Journal of Mechanics Engineering and Automation 12 (2022) 65-76
doi: 10.17265/2159-5275/2022.03.001

Study on Metal Detection with an Electromagnetic Induction Probe Utilizing a Rotating Magnetic Field

Kiyoshi Koyama
College of Industrial Technology, Nihon University, Narashino Chiba 275-8575, Japan

Abstract: The present paper describes an investigation conducted on metal detectors installed with a scanning probe. The authors applied a rotating magnetic field probe to metal detection. The rotating magnetic field probe is comprised of two vertically placed rectangular exciting coils and a circular detecting coil. The experimental results confirmed that the probe can detect metal objects and provide more information about their shape, direction, and electromagnetic characteristics than conventional metal detector probes. A two-dimensional signal display shows a low-resolution image of the metal object and the signal phase indicates the object's direction and electromagnetic characteristics. The experimental results show that excellent reconstruction of the surface shapes of metal objects can be obtained for both magnetic and nonmagnetic metals under present conditions. There is also the potential for the approximate shape of a metal object to be estimated from the reconstructed image.

Key words: Metal detection, rotating magnetic field, MD (metal detector), image reconstruction, metal shape restoration.

1. Introduction

Technologies to detect and remove concealed land mines have been developed to aid post-conflict reconstruction. One such technology is a composite detector that combines a metal detector that uses electromagnetic induction with a ground-penetrating radar element using electromagnetic waves [1-5]. In this composite detector, the metal detector first detects all metals, including land mines and shrapnel, after which the ground-penetrating radar accurately determines the location and shape of the metal objects for the purpose of mine detection. Since ground-penetrating radar is additionally used to determine whether or not the metal item spotted by the detector is a mine, conventional composite detectors have the disadvantages of being both slow and costly. It should be possible to reduce costs and save time if the metal detector can determine whether a detected object is similar to or completely different from the postulated target, in addition to determining whether any metal is present. This would allow only suspect objects to be investigated by the ground-penetrating radar to determine whether they are mines.

For a metal detector to determine whether a metal object is similar to the postulated target, it must have the ability to obtain more information, such as the location and shape of the detected metal object in addition to the presence or absence of metal. Although conventional metal detection probes [2-4] are highly capable of detecting metal, the detection signals are much the same for any shape and metal, making it difficult to obtain further information about the item. The authors therefore propose a probe that uses a rotating magnetic field (hereinafter referred to as a "rotating magnetic field probe") with the following characteristics [6]. The probe's detection signal changes according to the shape, material, and orientation of the metal; its detection sensitivity does not change even if the orientation of the metal object varies in the horizontal plane; and it does not generate a signal when there is no metal. A rotating magnetic field probe detects metal by generating a rotating magnetic field in which the flux direction changes in synchronization with the excitation current.

Corresponding author: Kiyoshi Koyama, PhD, professor, research field: study on electromagnetic induction nondestructive test.

Experimental results have shown that this type of probe can obtain more information, such as the shape and material of metal and the orientation of the metal object relative to the scan direction, than can conventional metal detection probes. This suggests the potential to estimate the approximate shape of a metal object from the detection signals.

However, with conventional metal detection probes and electromagnetic induction probes such as rotating magnetic field probes, the signals obtained by a probe scanned in two dimensions are blurred because magnetic flux has a spread, making it difficult to determine the exact shape of the metal from the scattered detection signals. We therefore tried to approximate the surface shape of metal objects by applying an image reconstruction method [7] to blurred detection signals. In this paper, we present the results of image reconstruction using point spread functions.

When applying the image reconstruction method, it is necessary to obtain a point spread function that is specific to the measurement system. We first attempted to reconstruct the metal shape using a point spread function obtained from magnetic metals. This attempt was successful for magnetic metals, but not for non-magnetic metals. This is because the detection principle of the rotating magnetic field probe is different for magnetic and non-magnetic metals. The detection signals therefore differ between them, even for the same shape. Since the point spread function is specific to the measurement system, different point spread functions are needed for magnetic and non-magnetic metals. We therefore used the difference between the detection signals of magnetic and non-magnetic metals to determine whether the detected metal was magnetic or non-magnetic, selected the point spread function to be used in the image reconstruction method, and then reconstructed the surface shape of the metal. Under the experimental conditions of this study, we were able to reconstruct surface shapes successfully for both magnetic and non-magnetic metals. This indicates the potential to estimate the shape of metal through image reconstruction.

2. Metal Detection Using a Rotating Magnetic Field Probe

The rotating magnetic field probe consists of two exciting coils, which are rectangular coils forming a crisscross pattern, as shown in Fig. 1, and a circular detecting coil placed in the center of the crisscross-patterned plane of the exciting coils. When an alternating current is applied to each of the two exciting coils with a phase difference of 90˚, a rotating magnetic field with a uniform magnitude, with its directional rotation synchronized with the excitation current, is generated beneath the crisscross-patterned plane of the exciting coils, as shown in Fig. 2a. This rotating magnetic field induces eddy currents with their direction rotating as shown in Fig. 2b on the surface of the metal being detected. Note that the eddy currents induced on the metal surface form a closed loop with their phase determined by the electromagnetic properties of the metal and the frequency; thus, the relationship between the eddy currents and the magnetic flux is not necessary as shown in Fig. 2, which is meant to be schematic.

