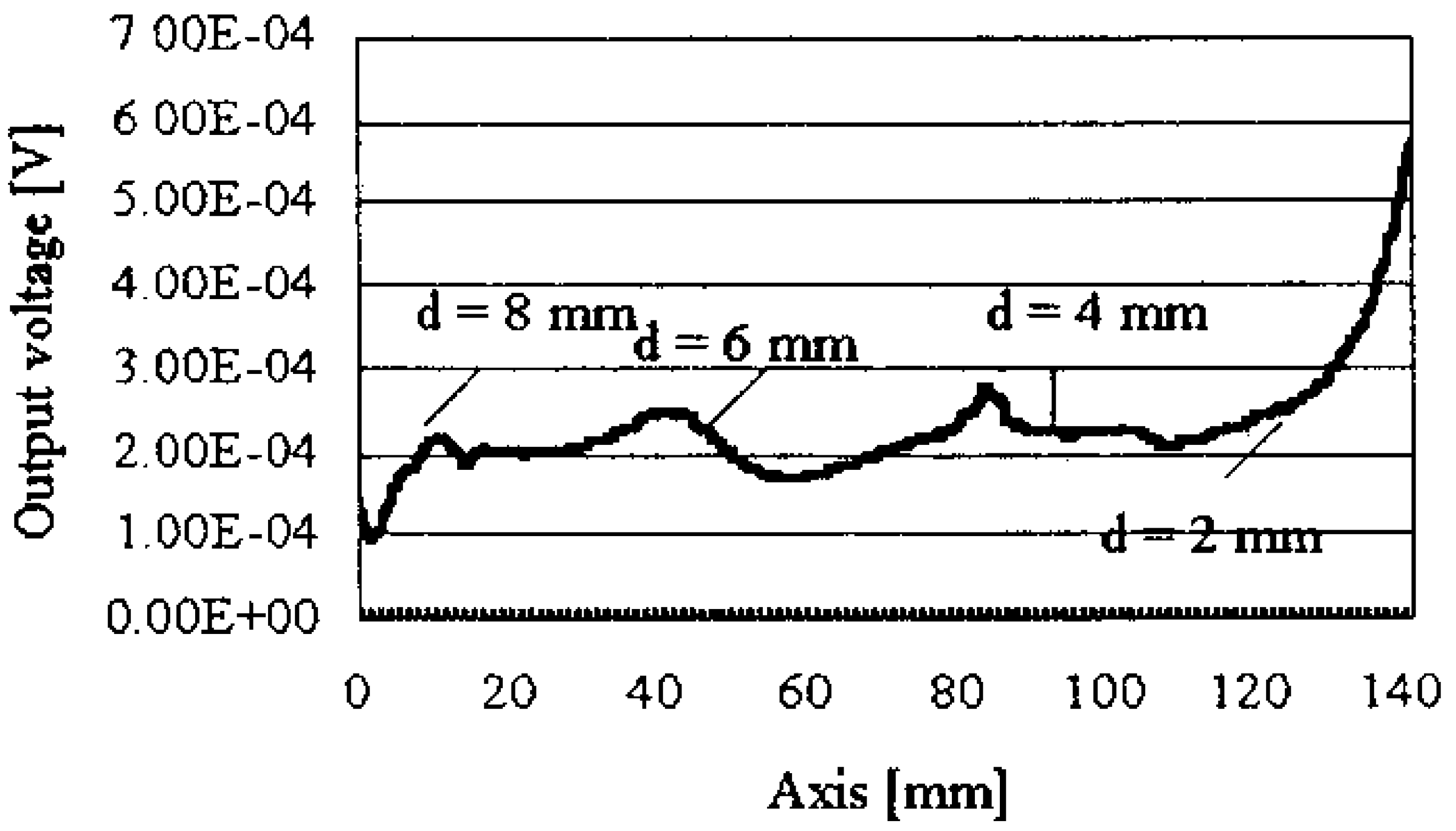


Fig. 13 Output voltage across the GMR sensor at 2.0 kHz.

