Relationship between Sensor Output of a Fluxgate Magnetic Sensor and the Magnetic Domain Structure of its Core

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We investigated the dependence of the sensitivity and noise of fluxgate sensors on the saturation flux density and magnetostriction of an amorphous ribbon core. The relationship between the sensing properties and the domain structures were also investigated with a Kerr microscope. The noise at the zero field increased with the increase in the magnetostriction properties of the core material. The sensitivity decreased with the increase in magnetostriction. Highly magnetostrictive amorphous ribbons had maze domains that were difficult to move by applying a low magnetic field of a few Oersteds. This caused a decrease in the sensitivity of the sensors, and affected noise such as the noise that caused zero drift.

Key words: fluxgate, noise, magnetic domain structure, maze domain, Kerr effect microscope, magnetostriction

1. Introduction

Fluxgate sensors are one of the most sensitive magnetic sensors. They are sensitive to the field direction in a range up to 1 mT with achievable resolution down to 10 pT[1),2)]. The fluxgate sensor can work at room temperature, and its temperature stability allows its use as a popular high-sensitivity magnetic sensor.

A fluxgate sensor consists of a magnetic bulk or ribbon core and electrical windings that provide the excitation and detection coils around the magnetic core. Therefore, it is not simple to miniaturize the sensor head. Several micro fluxgate sensors have been demonstrated, and were directly integrated on Si-wafers[3)-6)]. However, their thin-film fluxgate sensor element is expensive in comparison with a bulk element. This study aims to miniaturize a sensor head consisting of a magnetic ribbon core to produce a viable commercially-available fluxgate sensor. Generally, decreasing the sensor head size causes a decrease in its sensitivity. It is reported that a sensor having low noise and high sensitivity can be achieved using heat-treated permalloy (with 78–81% of nickel) or an amorphous ribbon with low magnetostriction[6)]. The output from the pick-up coil is induced by a change in the magnetic flux. Therefore, using amorphous ribbons with a high saturation flux density B_s as the core material is one of the possibilities to achieve the miniaturization of a sensor head with high sensitivity. However, amorphous ribbons with a high B_s generally have a large magnetostriction that produces low sensitivity due to change in magnetic domain structure and magnetization process. Little is known about their magnetic domains and magnetization process, which are important properties for the sensitivity of the fluxgate sensor [7), 8)].

In this study, the domain structure and magnetization process of amorphous cores were examined using a Kerr microscope. Moreover, we examined the dependence of the sensitivity and noise of fluxgate sensors on the saturation flux density by using different types of amorphous cores having different B_s. The relationships between the sensing properties and the domain structures are also investigated because the sensing properties are related to the domain structure of the core material.

2. Experimental method

2.1 Measurement of the sensor output

A schematic of the sensor element consisting of a conventional parallel-type fluxgate structure is shown in Fig. 1. An excitation coil is wound around an amorphous magnetic ribbon. The excitation current I_{exc} flowing through the excitation coil produces a field that periodically saturates (in both directions) in the soft magnetic material of the sensor core. During the saturation, the core permeability drops and the DC flux associated with the measured DC magnetic field B_0 decreases[9)]. When a measurable field is present, voltage is induced in the sensing pick-up coil at the second (and higher) harmonic(s) of the excitation frequency. This voltage, proportional to the measured field, is usually the sensor output.

Three types of amorphous ribbons made by Hitachi Metals Ltd. were used in this study. The composition, saturation flux density B_s, and magnetostriction λ_s of the core materials are shown in Table 1. The materials are a Co-based ribbon (2714A), a Ni-based ribbon (2826MB), and a Fe-based ribbon (2605SC). The Fe-based ribbon has the highest B_s = 1.6 T and $\lambda_s = 30 \times 10^{-6}$ and the Co-based ribbon has the lowest B_s = 0.57 T and $\lambda_s << 1 \times 10^{-6}$. The size of the samples is 1 mm wide, 20 mm long, and 15–20 μm thick.