Fig. 3 shows magnetic flux distribution without a metal object at t = 0. The magnetic flux is symmetrically distributed with respect to the axis passing through the center of the detecting coil (dashed line in Fig. 3). The total magnetic flux linked with the circular detecting coil placed at the center of the crisscross-patterned

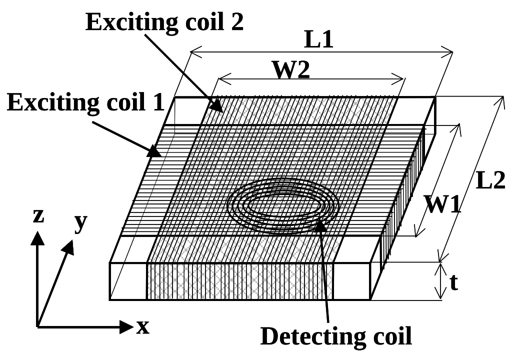
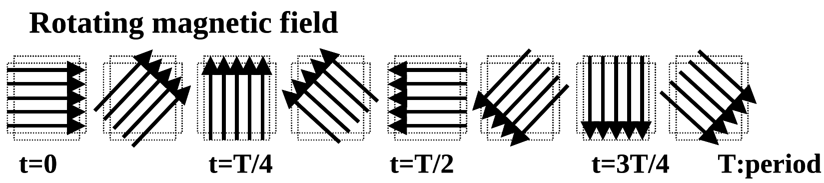
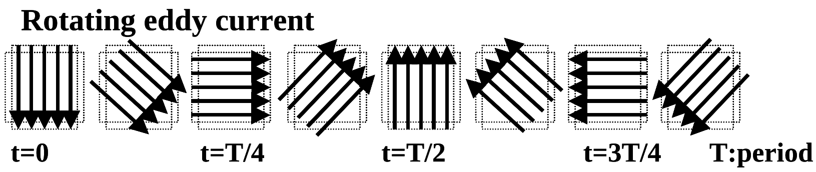


Fig. 1 Structure of the rotating magnetic field probe.



(a) rotating magnetic field

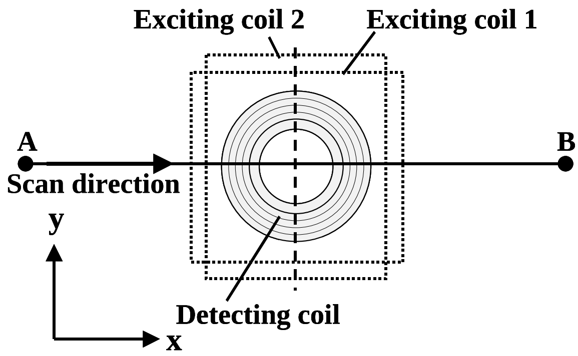


(b) rotating eddy current

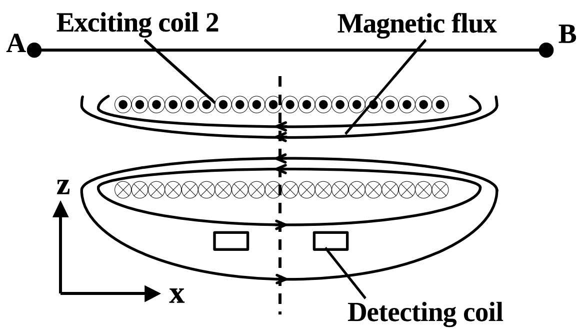
Fig. 2 Rotating magnetic field and induced eddy current.

plane of the exciting coils is equal to zero, so no electromotive force is generated in the detecting coil. In principle, therefore, no signal is generated in the absence of a metal object, so that no complex balancing circuit is required. While Fig. 3 describes the situation at t = 0, the symmetrical magnetic flux distribution rotates around the center of the detecting coil, and the sum of the magnetic fluxes linked with the detecting coil is always zero, so that, in principle, no signal is generated.

When using the rotating magnetic field probe for scanning, we first consider the case of a magnetic metal. While eddy currents are induced on the metal surface by electromagnetic induction, in the case of a magnetic metal, the magnetic flux through the metal has a major effect on the detection signals. We thus focus on the change in magnetic flux through the metal. Fig. 4 shows the principle of detecting a cuboid magnetic metal object. Fig. 4a shows the direction of magnetic flux at t = 0; Fig. 4b shows the orientation of the metal object with respect to the scan direction of the probe; and Figs. 4c and 4d show magnetic flux distributions. At t = 0, the excitation current of exciting coil 2 generates a magnetic flux in the direction shown in Fig. 4a. When the metal object is located beneath the detecting coil winding (Fig. 4c), the magnetic flux distribution changes and an electromotive force is generated in the detecting coil. When the probe moves to the point where the metal object is located beneath the other side of the detecting coil winding (Fig. 4d), the direction of magnetic flux through the detecting coil is reversed and an electromotive force of opposite phase is generated. When the metal object is located at the center of the detecting coil, the sum of the magnetic fluxes linked with the detecting coil becomes zero, so no electromotive force is generated.

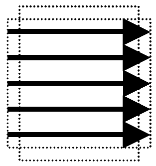


(Bottom view)

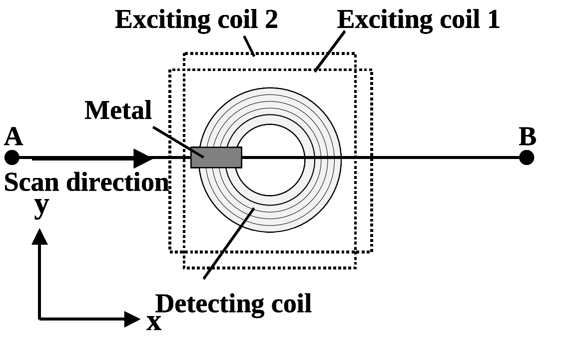


(Side view)

Fig. 3 Magnetic flux distribution when no metal object is present.

