Measurement of Axis Eccentric of Round Rod by Multi Giant Magnetoresistance Probe

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Eddy currents induced on the surface depend on properties on near-surface of conductive materials and the arrangement between exciting coil, detecting sensor, and materials, as lift-off height and inclination. We apply the multi-sensor probe for the applications of eddy-current testing to detect the center of small round metal. The measurement system detects the magnetic fields around the round metal simultaneously and estimates the gap and direction of axis eccentric. We describe the principle of detection and the experimental results.

Key Words: giant magnetoresistance, eddy current testing, round rod, axis eccentric

1. Introduction

Giant magnetoresistance (GMR) has paved the way for the non-destructive measurement of a wide range of applications. GMR sensors play an important part in physical systems, straddling a variety of applications such as industrial, medical robotic, military, consumer and automotive applications [1 and 2]. Quality control in hostile environments requires sensors which are durable, stable, fast, accurate as well reach safety requirements. Welding in the automation industry and rolling mills use round rods of different materials. Generally an optical gap sensor can be used for curved surface but this method can be complex due to a variety of reasons such as reflection. Gap sensors based on eddy currents are normally used for flat surfaces [3]. During the welding process it is important that the welding rod is in the right position and also unmoved. This procedure is challenging for the welding operator and any feedback if and when the rod moves would pave the way for a successful weld, as the technique can be adjusted accordingly.

This paper proposes a method that utilizes GMR sensors to measure axis eccentric of circular rods. The advantages of the proposed system are non-contact measurement. The proposed system has a good potential to be used for the measurement of axis eccentric of high temperature circular rods used in the welding industry.

2. Principles of Axis Eccentric Measurement

2.1 Structure of probe

The probe consists of 2 exciting coils and 36 sensors as shown in Fig. 1. Each exciting coil has diameter 26 mm and 40 turns. This probe is made for the measurement of 16 mm diameter rod. The sensors are designed in such away so that they are placed at the center of the 2 exciting coils as shown in Fig. 1(a) and are 10 degrees apart from each other as shown in Fig. 1(c). The sensors are numbered sequentially 1 to 36. These sensors use four spin-valve type giant magnetoresistance (SV-GMR) sensing areas in a bridge circuit design as shown in Fig. 2. The bridge circuit decreases the off-set voltage and temperature disturbance. As magnetic fields are applied, the resistance of one of R_1 or R_2 increases and the other decreases. The series circuit of R_1 and R_2 keeps the same resistance, then the constant current flows even if the constant voltage is applied. The characteristics of the GMR sensor are shown in Fig. 3. The sensor has high sensitivity (250 μV/μT) for y-axis component and for z- and x-axis has low sensitivity less than 5 μV/μT. The y-axis of the sensors is located on the probe in a round direction. The test rod used for experiments is stainless steel with diameter 16 mm, relative permeability 1.03, and conductivity 1.4×10^6 S/m.