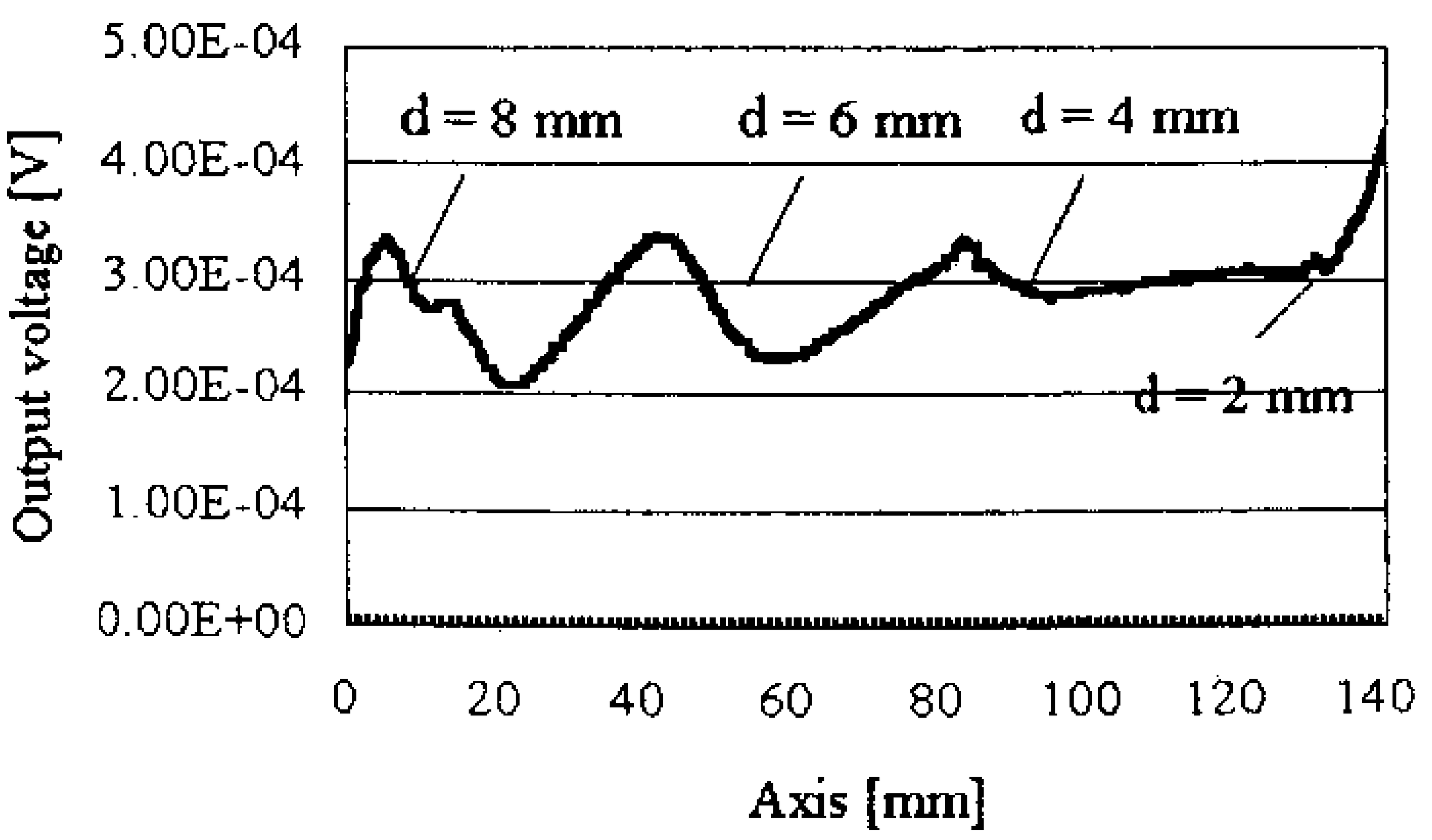


Fig. 14 Output voltage across the GMR sensor in the opposite surface testing at 5.0 kHz.

