Magneto-Inductive Effect in Amorphous Wires and MI Elements

K. Kawashima, T. Kohsawa, H. Yoshida, K. Mohri and L.V. Panina

Abstract—In the magneto-inductive effect (MI effect), the inductance L of a ferromagnetic wire element magnetized by an ac current Iac in the wire is changed by an external magnetic field Hex. When the current Iac is passed through the wire, a voltage etot is induced across the wire ends. The voltage has two components: a voltage e_r due to R_w I_ac (where R_w is the electrical resistance of the wire), and a voltage e_L equal to dφ/dt (where φ is the circumferential flux in the wire cross-section). e_L is detected by subtracting e_r from e_tot using a simple resistor circuit. The amplitude |e_L| of e_L decreases with decreases in L caused by increases in |H_hex|. That is, e_L is amplitude-modulated by |H_hex|. The waveform of |H_hex| is detected using a simple demodulator based on a diode and capacitor. A sensitive MI element is created by using a slightly negative magnetostrictive amorphous wire of length 2 mm and diameter 50 μm, without a coil. This MI element is expected to find applications in sensitive magnetic heads for accurate rotary encoders, in rigid disk drives, and in various magnetic cards.

I. Introduction

Highly sensitive magnetic field sensors with an ordinary coil-based core-excitation design have suffered from a number of problems: (1) because of the open-circuit excitation used, a demagnetizing field appears, so that the length of the magnetic core used in a high-sensitivity sensor cannot be made very short (in general it must be at least 20 mm in length); (2) because of the open-circuit excitation, magnetic flux appears in air, and becomes a source of magnetic field noise; (3) the stray capacitance of the coil tends to cause instability when the sensor response time is reduced under high-frequency excitation; and (4) the resistivity of the coil wire is susceptible to the influence of thermal fluctuations. Hence in order to construct a small, fast-response field sensor with high sensitivity, a coilless core excitation method is needed. We have found a "magneto-inductive (MI) effect" in which the amplitude of the voltage induced at the ends of
II. The Circumferential-Magnetization Electromotive Force Effect

When an ac current $I_{ac}$ is passed through a magnetic wire (radius $a$, length $l$), the circumferential ac field $H_\theta$ within the wire gives rise to a changing circumferential flux $\phi_\theta$. Hence from $\nabla \mathbf{E} = -\partial \mathbf{B} / \partial t$, an induced voltage $e_\perp = \partial \phi_\theta / \partial t$ appears across the wire. An Ohmic voltage $e_R = R_w I_{ac}$ (where $R_w$ is the wire resistance) also appears across the wire, and so the total voltage $e_{tot}$ is then

$$e_{tot} = R_w I_{ac} + \frac{\partial \phi_\theta}{\partial t}$$ (1)

In an MI device, a bridge circuit is used to cancel $e_R$, so that only $e_\perp$ is detected. Below we derive $e_\perp$ in terms of $I_{ac}$.

First, the circumferential field $H_\theta$ is, in terms of the distance $r$ in the radial direction,

$$H_\theta = \frac{r}{2\pi a^2} I_{ac} \quad (0 < r < a)$$ (2)

If we set $I_{ac} = I_m \sin \omega t$, then we have

$$H_\theta = H_m \sin \omega t$$
$$H_m = \frac{rI_m}{2\pi a^2}$$ (3)

The relation of the flux density in the circumferential direction $B_\theta$ to $H_\theta$ may be expressed as follows, taking nonlinearity and losses into account:

$$\beta \frac{dB_\theta}{dt} + \alpha B_\theta + rB_\parallel = (H_m - H_c) \sin \omega t$$

$$H_m > H_c$$ (4)

Here $\beta$ is a damping factor reflecting the effect of eddy current damping and spin relaxation in damping domain wall motion in the circumferential direction, and $H_c$ is the coercivity in the same direction. In order to solve eq. (4) analytically, we set $B = B_m \sin(\omega t - \varphi)$, and use the describing function method to obtain:

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**Fig. 1.** Circumferential magnetic field $H_\theta$ induced by an ac current in a wire.

an amorphous magnetic wire (hereafter an a-wire) when a high-frequency current is passed through the wire decreases in a sensitive manner in response to an external magnetic field [1,2].