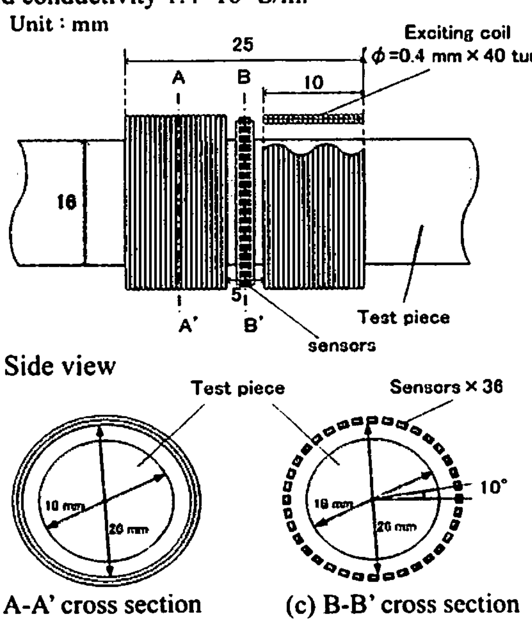

Fig. 1 Structure of the probe

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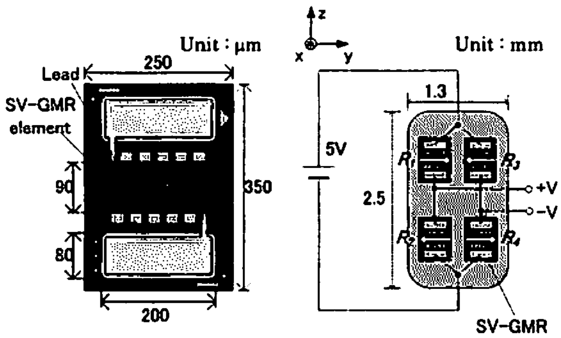


(a) SV-GMR (b) bridge circuit

Fig. 2 Bridge circuit of the SV-GMR sensor

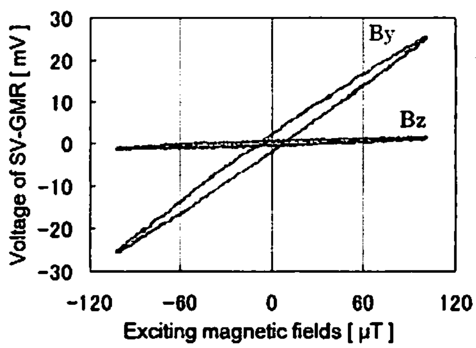


Fig. 3 Characteristics of the SV-GMR sensor

2.2 Distribution of magnetic flux

The exciting coils are fed with 400 mA current at 100 kHz, and each exciting current is opposite to each other. Exciting flux is generated in the axial direction and eddy currents are generated in the radial direction. The skin depth is about 1.3 mm. The distribution of magnetic flux is analyzed with axis symmetrical model as shown in Fig. 4. In the middle of two exciting coils, there is only r-direction magnetic flux lines because the two exciting coils' current has the same amplitude but opposite direction. When the round rod is central to the probe, ideally there is no circular direction magnetic flux lines on each sensor. If round rod moves from the center of the probe, magnetic flux is supposed to have a radial distribution from the center of the round rod as shown in Fig. 5. The distance of the round rod to the sensor (lift-off height) is L_n, and the radius of rod and the probe are r_1 and r_2.

On the sensors, magnetic flux is not only in the r-direction but also in the round direction as shown in Fig. 6. Therefore, sensors can detect the magnetic flux when round rod is not centered on the probe. The output voltage of the sensor number n is expressed in Eq. (1).

$$V_{out} = k_0 B_r \sin\phi_n$$
$$\approx k_0 B_r \phi_n \quad (k_0\text{: constant. } \phi_n \approx 0) \quad (1)$$

The lift-off height L_n can be expressed by Eq. (2) if axis eccentric distance d is small compared with the radius of the probe and normally in this case axis eccentric distance d is small.

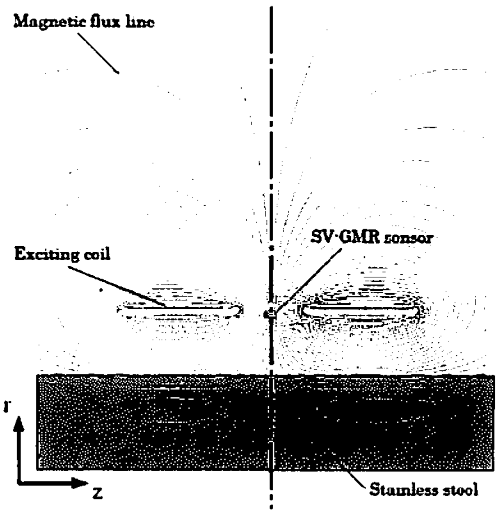


Fig. 4 Distribution of magnetic flux

$$L_n = \sqrt{(r_2\cos\theta_n - d)^2 + (r_2\sin\theta_n)^2} - r_1$$
$$\approx r_2\left(1 - \frac{d}{r_2}\cos\theta_n\right) - r_1 = (r_2 - r_1) - d\cos\theta_n, \quad (d \ll r_2) \quad (2)$$

In the center of the two exciting coils, the magnetic flux density B_r is inversely proportional to the sum of the radius of the round rod r_1 and lift-off height L_n in the center. The magnetic flux density B_r can be expressed by Eq. (3).

$$B_r \propto \frac{1}{r_1 + L_n}$$
$$B_r = k'\left(1 + \frac{d}{r_2}\cos\theta_n\right) \quad (d \ll r_2) \quad (3)$$

where k' is coefficient.

