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STATIC TORQUE MEASUREMENT USING GMI STRAIN GAUGE

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Torque detection characteristics using GMI strain gauge, which is based on CoFeSiB amorphous microwires, are investigated. The gauge factor of the negative magnetostrictive wire used in this paper is higher than 2000. The linear relation between the bridge sensor output and the applied static torque is obtained in the torque range of ± 5 Nm for a 13 mm in diameter brass shaft. The torque sensitivity is enhanced by the bias technique while the field sensitivity is reduced. Applying simultaneously dc bias current and dc bias field, the sensitivity reaches 14 mV/Nm. Both high sensitivity and small power consumption are advantages of GMI stain gauge. Based on the results obtained in this paper, GMI strain gauges would be useful for the power steering application in the automotive industry.

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Keywords: Torque detection, Strain gauge, GMI effect

1. Introduction

The stress sensitive magnetostrictive wires have been widely studied [1] and their application in sensors has been proposed [2]. Recently, a torsion measurement system using glass covered amorphous wires having a diameter less than 30 μm has been investigated [3]. These applications are mainly based on the Large Barkhausen Effect, the Matteucci Effect and the Inverse Wiedemann Effect. On the other hand, amorphous wire micro sensors, which are based on the Magneto-Impedance (MI) Effect, have been developed for the industrial applications [4,5]. Although original MI sensors are designed to detect the magnetic field, Co-based amorphous wire elements are also sensitive to applied stress. The inverse magnetostrictive effect leads to a change of permeability of wires so that applied stress can change the impedance of the amorphous wires due to the skin effect with high frequency current excitation. As a result of stress dependence impedance change (stress dependence of Giant Magneto-Impedance effect - GMI), a gauge factor, GF, of about 2000 has been obtained for $Co_{72.5}Si_{12.5}B_{15}$ and $Co_{68.15}Fe_{4.35}Si_{12.5}B_{15}$ amorphous wires [6,7]. GF is defined as $\Delta|Z|/|Z|/\varepsilon$, where ε is applied strain. In addition, both the thin form and good mechanical properties of amorphous wires are useful for the attachment of the wire gauge on the elastic element to produce a signal. A simple torque measuring system without torsion bar can be achieved using these high sensitive gauges. Hence, a static torque measurement system using GMI strain gauges is investigated.

2. Experimental and results

2.1 Stress dependence of GMI effect

When a strong skin effect is induced by a high frequency current, i_w, the wire impedance Z is expressed as

$$|Z| = (a/2\sqrt{\rho})\, R_{dc}\sqrt{\omega\mu_\theta(\sigma)} \quad \text{for } \delta << a \qquad (1)$$

where a is the radius of the wire, δ is the skin depth, ρ is the resistivity, R_{dc} is the dc resistance, ω is

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the angular frequency, μ_θ is the circumferential permeability, and σ is the applied stress to the wire. According to eq. (1), a change in μ_θ with σ due to the inverse-magnetostriction effect leads to an impedance change. It should be noted that eq, (1) applies for frequencies above 2 MHz for wires with a diameter of 21 μm.

Fig. 1 shows the impedance ratio $\Delta|Z|/|Z_0|$, versus strain, ε, characteristics of CoFeSiB amorphous wires prepared by the glass coated melt spinning method, after glass removal. The diameter, Φ, of the wire is 21 μm and the length, *l*, is 5 mm.

The peak to peak value of the applied current I_{p-p} is 5 mA and the frequency is 5vMHz. The voltage e_w, across the ends of the wire, was measured. The absolute value of the impedance was estimated using the relation $|Z| = V_m/I_m$, where V_m and I_m are the amplitude of voltage e_w and current i_w, respectively. $\Delta|Z|/|Z_0|$ is defined as $(|Z(\varepsilon)|-|Z(\varepsilon=0)|)/|Z(\varepsilon=0)|$. The large impedance change, which is due to the skin effect, was obtained by annealing with a dc current of 50 mA for 20 minutes flowing through the wires after glass removal. The linear increment in the impedance is observed between ε = - 0.01% and ε = 0.01%. The gauge factor S_e (= ΔZ/Z/ε) is estimated to be more than 2000 in this linear region. The value of S_e is more than double than that of CoSiB at 5 MHz [6].

