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Orthogonal fluxgate mechanism operated with dc biased excitation

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A mode of operation is presented for an orthogonal fluxgate built with a thin magnetic wire. By adding a proper dc bias to the wire excitation, the new mode is easily established. In this case, the fundamental component of the induced voltage at the sensing coil (secondary voltage) is made sensitive to the axial magnetic field, compared to the second harmonic in a conventional orthogonal fluxgate. The operating principle is explained using a magnetization rotation model. A method is proposed to cancel the offset that is inevitable when the magnetic anisotropy is present in a magnetic wire at an angle to its circumference. Experimental results are shown for a sensor head consisting of a 2-cm-long Co-based amorphous wire 120 μm in diameter with a 220-turn sensing coil. The sensitivity obtained is higher than that obtained using a conventional type of the orthogonal fluxgate built with the same sensor head. It is also demonstrated that the proposed method for canceling the offset works well. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1451899]

I. INTRODUCTION

A magnetometer is a key building block for industrial or automotive sensing systems. Hence, a method for providing a magnetometer in a miniature size at low cost is important. The magnetoimpedance effect, which was first discovered in a thin Mumetal wire by Harrison *et al.* in 1935,[1] has been shown to provide a high sensitivity magnetometer in a miniature size when a thin Co-based amorphous wire is used as a wire core.[2] The output response of this magnetometer, however, is an even function of the axially applied magnetic field in its basic form. Therefore, one has to give magnetic bias to the wire core to translate the response curve so that a linear portion can be used to discriminate the polarity of the applied magnetic field. The orthogonal fluxgate mechanism[3] facilitates a high sensitivity magnetometer in a very simple structure, since a thin magnetic wire of high permeability and a sense coil are essential parts of the magnetometer (sensor head afterward). In this case, the output response is an odd function of the axially applied magnetic field, and hence, its polarity is discriminated naturally.

In this article, a mode of operation for the orthogonal fluxgate mechanism is presented. A dc biased excitation is applied to the wire core and the fundamental component of the secondary voltage is rectified instead of the second harmonic as is the case in a conventional fluxgate. A prototype magnetometer was fabricated with an as-cast Co-based amorphous wire. It was found that the linearity is much improved with this new mode and that the sensitivity is increased compared to a conventional type of orthogonal fluxgate built with the same sensor head. Offset was found when using as-cast amorphous wires, however, its level was reduced to a practically negligible level with increasing dc bias current. Furthermore, a method for canceling the offset is proposed.

II. STRUCTURE AND OPERATING PRINCIPLE

Figure 1 shows a structure for the new mode of operation for the orthogonal fluxgate. The ac excitation is dc biased to give a unipolar excitation to the wire core and a phase-sensitive-detector (PSD) is tuned to the fundamental component of the ac excitation. The excitation current flowing in the magnetic wire generates the circular magnetic field. With the sensing coil wound on the wire as shown in Fig. 1, only the axial component of the magnetic flux is detected in principle. We assume that the external magnetic field is static or of very low frequency compared to the ac component of the excitation. A tuning capacitor placed in parallel to the sensing coil is optional. Figure 2(a) shows a magnetization rotation model for the magnetizing process with the positive dc bias. The vertical axis represents the axial direction of the wire and the horizontal axis is for the circumferential direction. The model is extended for the case using negative dc bias in (b) and for the case of an offset under the negative dc bias in (c). In all cases, we assume $|H_{dc}|>H_{ac}$ for simplicity. Since the excitation field takes its absolute maximum and minimum once a period due to dc

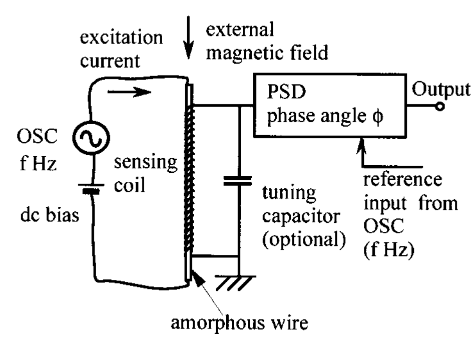

FIG. 1. Structure of an orthogonal fluxgate with dc biased excitation. Note that the phase-sensitive-detector is tuned to the fundamental frequency of the excitation.