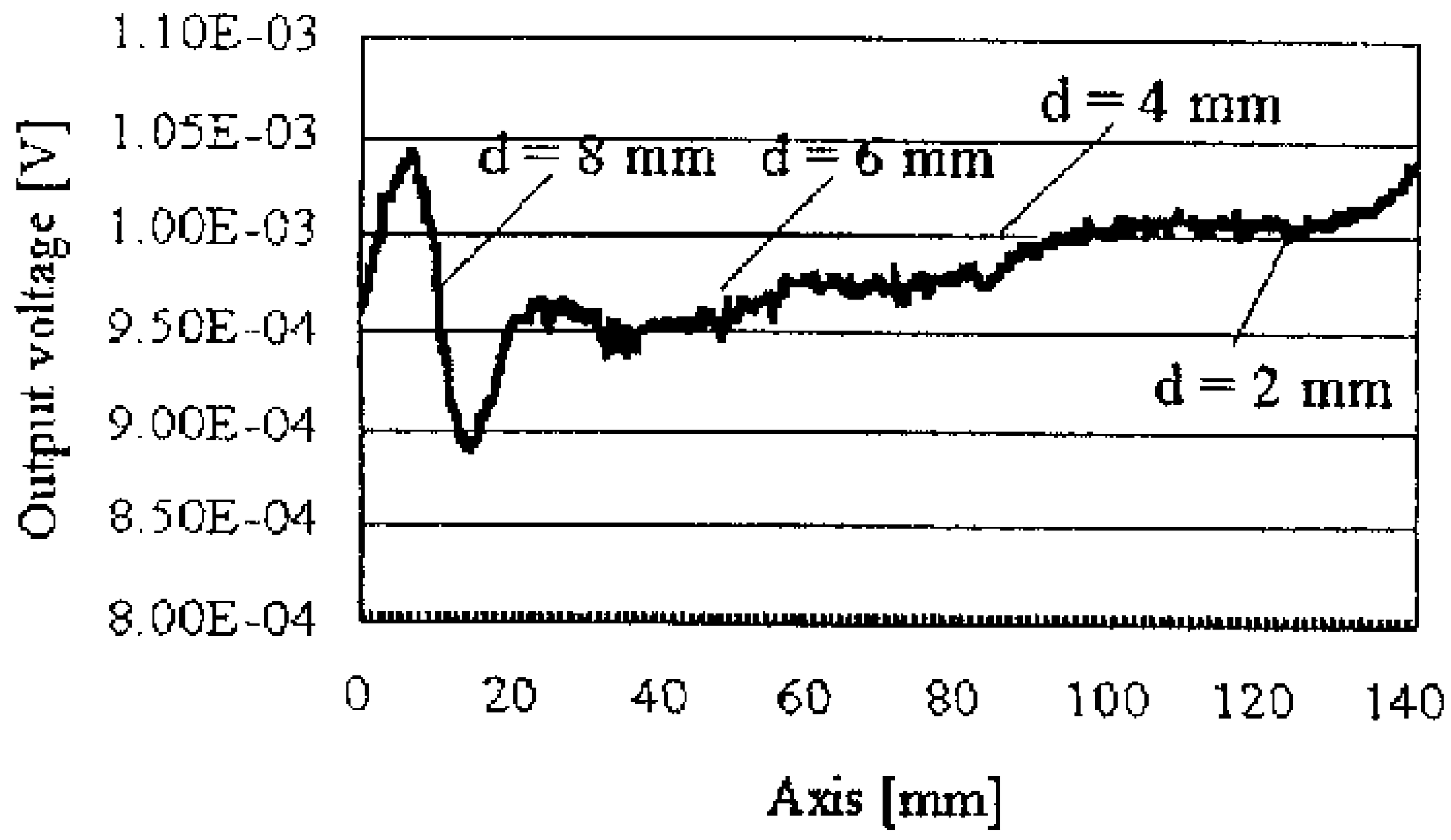


Fig. 15 Output voltage across the GMR sensor in the testing at 20 kHz.

3.3 Scratch on SUS plate

In practical use such as a SUS production, it is required to test slight defects existing on the surface of the object with high lift-off height. Therefore, we examined the sensitivity of ECT with the GMR sensor in the testing of scratch on a SUS plate with high lift-off height by using a high frequency exciting current.

3.3.1 Tested plate

The material of the tested plate is SUS 304, and its conductivity σ is 1.0×10^5 S/m, and its magnetic permeability μ is $4\pi\times10^{-7}$ H/m. As shown in Fig. 16, the plate has 4 scratches on the surface. Each scratch has the depth of 1.0, 0.7, 0.5 and 0.3 mm, and the separation interval is 50 mm between scratches.