The angle between the probe's normal line and magnetic flux is assumed to be ϕ_n as derived in Eqs. (4) and (5) as follows,

$$\cos\phi_n = \frac{r_2^2 + (L_n + r_1)^2 - d^2}{2r_2(L_n + r_1)} = 1 - \frac{\frac{1}{2}\left(\frac{d}{r_2}\right)^2 \sin^2\theta_n}{1 - \frac{d}{r_2}\cos\theta_n}$$
$$\approx 1 - \frac{1}{2}\left(\frac{d}{r_2}\right)^2\left(1 + \frac{d}{r_2}\cos\theta_n\right)\sin^2\theta_n \quad (d \ll r_2) \quad (4)$$

$$\phi_n \approx \frac{d}{r_2}\sin\phi_n\sqrt{1 + \frac{d}{r_2}\cos\theta_n} \approx \frac{d}{r_2}\sin\theta_n\left(1 + \frac{d}{2r_2}\cos\theta_n\right)$$
$$= \frac{d}{r_2}\sin\theta_n + \frac{1}{4}\left(\frac{d}{r_2}\right)^2 \sin 2\theta_n \quad (5)$$

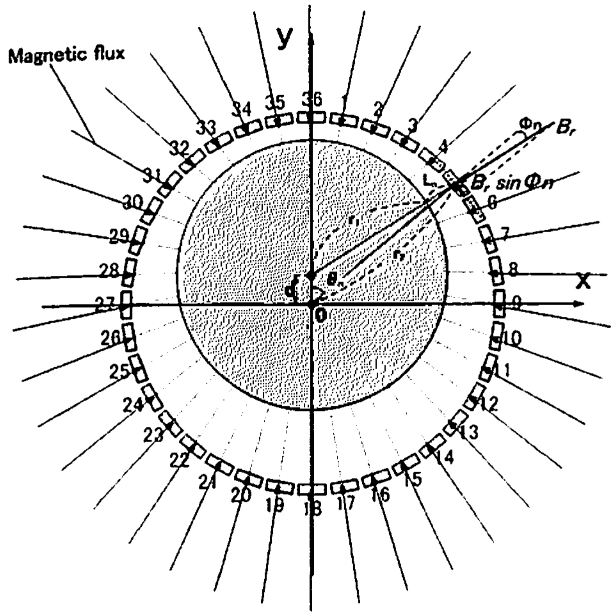


Fig. 5 magnetic flux lines during axis eccentric

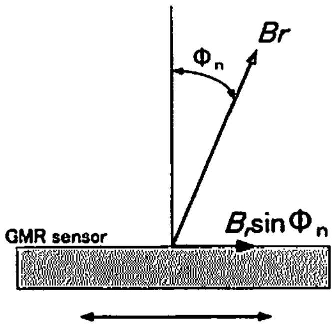


Fig. 6 Relationship between sensor and magnetic vector

$$V_{out} = a\sin(\theta_n - \theta_0) + b\sin 2(\theta_n - \theta_0) \quad (6)$$

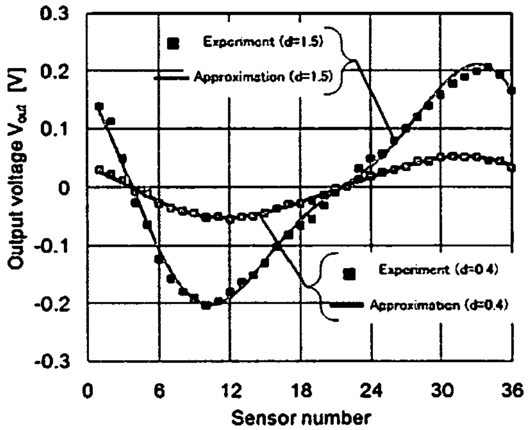
$$a = k_1 \frac{d}{r_2} \quad b = k_2\left(\frac{d}{r_2}\right)^2 \quad (7)$$