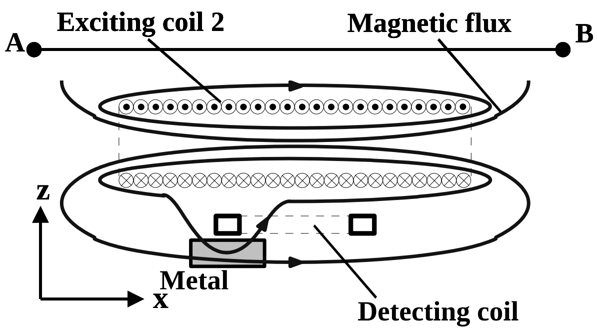


(a) Magnetic flux direction at $t = 0$



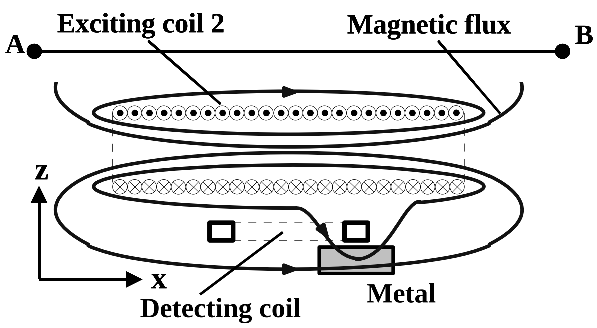
(Bottom view)

(b) Metal object direction parallel to the probe scan direction



(Side view)

(c) Magnetic flux distribution with metal object under the left side detection coil winding



(Side view)

(d) Magnetic flux distribution with metal object under the right side detection coil winding

Fig. 4 Principle of detection of magnetic metal object.

In the case of a magnetic metal, when the rotating magnetic field probe scans across the metal object, a signal is generated by the magnetic flux parallel to the longitudinal direction of the object, and detection signals with positive and negative peaks occur. The detection signals show a maximum value at the position where the metal object is perpendicular to the detecting coil winding (Fig. 4b).

With a non-magnetic metal, on the other hand, it is the change in magnetic flux due to eddy currents induced on the metal surface that is detected. Fig. 5 shows the principle of detecting a cuboid non-magnetic metal object. Fig. 5a shows the directions of magnetic flux and the eddy currents induced on the metal surface at $t = 0$; Fig. 5b shows the orientation of the metal object with respect to the scan direction of the probe; and Fig. 5c shows the magnetic flux distribution. When the metal object is located beneath the detecting coil winding, the magnetic flux distribution changes due to the eddy currents, and an electromotive force is generated in the detecting coil. When the probe moves to the point where the metal object is located beneath the other side of the detecting coil winding, the direction of magnetic flux penetrating the detecting coil is reversed and an electromotive force of opposite phase is generated. When the metal object is located at the center of the detecting coil, the sum of the magnetic fluxes linked with the detecting coil becomes zero, and no electromotive force is generated.

In the case of a non-magnetic metal, when the rotating magnetic field probe scans the metal object, a signal is generated by the eddy currents parallel to the longitudinal orientation of the object, and detection signals with positive and negative peaks occur. The detection signals peak at the position where the orientation of the metal object is parallel to the detecting coil winding (Fig. 5b).

As described above, in the case of magnetic metal, a signal occurs at the position where the metal object is perpendicular to the detecting coil winding, and in the case of a non-magnetic metal, a signal is generated at the position where the metal object is parallel to the detecting coil winding. Since the probe generates a

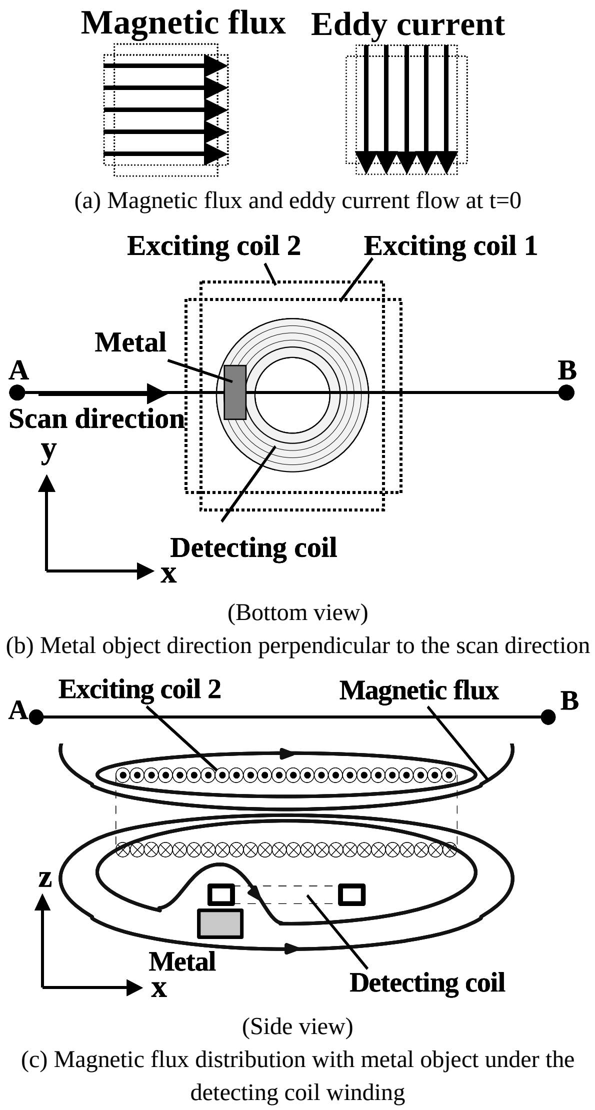


Fig. 5 Principle of detection of non-magnetic metal object.

rotating magnetic field synchronized with the excitation current, detection signals corresponding to the orientation of the metal object are obtained when the orientation of the metal object changes in the horizontal plane relative to the scan direction of the probe. It is possible to determine the orientation of the cuboid metal object from the detection signals obtained by two-dimensional scanning.