The ac current i_w, changes the circumferential BH loops when a strain is experienced by the wire under test. Fig. 2 shows the bridge circuit used for $B_\theta H_\theta$ loops measurement. H_θ is the circumferential magnetic field of $i_w/2\pi a$. B_θ is obtained from the relation $e_L = d\phi_\theta/dt$, where ϕ_θ is the circumferential flux and e_L is the inductive component of e_w. Assuming a linear response in the voltage, the wire impedance is expressed as $Z_w = R_{dc} + j\omega L$. When $R >> \omega L$ and $r = R_{dc}$, V_{ab} is given by

$$V_{ab} = \{E/(R+R_{dc})\}j\omega L = j\omega L I_w \qquad (2)$$

That means that $v_{ab}(t)$ is equivalent to $e_L(t)$. Even if e_L contains nonlinear components, the linear ohmic component of e_w is subtracted by means of a resistance bridge.

Fig. 3 shows the $B_\theta H_\theta$ loops for CoFeSiB wires. The saturation magnetostriction of the as quenched wires is $\lambda_s = -1\times10^{-7}$. The coercivity H_c depends on the strain, which induces internal stresses in the wire. The coercivity decreases with applying positive strain, while it increases with applying negative strain. It is also noted that μ tends to increase with decreasing H_c (Fig. 3). The change in μ seems to be reflected on the change of the impedance of the wires due to the skin effect.

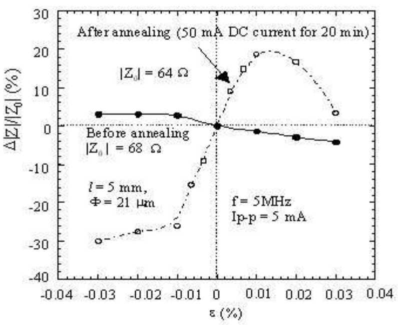

Fig. 1. Impedance Z versus ε characteristic for Co-based amorphous wires.

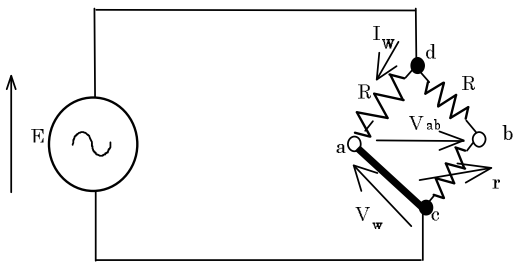

Fig. 2. Bridge circuit for $B_\theta H_\theta$ measurement (ac–amorphous wire).

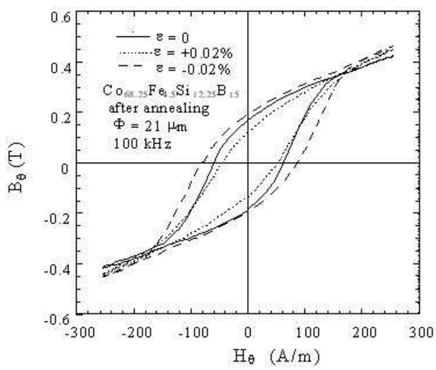

Fig. 3. Circumferential BH loops for CoFeSiB wires annealed by dc current.

2.2. Static torque measurements

Fig. 4 shows a torque measurement system employing the impedance strain gauge sensor, which is based on the 20 μm diameter wire prepared by the glass coated melt spinning method, after glass removal. A brass shaft, with the diameter of 13 mm was used in this experiment. When a torque T is applied to the metal shaft, the main direction of the stress makes an angle of ± 45 degrees with the shaft axis. Both ends of the amorphous wire are bonded on conductor pads, which are glued on the shaft, aligning the wire axis in the direction of 45 degree. The maximum strain in this direction is given by equation (3)

$$|\varepsilon| = 16T(1+\nu)/(\pi ED^3) \quad (3)$$

where ν is the Poisson's ratio, E is Young's Modulus and D is the diameter of the shaft. An ac voltage source was used to apply a high frequency current to the amorphous wires.