Finally, the output voltage V_{out} can be expressed by including axis eccentric direction θ_0 expressed in Eq. (6). The coefficient a of $\sin\theta$ is related to the axis eccentric distance d and the radius of probe r_2. The axis eccentric distance d can be obtained from the coefficient a.

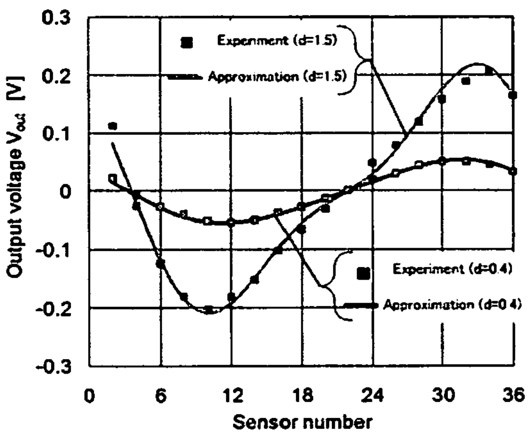
3. Measurement of Axis Eccentric

3.1 Data analysis

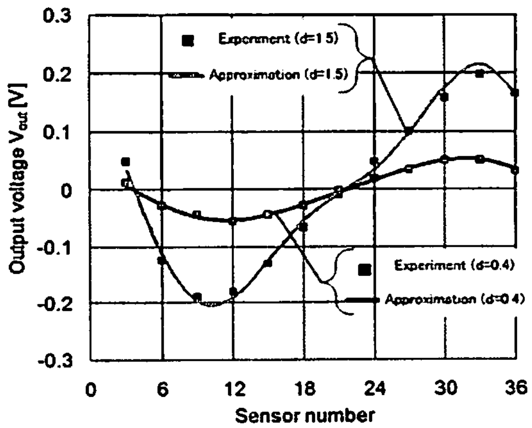
The multi-sensor can measure multiple points of magnetic flux simultaneously. The data expresses magnetic flux every 10 degrees around the circumference of the round rod. Data from experiments include noise or measurement error. It is possible to decrease the noise and measurement error by analyzing the measurement data with Fourier series expansion. Even if the round rod has crack, Fourier analysis decreases the effect of the crack. Even though the probe has 36 sensors, we do not need to use 36 sensors. Fourier analysis needs odd numbers of data, but since the 37th set of data is same as the 1st set of data, even number of data is obtained. Experimental and analysis results are shown in Fig. 7. Figures 7 (a), (b), and (c) indicate the results for 36, 18 and 12 sensors respectively. In these figures, the x-axis is the number of sensors with 10 degree spacing each, and the y-axis shows the output voltage of sensors. In the figure, the points are experimental results and the lines are analytical results.



(a)



(b)



(c)

Fig. 7 Result obtained by measuring flux density with (a) 36 sensors, (b) 18 sensors, and (c) 12 sensors.

3.2 Measurement of axis eccentric distance

The axis eccentric distance d is obtained by coefficient a in Eq. (6). It can be seen from Eq. (7) that the eccentric distance d is proportional to the amplitude. The relation of amplitude a and axis eccentric distance d for 36 and 12 sensors are shown in Figs. 8 and 9 respectively. Experiments were done with axis eccentric distance 0.4, 0.65, 1.05, and 1.5 mm. Each axis eccentric distance measured 12 different directions. It can be seen that the amplitude is linearly proportional to and axis eccentric. The gradient in Fig. 8 is 0.13 V/mm which is similar to the results obtained when using 36, 18 and 12 sensors.