In the case of a magnetic metal, the magnetic flux penetrating the metal object plays a major role in generating an electromotive force in the detecting coil. With a non-magnetic metal, on the other hand, an electromotive force is generated in the detecting coil by the change in magnetic flux due to the eddy currents induced on the metal surface. Since there is a phase difference of 90° or more between the magnetic flux due to the eddy currents and the magnetic flux through the metal due to the exciting coil, there is a phase difference of 90° or more between the detection signals from magnetic and non-magnetic metals. It is therefore possible to determine whether the object is magnetic or non-magnetic from the phase of the detection signals.

Next, we consider the cases of different metal shapes (a cube and a cuboid) of the same material. If the metal shape is cuboid, a detection signal is obtained at the position perpendicular to the detecting coil winding if it is a magnetic metal, and at the position parallel to the detecting coil winding if it is a non-magnetic metal. If the metal shape is cubic, on the other hand, a detection signal is obtained when the detecting coil winding is perpendicular to or parallel to the metal object, regardless of whether the metal is magnetic or not. With a cube, therefore, signals are generated at the left, right, top, and bottom positions of the detecting coil winding. The detection signals are therefore different for a cube and a cuboid.

As described above, in the rotating magnetic field probe, it is possible to obtain detection signals that reveal the type of metal object (magnetic or non-magnetic), its shape (e.g., cubic or cuboid), and its orientation in the horizontal plane relative to the scanning direction of the probe. A rotating magnetic field probe can therefore obtain more information about the metal object than conventional metal detection probes.

3. Reconstruction of Metal Object Shape Using Image Reconstruction

Metal detection using a rotating magnetic field probe provides more information about metal objects than conventional metal detection probes, and may allow us to estimate their approximate shape. However, since magnetic flux diverges, the detection signals become blurred, which makes it difficult to determine the exact shape of the metal object. We therefore decided to use image reconstruction.

3.1 Image Deterioration

Let the image of the detection signals obtained by two-dimensional probe scanning be $b(x,y)$, and let the original image representing the surface shape of the metal object be $d(x,y)$. Here, (x,y) represents the positional coordinates of the probe. If the measurement system is linear and invariant with respect to position, i.e., a linear invariant system, the image $b(x,y)$ of detection signals is given by the convolution integral of the original image $d(x,y)$ representing the surface profile of the metal object and the point spread function $p(x,y)$ specific to the measurement system, as shown in Fig. 6, which shows a model of image degradation [7].

$$b(x,y)=d(x,y) * p(x,y)+n(x,y) \quad (1)$$

Here, $*$ denotes the convolution integral and $n(x,y)$ denotes noise. By Fourier transforming both sides of Eq. (1) and applying the convolution theorem, we obtain the following equation,

$$B(u,v)=D(u,v) \cdot P(u,v)+N(u,v) \quad (2)$$

where $B(u,v)$, $D(u,v)$, $P(u,v)$, and $N(u,v)$ denote the Fourier transforms of $b(x,y)$, $d(x,y)$, $p(x,y)$, and $n(x,y)$, respectively, and (u,v) denotes the frequency component.

The point spread function specific to the measurement system is obtained from the response of the system to the input delta function. The detection signals are then obtained by two-dimensionally scanning a metal object having a delta-functional shape with the probe. Let $d_0(x,y)$ be the image representing the surface profile of a metal object with a known delta-functional shape, and $b_0(x,y)$ the image of the detection signals obtained. The point spread function specific to the measurement system is then obtained by:

$$P(u,v)=B_0(u,v)/D_0(u,v) \quad (3)$$

where $B_0(u,v)$ and $D_0(u,v)$ represent the Fourier transforms of $b_0(x,y)$ and $d_0(x,y)$, respectively.

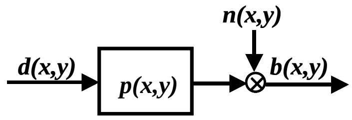


Fig. 6 Linear system and image degradation.

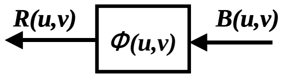


Fig. 7 Image restoration by de-convolution.

The detection principle of the rotating magnetic field probe is different between magnetic and non-magnetic metals, with the result that the detection signals for magnetic and non-magnetic metals are different, even if they have the same shape. Since the point spread function is specific to the measurement system, two different point spread functions are required for magnetic and non-magnetic metals.

3.2 Image Reconstruction

We used the Wiener filter, which is a method for image reconstruction, to reconstruct an image representing the surface shape of a metal object from the spectrum $B(u,v)$ of the image of detection signals. In the Wiener filter, the transfer function $\Phi(u,v)$ of the reconstruction system shown in Fig. 7 is given by

$$\Phi(u,v) = P^*(u,v) / [|P(u,v)|2+1/c] \quad (4)$$

where $P^*(u,v)$ denotes the conjugate complex number of $P(u,v)$; and c is given by $c=|B(u,v)|/|N(u,v)|$, where $B(u,v)$ is the spectrum of detection signals and $N(u,v)$ is the noise spectrum when there is no metal object.