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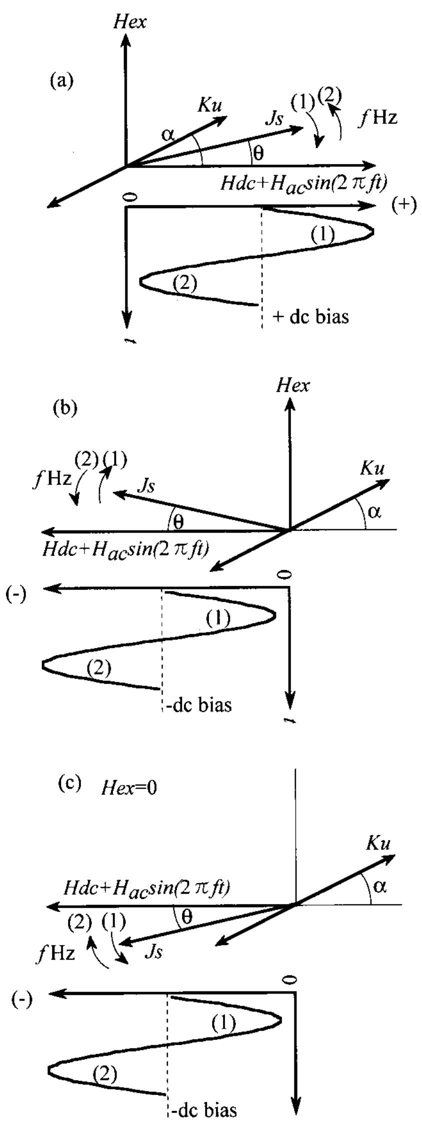

FIG. 2. Models for magnetization process: (a) for the positive bias, (b) for the negative bias, and (c) offset with negative bias.

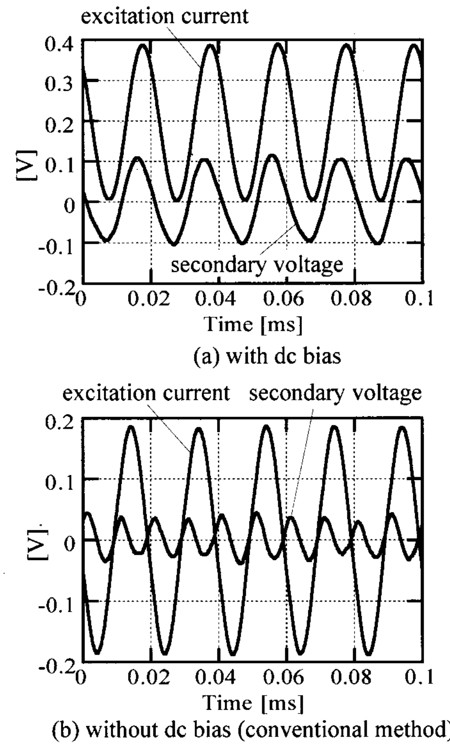

FIG. 3. Wave forms of the secondary voltages. Excitation currents were observed through a resistor of 10 Ω. It is clearly found that the mode is completely changed by adding dc bias to the excitation.

bias, the magnetization J_s vibrates back and forth once a period around its equilibrium position, as shown in Fig. 2. Arrows (1) and (2) indicate parts of motion corresponding to a maximum and a minimum of excitation. It is then understood that the fundamental component is most predominant in the secondary voltage induced at the sensing coil. In this case, the height of the excursion of the axial component of J_s, hence, the amplitude of the secondary voltage, depends on the strength of the axial magnetic field H_{ex}, through the torque balance with relevant magnetic fields and the magnetic anisotropy. For magnetic fields as large as the earth's magnetic field, the amplitude of the secondary voltage increases with the axial magnetic field because the angle theta in Fig. 2 increases with the axial magnetic field. Figure 3 shows wave forms that were taken for the same axial magnetic field using the sensor head described later, to show the effect of dc bias on the secondary voltage at the sensing coil. The output voltage is obtained through a phase-sensitive-detector tuned to the fundamental frequency. It is clearly found that the amplitude of the secondary voltage is larger in Fig. 3(a), the case with dc bias, than in (b) despite the lower frequency. This indicates that the inherent sensitivity is higher in the new mode of operation than for the conventional one. It should also be noted that the fundamental component is discarded in a conventional type of orthogonal fluxgate,[3] in which the second-harmonic component is detected. When the polarity of the applied magnetic field is inverted, the mode of vibration of the magnetization becomes a mirror image with respect to the horizontal axis of the model shown in Fig. 2(a). Hence, the polarity of the secondary voltage is inverted, and, in turn, the PSD yields an output with the polarity inverted. The effect of the magnetic anisotropy, K_u, has been so far neglected. However, roles of the magnetic anisotropy are important. When the angle alpha in Fig. 2 is not zero, the angle theta of J_s even for $H_{\mathrm{ex}}=0$ may deviate from zero. Hence, the excursion of the axial flux rises, resulting in the offset. On the other hand, the magnetic anisotropy serves to widen the dynamic range, although it does reduce the sensitivity. Another important effect of the dc bias is to reduce the offset, because, by increasing H_{dc}, the effect of K_u on J_s is reduced. An interesting thing to note is that the polarity of the output voltage is inverted by changing the polarity of the dc bias, yet the offset remains unchanged. This property is very important because it may lead to an offset free fluxgate mechanism. From Fig. 2(b), it can be seen that the phase of vibration of the magnetization J_s is 180° shifted from that in Fig. 2(a). Hence, in phase-sensitive-detection the polarity of the output voltage is inverted. Offsets that arise are considered using the model shown in Fig. 2(c) for the negative dc bias and its counterpart in (a) with