3.3 Measurement of axis eccentric direction

The axis eccentric direction can be obtained from Eq. (6). The output voltage V_{out} crosses the axis at 2 points. The cross points with the negative gradient is axis eccentric direction. The 36th sensor eccentric

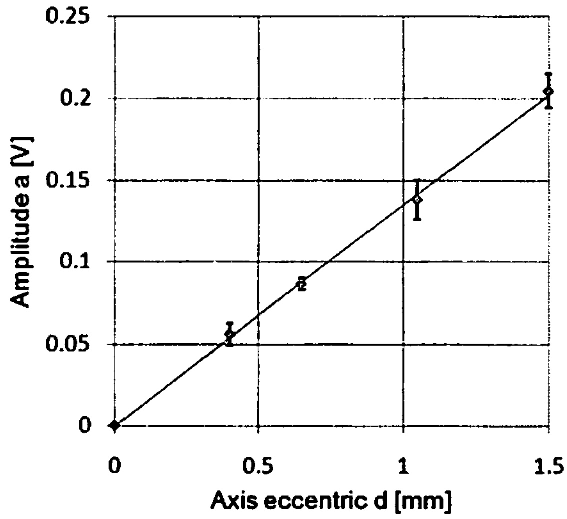


Fig. 8 Relationship between anplitude a and axis eccentric distance d with 36 sensors.

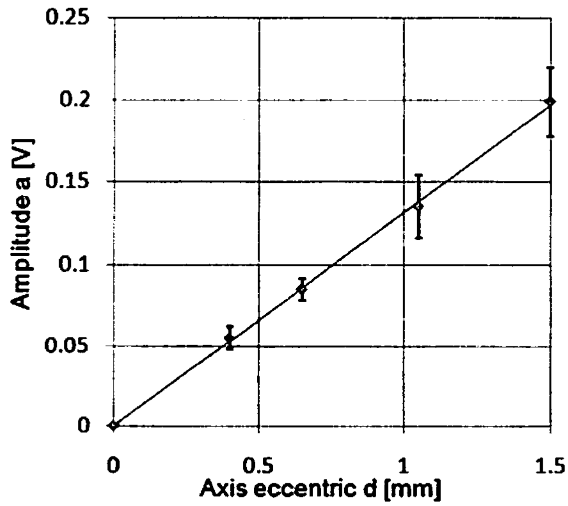


Fig. 9 Relationship between anplitude a and axis eccentric distance d with 12 sensors.

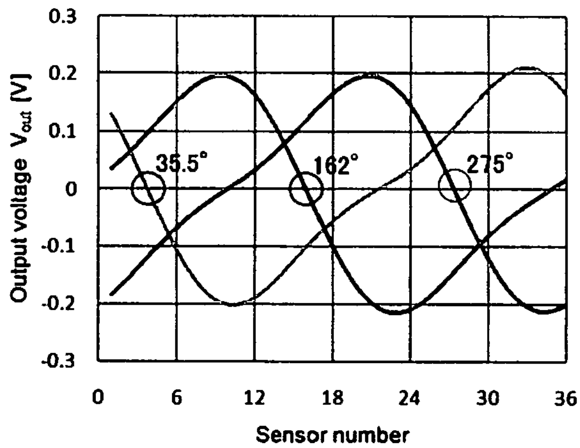


Fig. 10 Estimation of axis eccentric direction

positioned at 0°/360° is taken as the basis in the circular sensor arrangement. Hence, from the basis sensor No.1 is 10 degrees, sensor No.2 is 20 degrees etc in a clockwise direction.

The experiment results with axis eccentric distance 1.5 mm changed the axis eccentric direction by about 120 degrees as shown in Fig. 10. It can be clearly seen from Fig. 10, that each axis eccentric direction is 35.5, 162, and 275 degrees.

4. Conclusion

This paper describes a method for the measurement of axis eccentric of a round rod by eddy-current technique. The axis eccentric distance and direction can be measured by the measurement of the magnetic flux density with multi-sensor and Fourier analysis. This experiment used only one type of stainless steel. Different types of test rods with different characteristics should be considered in future and experiments should be performed to measure axis eccentric.

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