With the reconstruction system whose transfer function is $\Phi(u,v)$, the spectrum $R(u,v)$ of the reconstructed image is given by:

$$R(u,v) = B(u,v) \cdot \Phi(u,v) \quad (5)$$

By inverse Fourier transforming the $R(u,v)$ obtained using the above equation, we obtain the reconstructed image $r(x,y)$, which is an image representing the surface shape of the metal object.

3.3 Process of Reconstructing the Surface Shape of Metal Objects

The steps of reconstructing the surface shape of a metal object are as follows.

(1) Determine a point spread function for magnetic metal objects and that for non-magnetic metal objects, with both having a delta-functional shape.

(2) Using the difference in detection signals between magnetic and non-magnetic metals, determine whether the metal object is magnetic or non-magnetic based on the phase of the detection signal.

(3) Based on this determination, the point spread function to be used for the reconstruction is selected, and the surface shape of the metal object is reconstructed.

4. Experimental Method

The dimensions of the exciting coils of the rotating magnetic field probe used in the experiment are 150 mm wide (W1 and W2 in Fig. 1), 160 mm long (L1 and L2 in Fig. 1), and 30 mm high (*t* in Fig. 1). The dimensions of the detecting coil are 70 mm in outer diameter, 50 mm in inner diameter, and 1 mm in winding thickness. The exciting coil has single-layer winding with about 300 turns. The detecting coil has about 160 turns. Table 1 shows the dimensions, materials, and shapes of the metal objects used. The metal detectors designed for detecting land mines are required to be able to detect about 1 g of metal contained in a buried mine. Since the weight of the metal objects used in the experiment was set to 1 g or less, even the longest metal object was limited to 30 mm in length, which was shorter than the detecting coil diameter of 70 mm. The intensity of the eddy currents induced in a metal object is a function of the product of the test frequency and the electromagnetic properties (e.g., magnetic permeability and electric conductivity) of the metal object. After testing at various frequencies, we adopted 5 kHz in this experiment, at which the detection sensitivity was almost the same for magnetic and non-magnetic objects. The distance between the probe and the metal object (hereinafter referred to as "lift-off") was set to 50 mm. To verify the metal detection characteristics of the rotating magnetic field probe, we fabricated a probe that is the same shape as a conventional metal detection probe to conduct a comparison experiment. Refer to Refs. [2-4] for conventional metal detection probes.

Table 1 Dimensions of sample used in the experiment.

Length	Width	Thickness	Materials	Shape
Unit: mm				
5	5	5	Iron	Cube
10	5	5	Iron	Cuboid
20	5	5	Iron	Cuboid
30	5	5	Iron	Cuboid
30	5	1	Iron	Cuboid
30	1	1	iron	Cuboid
20	2 diameter		Ferrite	Cylinder
5	5	5	Copper	Cube
30	5	5	Copper	Cuboid
30	5	5	Brass	Cuboid
30	5	5	Aluminum	Cuboid

Detection signals were obtained by two-dimensionally scanning a range of ±100 mm at 1 mm intervals with the probe, so that the image generated by the detection signals measured 201 × 201 pixels. The scanning interval of the probe is the resolution of the image generated by the detection signals. Since the minimum width of the metal object studied was 1 mm, the scanning interval was set to 1 mm in consideration of the measurement time required. The scanning interval of the probe, i.e., the resolution of the image, must be appropriately determined according to the size of the metal object to be detected, which in turn determines the resolution of the reconstructed image. Point spread functions specific to the measurement system were obtained for magnetic and non-magnetic metals, respectively, for image reconstruction from detection signals obtained with the rotating magnetic field probe. These signals were obtained from a metal object having a delta-functional cubic shape with a side of 5 mm in consideration of the detection sensitivity of the measurement system. That is, $B_0(u,v)$ in Eq. (3) is the Fourier transform of the detection signal $b_0(x,y)$ of a cubic metal object with a side of 5 mm, and $D_0(u,v)$ is the Fourier transform of the image $d_0(x,y)$ representing the surface shape of the cubic metal. From the obtained point spread functions and Eq. (4), we obtained the transfer functions of the reconstruction system. From the spectrum of the blurred image of detection signals obtained by probe scanning, $R(u,v)$ was obtained from Eq. (5), and inverse Fourier transformation was performed to obtain a reconstructed image representing the surface shape of the metal object. In applying the image reconstruction method, the lift-off for determining point spread functions must be almost the same as the lift-off for obtaining the signals of the metal object being reconstructed. In other words, when the lift-off changes, the intensity and distribution of magnetic flux acting on the metal object change, and the amplitude and blurring of the detection signals become different, even for the same metal object. The measurement system must be a linear invariant system.

The point spread function needs to be determined only once, and the Fourier transformation allows the convolution integral to be performed easily by multiplication and division.

5. Experimental Results

5.1 Metal Object Detection Signals

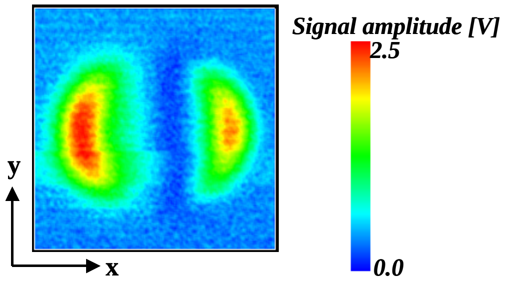
Figs. 8 and 9 show images of detection signals for different orientations of a metal object with respect to the scan direction of the probe (x-axis direction). The detection signals in these figures are given as signal amplitude, although they are an AC (alternating current) excitation current and are therefore obtained as complex signals. In the image, the color changes gradually from blue (low signal) to red (high signal). The metal object is an iron cuboid 30 mm in length and 5 mm in width and thickness. Figs. 8a and 9a show a case in which the orientation of the object is parallel to the scan direction, and Figs. 8b and 9b show a case where the orientation of the object is perpendicular to the direction of scan. In the conventional metal detection probe shown in Fig. 8, signals are generated at the left and right positions of the detecting coil winding regardless of the orientation of the metal object, and four signal peaks are generated when the orientation of the metal object is perpendicular to the scan direction. In contrast, in the rotating magnetic field probe shown in Fig. 9, signals are generated at the left and right positions of the detecting coil winding in the parallel case (a) and at the top and bottom positions in the perpendicular case (b), with the signal amplitudes being the same for both cases. Detection signals are also obtained for the orientation of the metal object at 45° and 135° to the scan direction. With the rotating magnetic field probe, the rotating magnetic field, which has uniform intensity, rotates in synchronization with the excitation current. According to the detection principle, a signal occurs at the position where the orientation of the cuboid magnetic metal object is perpendicular to the detecting coil winding. The detection signals therefore indicate the orientation of the metal object.