This MI effect element has a number of features: (i) because flux changes in the circumferential direction (i.e. a closed flux path) due to the wire current are used, there is no demagnetizing field due to excitation, nor does excitation generate flux elsewhere; (ii) no coils are needed for either excitation or detection, obviating the problem of stray capacitances in high-frequency excitation; and (iii) the changes in characteristics due to thermal fluctuations of the magnetic wire can be suppressed. Thus it may be possible to eliminate many of the problems associated with coil-based sensors described above. That is, a cold-drawn and tension-annealed zero magnetostrictive a-wire only 1 to 2 mm in length may be used to construct a high-sensitivity field sensor comparable to sensors based on wire 30 mm in length or longer. In addition, excitation frequencies of up to several MHz can be used.

Further, MI elements are, like magnetostrictive (MR) elements, sensitive to magnetic flux itself rather than changes in flux, and so the detection sensitivity is, like that of MR elements, quite high. Hence applications in flux-detecting magnetic heads for microminiature rigid disk drives and in rotary encoders of spindle motors, are anticipated.

In this paper we report on the basic principle of operation of MI elements, give an analysis of their operation, and describe their basic characteristics.
From eq. (5) we obtain the following expression for the differential permeability in the circumferential direction $\mu_\varphi$:

$$\mu_\varphi = \frac{1}{\sqrt{(a + \frac{3}{4} r B_n^2)^2 + \omega^2 B^2}}$$

(6)

Hence the flux in the circumferential direction $\phi_\varphi$ is

$$\phi_\varphi = \int_0^a B_0(r) \, dr$$

$$= \int \mu_\varphi \omega B_n (H_m(r) - H_c) \sin(\omega t - \phi) \, dr$$

(7)

If we assume that $\mu_\varphi$ does not depend on $r$, then from eq. (2) we have

$$\phi_\varphi = \left(\frac{1}{4\pi}\right) \mu_\varphi \omega B_n l (I_m - I_c) \sin(\omega t - \phi)$$

(8)

Here $I_c = 4\pi a H_c$. Hence $e_L$ becomes

$$e_L = \frac{\omega}{4\pi} \mu_\varphi \omega B_n l (I_m - I_c) \cos(\omega t - \phi)$$

(9)

and the amplitude $|e_L|$ of $e_L$ is

$$|e_L| = \frac{\omega}{4\pi} \mu_\varphi \omega B_n l (I_m - I_c)$$

(10)

Hence the linearized inductance $L$ of the wire is given by

$$L = \frac{1}{4\pi} \mu_\varphi \omega B_n l$$

(11)

In eqs. (10) and (11), the wire radius $a$ does not appear explicitly as a factor in $|e_L|$. But since $I_c = 4\pi a H_c$, if $H_c$ is constant $I_c$ will grow in proportion to $a$, and $|e_L|$ will decrease.

Fig. 2 is a resistance circuit for detecting $e_L$ only, using a bridge circuit to cancel $e_R$. If the linearized inductance $L$ is used to represent the impedance of the a-wire as $R_w + j\omega L$, then in the bridge circuits (a) and (b) of Fig. 3, $e_L$ is as follows.

(a) $e_L = \frac{R_w - R'_w + j\omega L}{R_w + R'_w + j\omega L} E$

(12)

(b) $e_L = \frac{R(R_w - R'_w) + j\omega LR}{(R + R'_w)(R_w + R + j\omega L)} E$

(13)

If the variable resistance $VR$ is adjusted such that $R_w = R'_w$, then when $R_w >> \omega L$, eq. (12) becomes

$$e_L = \frac{j\omega L}{2R_w} E$$

(14)

And if we set $R_w = R'_w$, $R >> R_w$, $R >> \omega L$, then eq. (13) becomes

$$e_L = \frac{j\omega L}{R} E$$

(15)

so that $e_L$ becomes purely inductive. Fig. 2 is the circuit represented by Fig. 3(a).