The *B*-*H* loop of each sample is measured with a *B*-*H* analyzer, and the results are shown in Fig. 2. The flux density at 10 Oe of Co-based, Ni-based, and Fe-based ribbons are 537, 676, and 1119 mT, respectively. The coercive force of Co-based, Ni-based, and Fe-based ribbons are 0.61, 0.63, and 0.33 Oe, respectively.

Figure 3 is a block diagram of the electrical circuit used in the experiment. A square wave of 18 kHz is produced by a function generator and is diverted to an excitation coil as an exciting current. The sensor output is obtained by performing synchronization rectification of the output voltage of the pick-up coil at a frequency

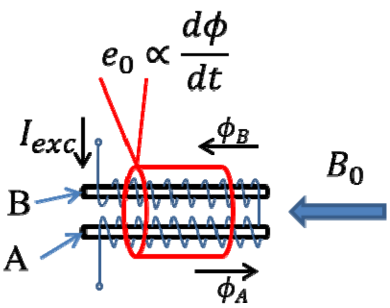

Fig. 1 Schematic of a sensor head.

Table 1 Parameters of the amorphous ribbons for the sensor core.

	Composition	B_s [T]	$\lambda_s \times 10^{-6}$
2714A Co-based	$Co_{66}Fe_4Ni_1Si_4B_{15}$	0.57	<< 1
2826MB Ni-based	$Fe_{40}Ni_{38}Mo_4B_{18}$	0.86	12
2605SC Fe-based	$Fe_{81}B_{13.5}Si_{13.5}C_2$	1.60	30

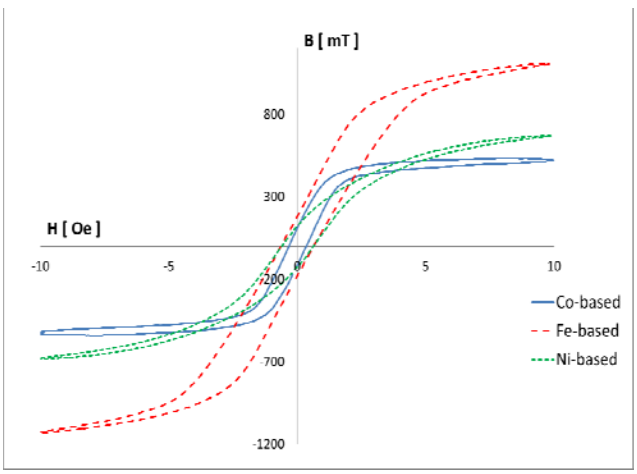

Fig. 2 B-H curves.

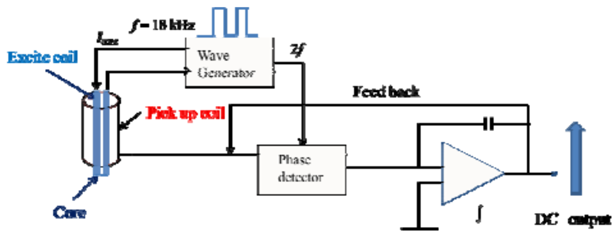

Fig. 3 Block diagram of a fluxgate magnetometer.

that is twice the excitation frequency. Suitable negative feedback to the pick-up coil is applied to this signal, and a DC sensor output voltage is measured with a memory recorder in order to evaluate the zero drift of the sensor.

Then, wave pattern of the output voltage from the pick-up coil without the negative feedback was observed with an oscilloscope. The wave pattern of the sensor output from the three cores was observed and the B_s dependence of the sensor output was investigated. In this experiment, the excitation frequency was decreased to 8 kHz in order to clearly observe the transient response of the sensor output induced in one period of the excitation cycle.

2.2 Magnetic domain observation

Magnetic domains of the three core materials of the fluxgate sensor were examined using a magnetic Kerr effect microscope. The observed sample was fixed with an adhesive on a glass substrate, and the magnetic domain of the center area of the sample was observed. When a magnetic field from +20 Oe to −20 Oe was applied to the longitudinal direction of the sample, the change in the magnetic domain structure in the static magnetization process was observed.