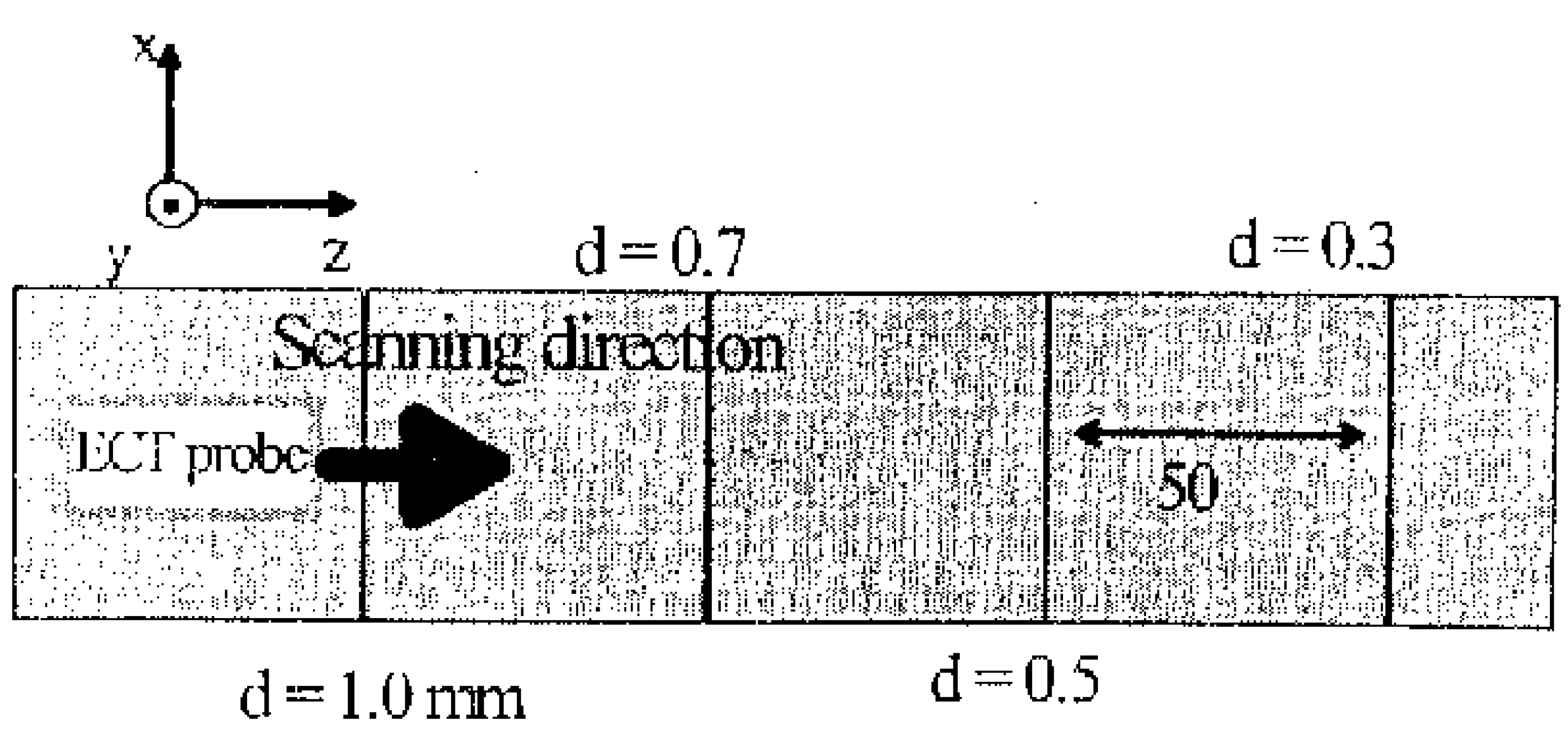


Fig. 16 Tested SUS plate with slight scratches

3.3.2 Detection with high lift-off height

In order to detect the slight notches, high frequencies of exciting current (0.1A, 80 - 180 kHz) were applied to the exciting coil. The lift-off heights were 2.21 and 4.29 mm. The probe unit was moved along the z-axis to scan all the notches.

Fig. 17 shows the output voltage across the GMR sensor when the probe is scanned along the z-axis at 180 kHz with 2.21 mm of lift-off. All the notches are detected despite the high lift-off height.