Fig. 10 shows an image of detection signals from a cube of iron with a side of 5 mm. In the conventional metal detection probe shown in Fig. 10a, signals are generated at the left and right positions of the detecting coil winding as in the case of the cuboid metal object, with the only difference being that the signal amplitude is reduced. With the rotating magnetic field probe shown in Fig. 10b, however, signals are generated at the top, bottom, left and right positions of the detecting coil winding. The detection signals differ between the cubic and cuboid metal objects. If the metal object has a circular surface shape (e.g., it is a cylinder or sphere), signals occur at all positions of the detecting coil winding and form a ring.

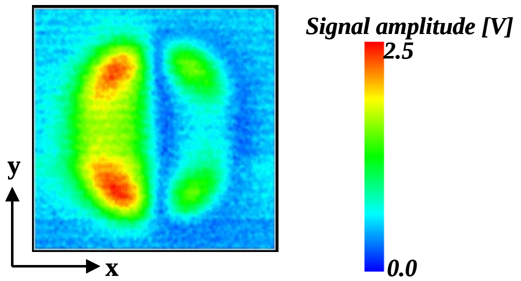
As described above, while conventional metal detection probes do not provide information on the shape or orientation of metal objects, the rotating magnetic field probe provides detection signals that reveal the shape and orientation of the metal.

Fig. 11 shows images of detection signals from metal objects made of different materials. Figs. 11a and 11b show signals from iron and copper objects, respectively, which have a cuboid shape 30 mm in length and 5 mm in width and thickness. The orientation of the metal object is parallel to the scan direction (x-axis direction). With iron, which is a magnetic metal, signals occur at the left and right positions if the metal object is perpendicular to the detecting coil winding. This is because the change in magnetic flux through the metal object is detected. However, for copper, which is a non-magnetic metal, signals are generated at the top and bottom positions where the metal object is parallel to the detecting coil winding because the change of magnetic flux due to eddy currents induced in the metal object is detected. With ferrite, which is another magnetic material, we obtained signals similar to those in Fig. 11a. Aluminum and brass, which are non-magnetic metals, give signals similar to those in Fig. 11b. Detection signals obtained from magnetic and non-magnetic objects are therefore different, even when they have the same shape.

Comparing the detection signals in Figs. 9b and 11b, we can see that they are similar to each other, with signals generated at the top and bottom positions of the detecting coil winding, even though the metal object orientations (perpendicular or parallel to the scan direction) differ from each other by 90°. Fig. 12 shows the pattern of detection signals along the direction passing through the maximum signal points (shown by the arrowed line in the former figures), as plotted on a complex plane. It shows that the signal phase, which is the tilt angle of the signal pattern in Fig. 12, is different between copper and iron. This is because the detection principle is different for magnetic and non-magnetic metals in the rotating magnetic field probe. Fig. 13 shows the signal phases of various metals. The signal phase was determined from the tilt angle of the signal pattern drawn in the direction passing through the two peak points in the image of the detection signals. We can see that signal phases are clearly different between magnetic and non-magnetic materials. The phase difference of detection signals can be used to determine whether the metal object is magnetic or non-magnetic. This difference is used to select a point spread function for image reconstruction as described below.

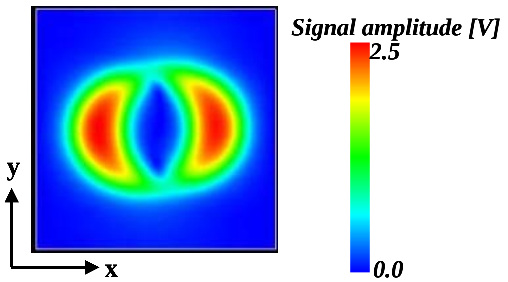


(a) Metal object direction parallel to the scan line

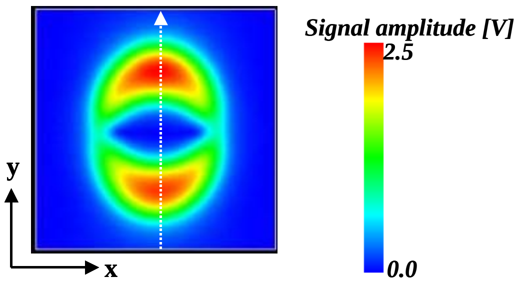


(b) Metal object direction perpendicular to the scan line

Fig. 8 Metal detection signal displays for different metal object directions: Conventional MD probe.