Fig. 5 shows the response of the gauge sensor for torque detection. A linear response was obtained in the range of ± 5 Nm, which corresponds to a strain range of ± 0.15% in the wire. In power steering applications in the automotive industry, a torque sensor having a full scale of ± 10 Nm is needed [8]. Assuming that a 13 mm diameter steel shaft is used, the corresponding strain range is ± 0.015% for full scale. Based on the experimental results presented here, impedance wire gauges have the sensitivity and an excellent linearity for detecting the steering torque in that range.

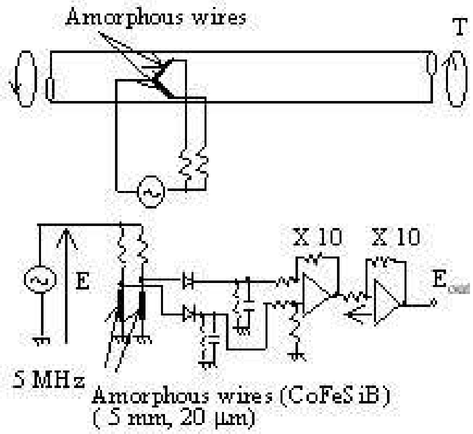

Fig. 4. Torque measurement system based on the amorphous wire impedance gauge.

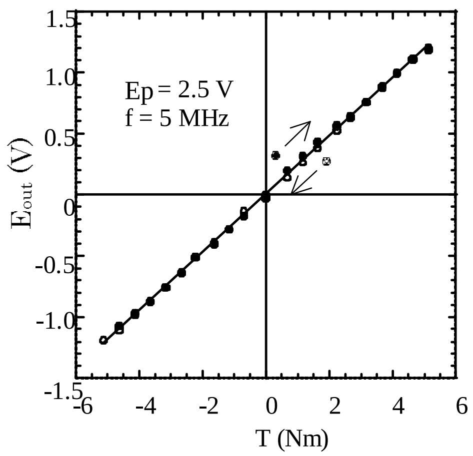

Fig. 5. Bridge sensor response for the torque detection.

2.3. Bias effect

The influence of magnetic field on e_w is investigated when no torque is applied. Fig. 6 shows e_m (amplitude of e_w) versus H_{ex} characteristics of a wire attached on the brass shaft. H_{ex} is applied parallel to the shaft axis so that the direction of H_{ex} makes an angle of 45 degree to the wire axis.

A symmetrical change in e_m is obtained for a sinusoidal wave excitation while an asymmetrical change is observed in the case of a dc current biased sinusoidal excitation.

A symmetrical MI characteristics have been reported in amorphous wires having helical anisotropy [9,10]. The change in e_m is significantly reduced by applying a dc current in the range of magnetic fields from -100 A/m to 400 A/m.

Fig. 7 shows the sensor output voltage as a function of the applied torque in the case of a dc current biased square wave excitation. The square wave excitation is investigated with practical applications in mind because a square wave voltage can be generated by a simple switching technique using semiconductor devices. The dc current bias technique leads to a high sensitivity although at the same time leads to a slight nonlinear response. Applying both dc current and dc field to the wire, the sensitivity is enhanced, being 5 times larger than the original sensitivity shown in Fig. 5.

Fig. 8 illustrates the torque sensitivity dependence on the bias magnetic field in the case of a dc biased square wave excitation. The maximum sensitivity before amplification reaches 14 mV/Nm. The sensitivity is almost constant in the range of H_b from 200 A/m to 400 A/m.

Fig. 9 shows the influence of the magnetic field on torque detection characteristics. Assuming a bias field H_{ex} of 250 A/m, the change in sensor output is less than ± 2% full scale for the disturbance field ΔH_{ex} of ± 50 A/m. The bias technique improves the torque sensitivity at the expenses of the field sensitivity.