3. Results and discussion

Figure 4 shows the time response of the zero drift of the sensor DC output with a feedback for 10 minutes with no applied field. Although the theoretical sensor output with zero field is zero, an output voltage of approximately 0.5 mV is measured at the Fe-based ribbon core. In addition, zero drift of the Fe-based ribbon was higher than that of the Ni-based and Co-based cores, and a voltage drop of approximately 0.8 mV was observed for those 10 minutes. On the other hand, an output voltage of 0.05 mV was obtained, and the zero drift was hardly measurable in case of the Co-based ribbon core. These data indicate that the output voltage at zero field increases with an increase in magnetostriction of the core.

Figures 5 and 6 show the wave patterns of the output voltage from the pick-up coil (without the negative feedback) at zero field and 1 Oe. When the applied field is zero, the output voltage of the Fe-based, Ni-based, and Co-based ribbons is 1.8 $V_{p\text{-}p}$, 1.3 $V_{p\text{-}p}$, and

0.46 $V_{p\text{-}p}$, respectively (Fig. 5). The magnetostriction dependence of the output voltage is similar to that of the DC output voltage with feedback (Fig. 4).

When the applied field was 1 Oe, the output voltage of the Fe-based, Ni-based, and Co-based ribbons increased to 8 $V_{p\text{-}p}$, 8 $V_{p\text{-}p}$, and 22 $V_{p\text{-}p}$, respectively (Fig. 6). Although Co-based ribbon has the smallest B_s, its output voltage is the highest. It is determined that the sensitivity decreases with the increase in magnetostriction of the core material.

Magnetic domain images in the static magnetization process are shown in Figs. 7, 8, and 9. Figure 7 shows the magnetic domain images of the Co-based ribbon. The bright and dark domains are magnetized in the upward and downward direction, respectively. When the applied field is −0.036 Oe, all observed areas exhibit dark domains having downward magnetization components (Fig. 7(a)). These data indicate that a saturated state is obtained at this field value. When the magnetic field is changed to +0.096 Oe, bright domains having upward magnetization components appear (as indicated by the arrow in Fig. 7(b)).

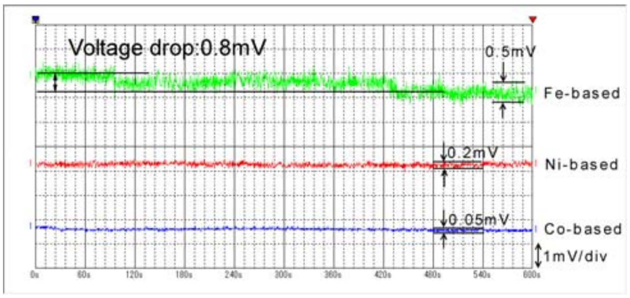

Fig. 4 Time response of zero drift.

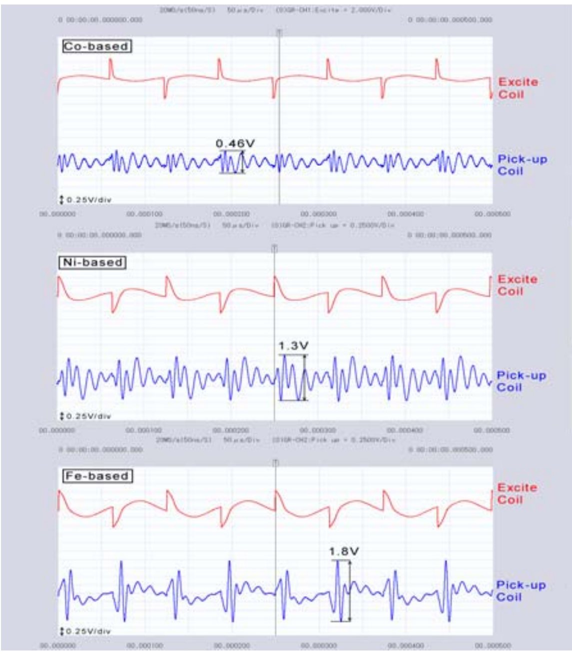

Fig. 5 Wave pattern of the sensor output at 0 Oe.