The circuit of Fig. 2 was used to measure $|e_L|$ in a zero magnetostrictive wire (saturation magnetostriction constant $\lambda_s = -10^{-7}$) of composition $(\text{Fe}_{0.06}\text{Co}_{0.94})_{72.5}\text{Si}_{12.5}\text{B}_{15}$ at%. $|e_L|$ was measured for a negative magnetostrictive and a highly positive magnetostrictive wire in addition to the zero magnetostrictive wire. The $|e_L|$ for the highly positive magnetostrictive wire was nearly zero, and that of the negative magnetostrictive wire was about 1/5 that of the zero
magnetostrictive wire. These results can be explained in terms of the a-wire domain model [3] of Fig. 4. Here (a) is a positive magnetostrictive wire, (b) a negative magnetostrictive wire, and (c) a zero magnetostrictive wire after annealing under tension. In (a) the outer shell is a perpendicular magnetization layer, and \( \mu_b \) is expected to be extremely low. In (b) and (c) the outer shell has its easy axis in the circumferential direction, and when \( \lambda \) is less than or about equal to zero, \( \mu_b \) is quite high. Since \( |e_{\text{el}}| \approx \mu_b \) the value of \( |e_{\text{el}}| \) is maximum.

Fig. 5 shows the measured results for \( |e_{\text{el}}| \) as a function of the frequency \( f \) of the sinusoidal current in the zero magnetostrictive wire. The wire length was 5 mm, and the circumferential field \( H_{\text{bmax}} = (I_m/2\pi a) \) was 320 A/m. Wires with four different diameters were used. The 135 \( \mu \)m dia. wire was as-cast, and the wire with diameters of 100 \( \mu \)m, 50 \( \mu \)m and 30 \( \mu \)m were first cold-drawn and then subjected to annealing at 520°C for 1.8 s under a tension of 3 kg/mm^2 (tension annealing). At frequencies 700 kHz<\( f \)<5 MHz, \( |e_{\text{el}}| \) was nearly constant, and even when using 30 \( \mu \)m wire (with a current of 30 mA) the value of \( |e_{\text{el}}| \) was a high 60 mV. This is thought to be because \( H_{\text{bmax}} \) in eq. (3) is maximum, as is \( \mu_b(\omega B_m) \). For 30 \( \mu \)m wire, when \( I_m > 30 \) mA, \( |e_{\text{el}}| \) declines. It may be that on increasing \( I_m \) the value of \( B_m \) in eq. (6) rises, and that the rate of decrease in \( \mu_b \) caused by \( \gamma B_m^2 \) is greater than the rate of increase of \( I_m \). When \( I_m > 30 \) mA, it is expected that the heat dissipation due to \( R_w I_m^2 \) also acts to decrease \( \mu_b \).

### III. The MI Effect

According to the domain model of Fig. 4(b), when an external field \( H_{\text{ex}} \) is applied in the length direction of the a-wire, the magnetization vector in the circumferential direction (the easy axis direction) rotates in the wire length direction (with rotation angle \( \varphi \)), so that the flux in the circumferential direction decreases by a factor \( \cos \varphi \). It is expected that this magnetization rotation causes \( \mu_b \) to decrease, so that \( |e_{\text{el}}| \) declines.

Fig. 7 shows the theoretical curves (b) [4] and measured results (c) for the circumferential direction B-H curves of an FeCoSiB zero magnetostrictive a-wire. The curves in (b) were computed taking the distribution of the uniaxial
Fig. 7. $B_\phi$-$H_\phi$ hysteresis loops of FeCoSiB wire in the presence of an external magnetic field in the wire length direction: (a) domain structure, (b) calculated loops, and (c) measured loops.

The anisotropy constant $K_u$ into account, and assuming a rotational magnetization hysteresis curve. Here $h_\theta$ represents the field $H_\theta$ normalized by the anisotropy field, $h_\theta = H_\theta M_s/2K_u$. In (c), $B_\theta$ is the voltage output by an integrator which takes $e_L(t)$ as input, using the relation $B_\theta = (1/a)\int e_L dt$, and $H_\theta$ was taken to be equal to $L_{\mu}/2\pi a$. The external field $H_{ex}$ was assumed to be a uniform dc magnetic field. We see that while $H_{ex}$ causes a decline in the coercivity, the differential permeability of the B-H loop drops dramatically, so that $|e_L|/|H_{ex}|$ decreases in a sensitive manner in response to the external field.