Fig. 18 shows the output voltage across the GMR sensor when the probe is scanned along the z-axis at 120 kHz with 4.29 mm of lift-off. All the notches are detected despite the high lift-off height. The result is not smooth because the signals of the scratch are smaller than the resolution of the lock-in amplifier.

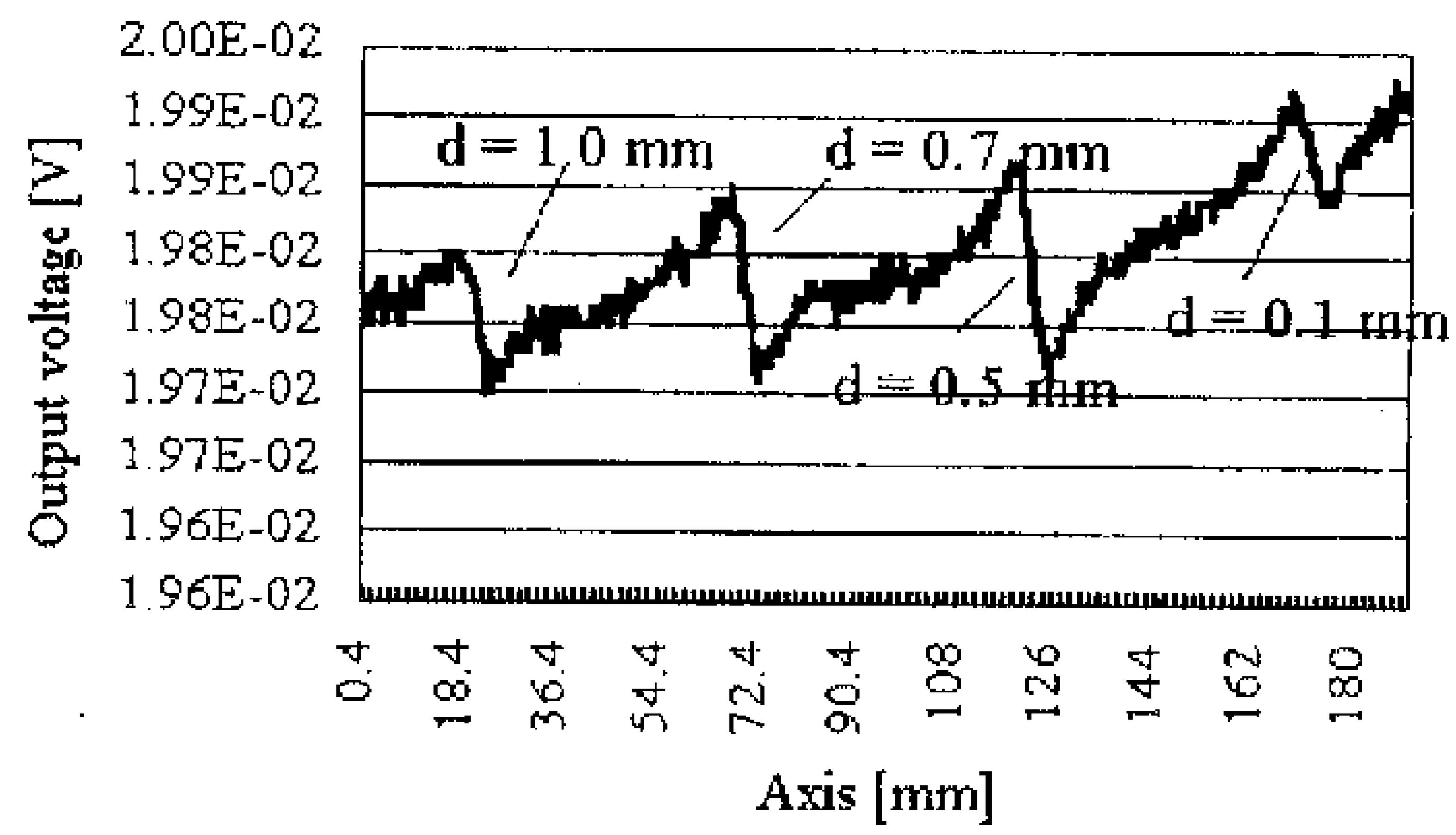


Fig. 17 Output voltage at 180 kHz with the lift-off height of 2.21 mm

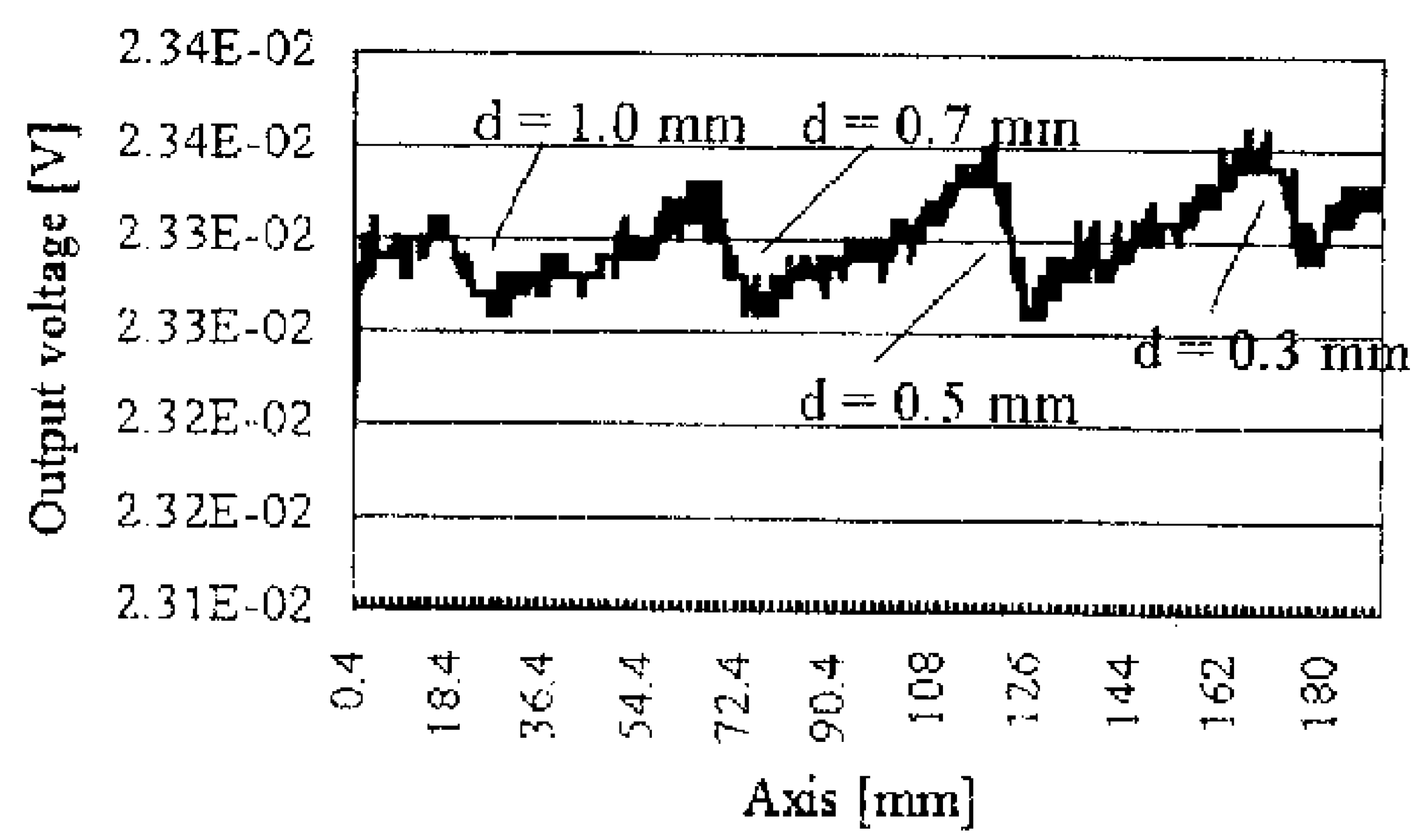


Fig. 18 Output voltage across the GMR sensor at 120 kHz with 4.29 mm lift-off height

4. CONCLUSION

We have examined the application of a GMR sensor for ECT inspection of thick SUS plates at low frequencies also examined its sensitivity to slight scratches with high lift-off heights. It is confirmed that high sensitivity ECT testing can be achieved by using the GMR as a sensor.

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