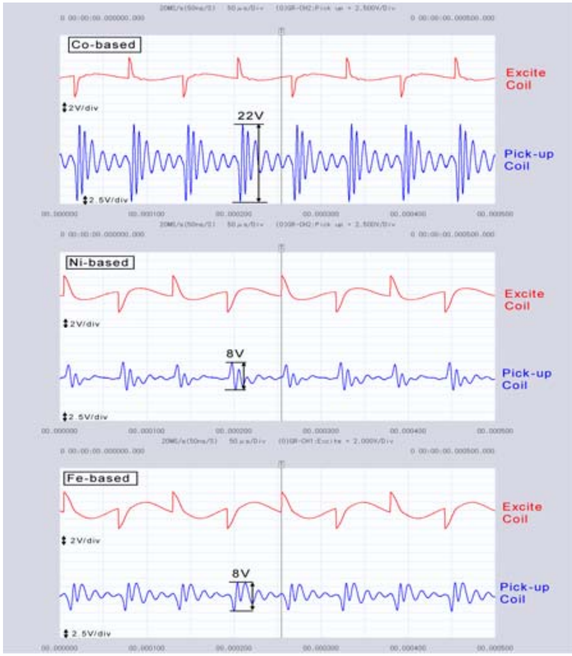

Fig. 6 Wave pattern of the sensor output at 1 Oe.

The areas of the bright domains increase when the field is increased to +0.54 Oe (Fig. 7(e)). It was determined that a smooth magnetic domain wall motion occurred by applying a field of approximately 0.5 Oe in the case of the Co-based ribbon.

Figure 8 shows the domain images of the Ni-based ribbon. The domain wall motion also occurs when applying a magnetic field of a few oersteds (Fig. 8(b) to (d)). However, in the case of the Ni-based ribbon, maze-patterned domains are observed, as marked by the outline in Fig. 8, and the maze domains hardly move when applying a high field of +3.6 Oe (Fig. 8(e)).

Figure 9 shows the domain images of the Fe-based ribbon. The magnetic domain structure of the Fe-based ribbon contains a maze pattern similar to the magnetic domain structure of the Ni-based ribbon as marked by the outline in Fig. 9. When a field of −0.86 Oe is applied, large-sized domains move to the center of the image (Fig. 9(c)). However, the maze domain does not change even if the field is increased to +5.3 Oe (Fig. 9(e)).

As a result, the maze domains contained in the Ni-based and Fe-based ribbons are difficult to move compared with their large-sized domains.
This is attributed to the decrease in sensitivity of the sensor with Ni-based and Fe-based ribbon cores. On the other hand, because smooth wall motion occurs in the Co-based ribbon by applying a low field, its sensitivity is high. Residual stress applied by the substrate is the primary cause of maze domains due to the inverse magnetostriction effect.

In addition, the local stress produced by the substrate causes pinning sites of the domain wall motion in the case of the high magnetostrictive ribbons. This causes an increase in Barkhausen noise that affects the noise such as the noise that causes zero drift

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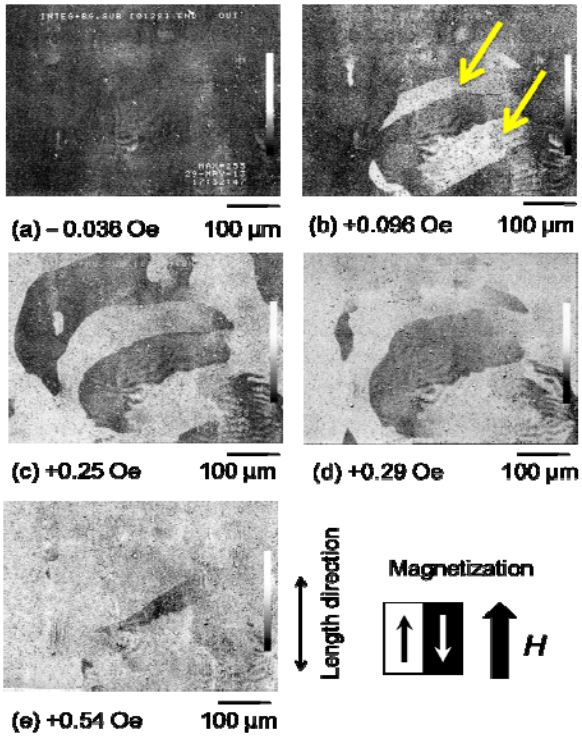

Fig. 7 Domain images of the Co-based ribbon.