Fig. 8 shows the measurement results for the $|e_L|/|H_{ex}|$ characteristics (hereafter the "MI characteristics") for zero magnetostrictive a-wire. (a) shows the results for as-cast wire 135 µm in diameter; at wire lengths of under 10 mm, a region of insensitivity appears in which $|e_L|$ fails to respond to $H_{ex}$, and as the length l is reduced the extent of this region increases. In (b), the results for tension-annealed wire 50 µm in diameter, the MI characteristics are nearly the same and independent of the wire length l; even very short wire with l=2 mm yields an MI characteristic with high sensitivity. The differences in the characteristics in Figs. 8(a) and (b) are attributed to the different domain models in Figs. 4(b) and (c). That is, the inner core of as-cast wire is thought to have a strong anisotropy with easy axis of magnetization in the wire length direction, so that the core easy reaches saturation under the action of $H_{ex}$, giving rise to a demagnetizing field $H_{dem}$ (with maximum value $N_{dem}M_s/H_\theta$, where $N_{dem}$ is the demagnetizing factor). This $H_{dem}$ is thought to be caused by the magnetic poles appearing at the ends of the inner core, and a magnetic field weaker than $H_{dem}$ appears in the external shell, with direction opposite that of $H_{ex}$. These relations are indicated in Fig. 9.

Fig. 9 shows the calculated maximum values of the demagnetizing field ($H_{dem}$) (the solid line), the demagnetizing field as determined from the B-H loop in the wire length direction (empty
circles), and the maximum field $H^*$ in the insensitive region of Fig. 8(a) (filled circles), all as functions of the wire aspect ratio $l/D_0$. $H^*$ is smaller than the maximum value of $H_{\text{dem}}$, and may possibly be the magnetic field due to the magnetic poles at the ends of the inner core. That is, in the case of a tension-annealed negative magnetostrictive wire like that of Fig. 4(c), it is conceivable that the reverse magnetostrictive effect may cause cancellation in the wire core, so that the wire overall has its easy axis in the circumferential direction. If we suppose that the insensitive region in the MI characteristic is due to the magnetic poles in the wire core, then no insensitive region should appear in Fig. 8(b).

And, wire for which $\lambda$ is near zero will have a low anisotropy energy, so that a demagnetizing field should not readily appear as a result of the $\mu^*$ effect [5].

IV. Temperature Stability of the MI Characteristic

Fig. 10 shows the change with temperature in the MI characteristic of tension-annealed zero magnetostrictive wire 50 $\mu$m in diameter, with a core length of 5 mm. When the wire alone was placed in an electric furnace and the ambient temperature was raised to 180$^\circ$C, the amount of change (decrease) in $|e_L|$ for $H_{\text{ex}}$ varied between 0 and 10 Oe was, at room temperature (RT) (20$^\circ$C), about 20% (0.125%/°C). This relatively good thermal stability is attributed to the stabilization of individual atoms at low energy states through tension annealing. The temperature characteristic of Fig. 10 shows the temperature dependence of the output voltage from a bridge circuit. Using the equation of operation of the bridge circuit of Fig. 3(a) (eq. (12)), this is as follows.

$$|e_L| = \frac{(R_w(T) - R'_w) + (\omega L(d_{\text{mm}}T))^2}{(R_w(T) + R'_w) + (\omega L(d_{\text{mm}}T))^2} \cdot \frac{E}{\sqrt{2}}$$

At room temperature, the variable resistance is adjusted such that $R_w(T)$=R$'_w$, but at temperature $T$ we have $R_w$=R$(T)$(1+$\alpha(T-T_R))$, so that $R_w$>$R'_w$. If we set $R_w$-$R'_w$=$\Delta R_w(T)$, then the effect of $\Delta R_w$ on the denominator in eq. (16) is nearly the same, and the change in $|e_L|$ is small. It is therefore thought that the decline in $|e_L|$ with $T$ is due to the decrease in $L$ due to the lower $\mu_0$, caused by the reduction in $M_s$ resulting from the rise in temperature.

V. Application of MI Elements to Rotary Encoder Heads

Fig. 11 shows an example of detection of the surface flux of a multipole ring magnet, employing an element for detection of $H_{\text{ex}}$ waveforms
Fig. 11. (a) Construction of a non-contact accurate rotary encoder; (b) output waveform for a 64 mm 100-pole ring magnet; (c) output waveform for a 30 mm 120-pole ring magnet.

Fig. 12. Magnetic field sensor circuit.

based on a 5 mm long, 50 μm dia. zero magnetostrictive a-wire (tension-annealed) with electrodes at both wire ends, and with a circuit for detection of eL (an AM waveform) based on a diode and capacitor (demodulation circuit). (a) shows the construction of a contact-free rotary encoder, (b) presents the output waveform for a 64 mm dia. 100-pole ring magnet (Iac at 100 kHz, Im = 30 mA), and (c) is the waveform for a 30 mm dia. 120-pole ring magnet (Iac at 100 kHz, Im = 1 mA). In both cases a distinct |Hex| waveform was obtained even when the wire ends were removed about 1.5 mm from the magnet surface.