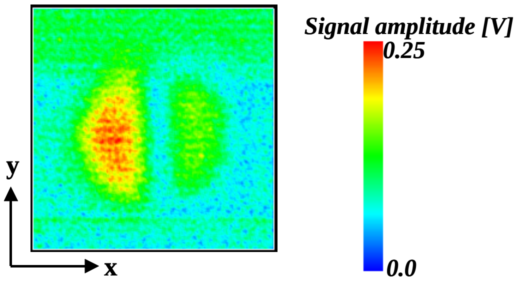


(a) Metal object direction parallel to the scan line

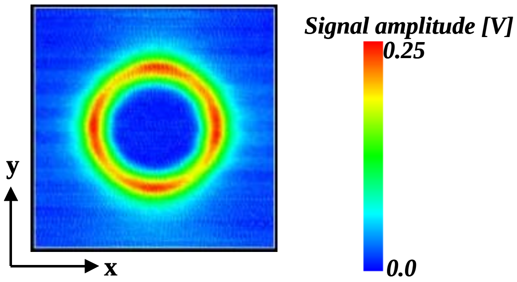


(b) Metal object direction perpendicular to the scan line

Fig. 9 Metal detection signal displays for different metal object directions: Rotating magnetic field probe.

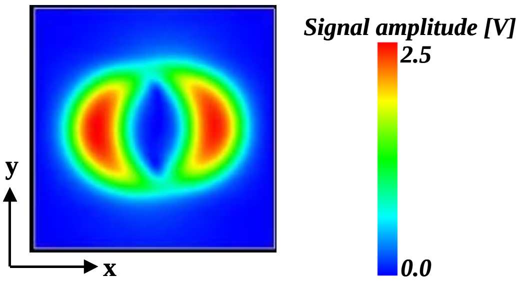


(a) Conventional MD probe

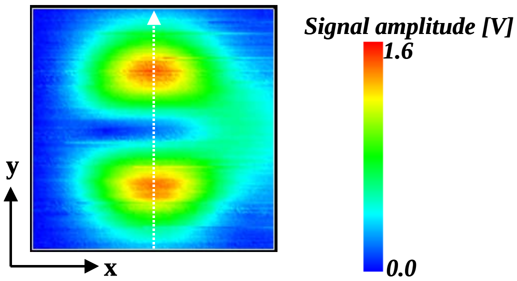


(b) Rotating magnetic field probe

Fig. 10 Metal detection signal display of cubic metal object.



(a) Magnetic metal (iron)



(b) Non-magnetic metal (copper)

Fig. 11 Metal detection signal displays for different metal characteristics.

The following is an algorithm for estimating the approximate shape and orientation of a metal object and identifying whether the object is magnetic or non-magnetic on the basis of the above-described detection results obtained by the rotating magnetic field probe.

(1) Determine whether the metal object is cubic or cuboid based on the images of detection signals, as shown in Figs. 9b and 10b.

(2) If it is a cuboid, draw a pattern of signals in the direction connecting the peaks of detection signals on a complex plane. Determine the signal phase from the drawn signal pattern to identify whether the metal object is magnetic or non-magnetic.

(3) Determine the orientation of the metal object from the peak-to-peak orientation of the detection signal image. For a magnetic metal, as indicated by the detection principle, the orientation connecting between the peaks on the image is the orientation of the metal object; and for a non-magnetic metal, the orientation perpendicular to the line connecting between the peaks on the image is the orientation of the object.

In this way, it is possible to roughly estimate the size and type of metal objects. We also applied the image reconstruction method to estimate the shape of metal objects in detail.

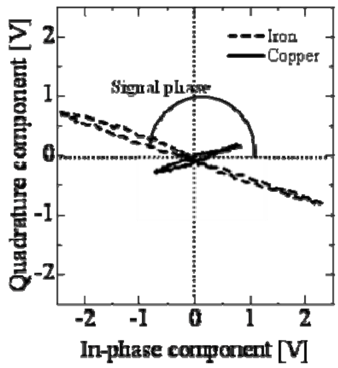


Fig. 12 Patterns of metal detecting signals.

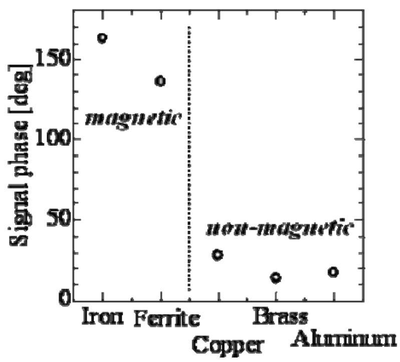
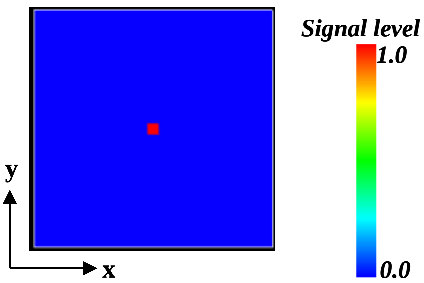


Fig. 13 Phases of metal detecting signals.

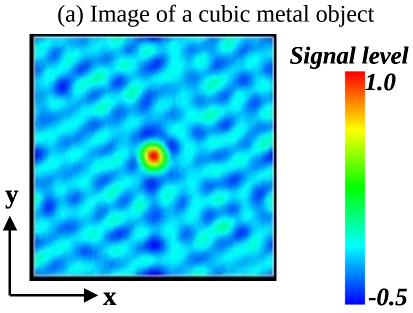
5.2 Results of Reconstructing the Shape of Metal Objects

This section shows the results of reconstructing the surface shape of metal objects using our image reconstruction method. Fig. 14 shows the results for an iron cube with a side of 5 mm, and Figs. 15 and 16 show the results for an iron cuboid 30 mm in length and 5 mm in width and thickness. Figs. 15 and 16 show the cases of object orientation of 45° and perpendicular, respectively, to the scan direction. Each of Figs. 15a and 16a shows the actual surface shape of the metal object, and each of Figs. 15b and 16b is an image of the reconstructed shape of the metal object. It shows that the image of the reconstructed surface shape of the metal object is closer to the original image representing the object shape.