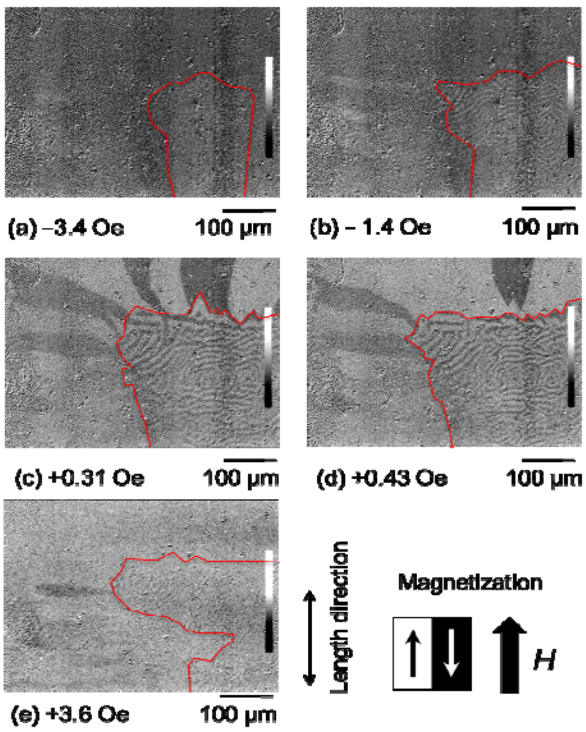

Fig. 8 Domain images of the Ni-based ribbon.

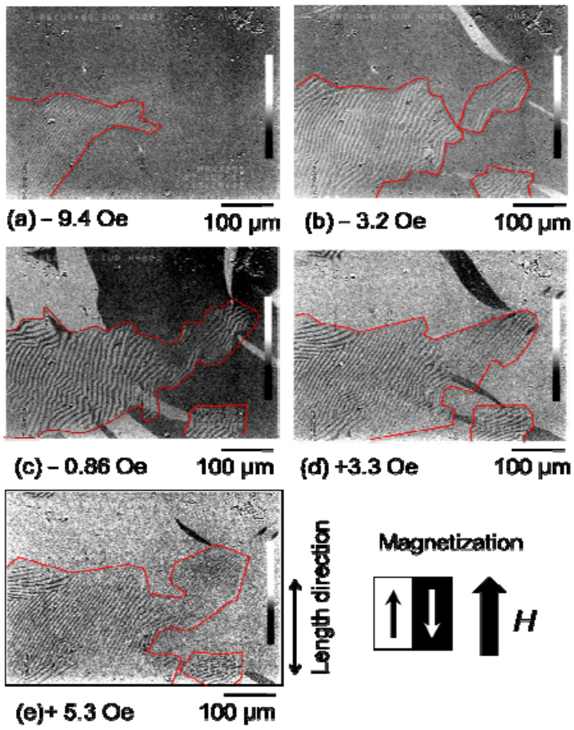

Fig. 9 Domain images of the Fe-based ribbon.

4. Summary

We investigated the dependence of sensitivity and noise of fluxgate sensors on the saturation flux density and magnetostriction of amorphous ribbon cores. Moreover, the relationships between the sensing properties and the domain structures are investigated with a Kerr microscope. The noise at zero field increases with an increase in magnetostriction property of the core material. Sensitivity of the material decreases with the increase in magnetostriction. Fe-based and Ni-based, high magnetostrictive, amorphous ribbons have maze domains that are difficult to move by applying a low magnetic field of a few oersteds. This causes a decrease in the sensitivity of a sensor with Ni-based or Fe-based ribbon cores. In addition, the local stress produced by the substrate causes pinning sites of the domain wall motion in the case of high magnetostrictive ribbons. This causes an increase in Barkhausen noise that affects the noise response of the sensor such as the zero drift effect. In our future work, it will be necessary to control magnetic domain structure of the amorphous core for reduction of maze domains, which can realize miniaturization of the fluxgate sensor.

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