Using a-wire, a remarkable directionality was observed, with |eL| declining in a sensitive manner in response to fields in the wire length direction. It may therefore be that by etching the wire ends to form sharpened tips, the wire may be better suited to detection of local magnetic fields. It is also possible that by using an existing magnetic head as a flux-concentrating yoke and positioning an MI element within the head, a flux-detecting head may be constructed for reading magnetic media.

VI. Magnetic Field Sensors

Fig. 12 shows the circuit diagram of a magnetic field sensor which utilizes the MI effect. When an ac current is passed through the a-wires, the resistance Rw of the wire itself gives rise to a voltage eR which is superimposed on eL; the circuitry eliminates this voltage RWIw so that only eL is detected [3]. In addition, a dc bias field Hb is applied to both the a-wires, in opposite directions. The field Hb is applied by passing a direct current through a coil. Because of this bias field, the MI characteristics of the a-wires are shifted in the negative direction for a total Hex+Hb field, and in the positive direction for an Hex-Hb field, as shown in Fig. 13.

\[ |e_{L1}| = \sum_{k=0}^{n} a_k (H_{ex} - H_0)^k \]  
\[ |e_{L2}| = \sum_{k=0}^{n} (-1)^k a_k (H_{ex} + H_b)^k \]  
\[ E_0 = |e_{L1}| + |e_{L2}| = 2[(a_1 - a_2 H_b)H_{ex} + a_3 H_{ex}^2 + \cdots] \]
\[ \approx 2(a_1 - a_2 H_b)H_{ex} \]

By taking the difference in the |eL| values of the two a-wires, an output E0 proportional to the external magnetic field is obtained.
FeCoSiB tension-annealed 50 \( \mu \)m
Iac = 30 mA  \( f = 100 \) kHz

\[
\begin{array}{c|c}
H_b &= 150 \text{ A/m} \\
I &= 2 \text{ mm} \\
\end{array}
\]

\[
E = \frac{a_2}{H_b} > 0.1
\]

\[
-200 \quad -100 \quad 0 \quad 100 \quad 200
\]

\[
H_{Ex} (\text{A/m})
\]

Fig. 14. Measured \( E \) vs. \( H_b \) sensor characteristic.

Fig. 14 shows the sensor detection characteristic. The wires are 50 \( \mu \)m in diameter and 2 mm long; a bias field \( H_b \) of 300 A/m was applied. Between \(-200 \text{ A/m} \) and \( 200 \text{ A/m} \), a hysteresis-free, high-sensitivity detection characteristic was obtained with a nonlinearity of under 4%. The maximum value of \( E \) varies depending on \( H_b \), but the value of \( a_2 \) in eq. (19) is sufficiently small that \( a_2 \gg a_2 H_b \), so that there is little change in the detection sensitivity. This sensor can be regarded as a magnetic field sensor with about the same physical dimensions as a Hall element, but with sensitivity several tens of times greater. It is believed to be suited to use in measurement of local magnetic field distributions and other applications.

**VII. Conclusion**

By focusing on the fact that certain zero magnetostrictive and negative magnetostrictive amorphous wires have their easy axis of magnetization in the circumferential direction, we found that the voltage induced across the wire ends due to a "circumferential magnetization emf effect" arising when an alternating current is passed through the wire can be detected using a bridge circuit. Moreover, the amplitude of the induced voltage decreases in a sensitive manner in response to external magnetic fields in the wire length direction (the "magneto-inductive effect"). This effect appears in tension-annealed zero magnetostrictive wire as short as 1 to 2 mm with sensitivity comparable to that of ordinary wire 30 mm in length, making possible the construction of miniature flux-detecting elements. Such elements do not require that a coil be wound around the wire, so that an element construction similar to that of MR elements is possible. It is expected that such devices will find applications in the areas in which MR elements are currently used, as flux-detection devices offering greatly improved sensitivity. Further, two MI elements can be used to construct a magnetic field sensor with physical dimensions comparable to those of a Hall element sensor head, but with sensitivity several tens of times higher. Such a device can be used for the measurement of local magnetic field distributions. Hereafter we intend to design sensor heads which are even smaller in size.

**References**