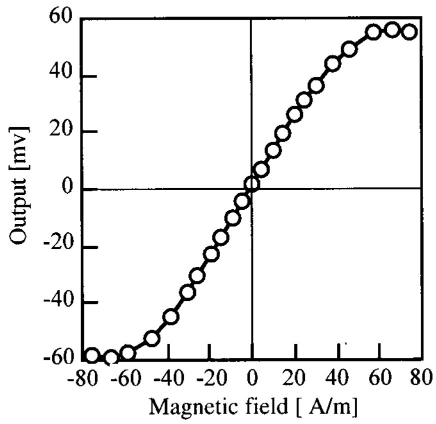

FIG. 4. Input–output characteristic under an ac excitation of 50 kHz at 22 mA and with dc bias of 63.6 mA.

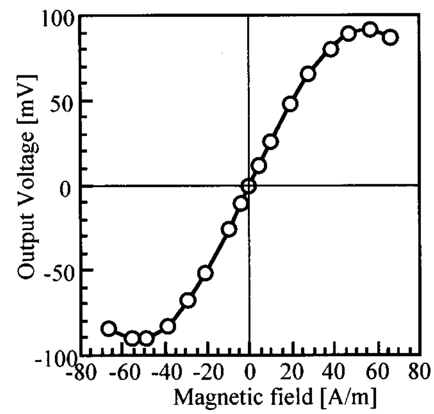

FIG. 6. Input–output characteristic obtained by subtracting vertically corresponding data points in Fig. 5. The offset is canceled.

$H_{ex}=0$ for the positive dc bias. The part of motion (1) in Fig. 2(a) is equivalent to (2) in Fig. 2(c) and vice versa. Furthermore, the directions of those corresponding motions are opposite each other. This means that secondary voltages yielding offsets are 180° shifted and inverted with respect to each other. Again with the phase-sensitive-detection, these secondary voltages yield the same offset.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A magnetometer was fabricated with a Co-based amorphous wire 120 μm in diameter (AC-20 made by Unitica) and 2 cm in length, with a 220-turn sensing coil wound on the wire. Figure 4 shows the input–output characteristic obtained with a 50 kHz excitation of 22 mA rms and 63.6 mA dc bias. A small offset can be seen in Fig. 4. The sensitivity is 1.28 mV/(A/m). A conventional type of orthogonal fluxgate was also examined with the same sensor head and the same excitation condition but with no dc bias. The input–output characteristic showed nonlinearity. In addition smaller sensitivity, 0.50 mV/(A/m), was observed over all. In order to evaluate a method for canceling the offset, output voltages were measured twice for each of the axially applied magnetic fields. In each case the polarity of the dc bias was switched between positive and negative. Figure 5 shows two input–output characteristics, where one is obtained with the positive dc bias and the other with the negative dc bias. It can be seen that offsets for the positive bias and for the negative bias are almost the same. By subtracting vertically corresponding data pairs at each applied magnetic field point and multiplying by 1/2, an offset free input–output characteristic is obtained (Fig. 6). This simple algorithm can be implemented using ordinal analog switches by which the dc bias is switched periodically along with the outputs from two PSDs, one of which is synchronized 180° shifted, which are switched and averaged with a low-pass filter. It is also important to control the magnetic anisotropy in the amorphous wire such that its easy axis is in the circumferential direction by applying a proper heat treatment.

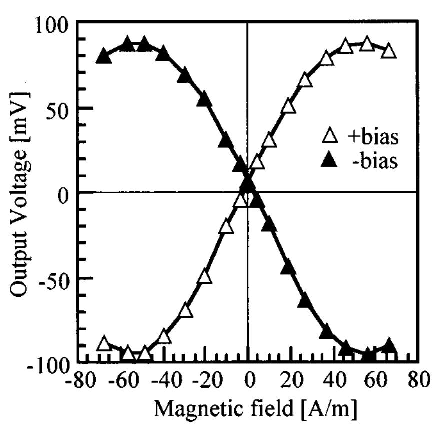

FIG. 5. Input–output characteristics for the positive dc bias of 31.6 mA and the negative dc bias of the same strength. The ac excitation is the same as in Fig. 4. Note that one is flipped horizontally with respect to the offset point.

IV. SUMMARY

By adding dc bias to the excitation current to the magnetic wire, a new mode of operation is established for the orthogonal fluxgate, where the fundamental component in the induced voltage at the sense coil is a measure of the axially applied magnetic field. The orthogonal fluxgate based on this mode of operation has been shown to exhibit higher sensitivity compared to the conventional orthogonal fluxgate. A method is proposed by which an offset free orthogonal fluxgate can be built.

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