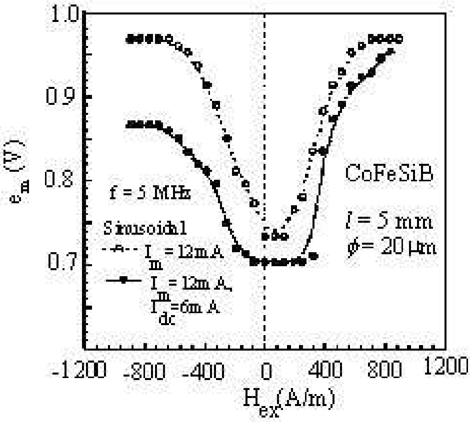

Fig. 6. e_m versus H_{ex} characteristics for the wire attached on the brass shaft.

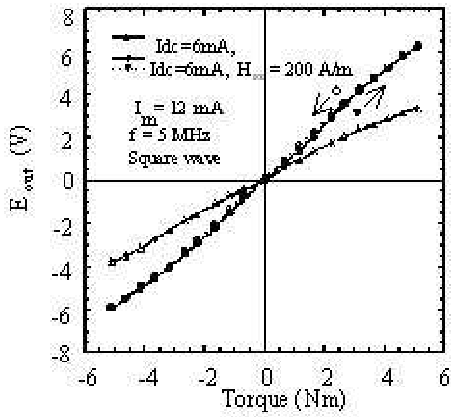

Fig. 7. Sensor output voltages as a function of the applied torque for the case of dc biased square wave excitation.

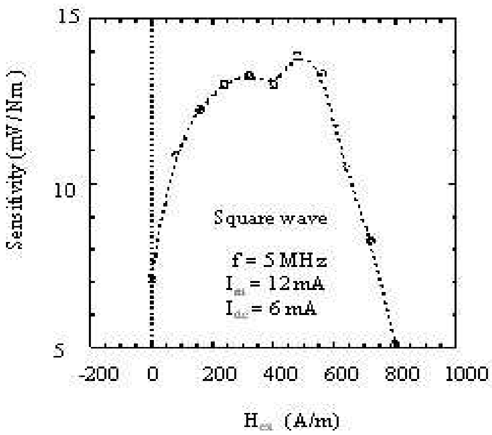

Fig. 8. Sensitivity dependence on the bias dc magnetic field.

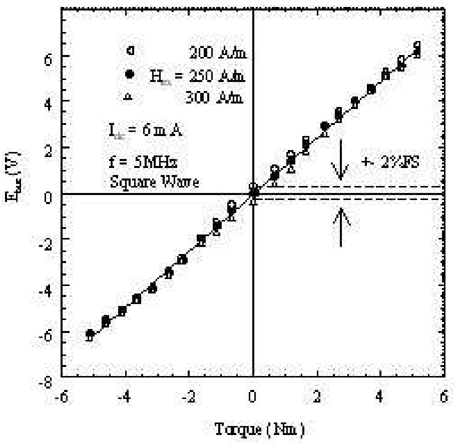

Fig. 9. Influence of magnetic field on torque detection characteristics.

Table 1 shows the basic features of some GMI gauge type torque transducers as compared to a metallic gauge [11]. Both high sensitivity and low power consumption are advantages of the GMI strain gauge type torque transducer. The dynamic range in ε is narrower for the case of GMI gauge but it is not a disadvantage. Increasing the diameter of the sensing segment allows the GMI torque sensor to have a wide dynamic range in torque detection.

Table 1. Torque detecting characteristics for GMI strain gauge in comparison with that for metallic gauge.

	Dynamic range, ε	Sensitivity	Power
GMI gauge	± 0.015	400 V/ε	V_m = 2.5 V (f = 5 MHz)
Metallic gauge	± 0.3%	4 V/ε	V_{dc} = 8 V

3. Conclusions

The static torque measurements were carried out using the GMI strain gauge based on amorphous microwires. The half bridge type torque transducer shows both high sensitivity and good linearity with small mechanical hysteresis. The GMI torque transducer may be employed for power steering applications in the automotive industry. The novel bias techniques are responsible for the high accuracy of torque detection.

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