We also obtained reconstructed images for other metal objects and confirmed that they could be used to estimate the shape of the objects. We have confirmed that good image reconstruction results can be obtained for both magnetic and non-magnetic metals by obtaining separate point spread functions for magnetic and non-magnetic metals.

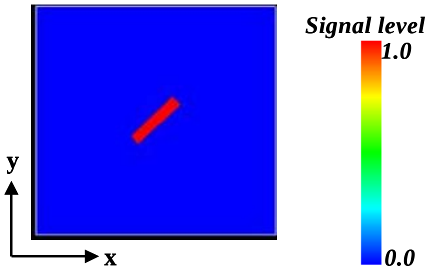


(a) Image of a cubic metal object

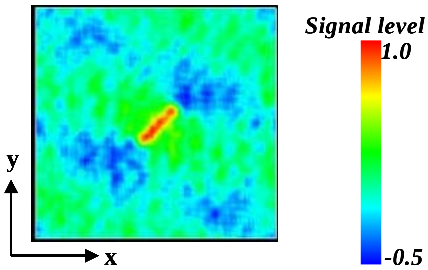


(b) Image restored from the detecting signal

Fig. 14 Image restoration result for a cubic metal object.

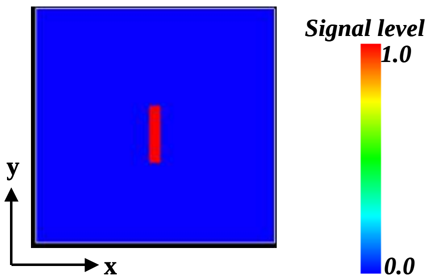


(a) Image of a cuboid metal object

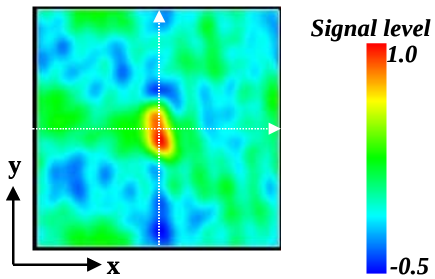


(b) Image restored from the detecting signal

Fig. 15 Image restoration result for a cuboid metal object when the metal direction is angle 45° to the scan line.



(a) Image of a cuboid metal object



(b) Image restored from the detecting signal

Fig. 16 Image restoration result for a cuboid metal object when the metal direction is perpendicular to the scan line.

6. Conclusions

We investigated metal detection using a rotating magnetic field probe and applied an image reconstruction method to discern the surface shape of metal objects using the detection signals. As a result, we obtained the following findings.

(1) The rotating magnetic field probe makes it possible to obtain detection signals that carry information on the shape of the metal object and its orientation with respect to the direction of scan. The detection signal amplitude remains the same even when the orientation of the metal object with respect to the scan direction changes in the horizontal plane.

(2) The phase of the detection signals varies according to whether the metal object is magnetic or non-magnetic, and can therefore be used to determine whether a metal object is magnetic or non-magnetic.

(3) We presented an algorithm for estimating the orientation and approximate shape of the metal object from the detection signals.

(4) Due to the difference in detection principle between magnetic and non-magnetic metals in the rotating magnetic field probe, it is necessary to obtain separate point spread functions for magnetic and non-magnetic metals when reconstructing the surface shape of a metal object using the image reconstruction method.

(5) We have confirmed that by applying the image reconstruction method to detection signals, it is possible to obtain an image that closely approaches the shape of the metal object. This indicates the potential to determine the approximate shape of a metal object through image reconstruction.

In the future, we plan to conduct more detailed investigations, such as addressing cases where a metal object is tilted in the z-axis direction relative to the scan direction and where multiple metal objects are present.

References

[1] Sato, M. 2005. “Dual Sensor ALIS Evaluation Test in Afghanistan.” In *Proceedings of the IEEE Geoscience and Remote Sensing Society Newsletter*, pp. 22-7.

[2] Kruger, H., Ewald, H., Fechiner, T., and Bergeler, S. 2006. “New Signal Processing for Metal Detectors in the Humanitarian Mine Clearance.” In *Proceedings of the* 9th *European Conference on NDT, Proceedings BB 103-CD.*

[3] Takahashi, K., Preetz, H., and Igel, J. 2011. “Soil Properties and Performance of Landmine Detection by Metal Detector and Ground-Penetrating Radar: Soil Characterization and Its Verification by a Field Test.” *J. Applied Geophysics* 73: 368-77.

[4] Takahashi, K., Preetz, H., and Igel, J. 2013. “Influence of Soil Properties on the Performance of Metal Detectors and GPR.” *J. ERW and Mine Action* 17 (1): 52-6.

[5] Lopez, A. E. C., Fukushima, E. F., and Endo, G. 2016. “Normalizing Abstractions of Heterogeneous Robotic Systems by Using Roles: Usability Study in the Administration of Software and Development Tools.” *Advanced Robotics* 30 (9): 565-84.

[6] Hoshikawa, H., and Koyama, K. 1998. “A New Eddy Current Probe Using Uniform Rotating Eddy Current.” *Materials Evaluation* 56 (1): 85-9.

[7] Huang, T. S., Schreiber, W. F., and Tretiak, O. J. 1971. “Image Processing.” *Proceedings of the IEEE* 59 (11): 1586-609.