High Sensitivity Magnetic Sensors Based on Off-diagonal Magnetoimpedance in Amorphous FeCoSiB Wires

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The magnetoimpedance (MI) effect has a potential for the development of high performance magnetic sensors. For sensor applications, off-diagonal configuration is preferable when the MI element is excited by ac current and the output is detected from the coil. In the present work, the off-diagonal sensor design was advanced by utilising a complex waveform excitation produced by a microcontroller and applied to a multiple wire MI element. For optimised excitation with a waveform close to a positive half sine form and characteristic frequency of 8 MHz the field resolution of about 60 mV/Oe was achieved. The pulse excitation does not require an additional bias since it includes controllable low frequency components. The concept of microcontroller driven sensor element could be attractive for the development of intellectual sensors.

Keywords: Magnetoimpedance, Off-diagonal impedance, MI sensor, Pulse excitation.

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1. INTRODUCTION

Magnetic field miniature sensors find a wide range of applications in areas such as security electronics, recording heads, and recently life science. All these applications require improved sensitivity, smaller size, faster response and compatibility with electronic systems [1, 2]. Recently, magnetoimpedance (MI) sensors have generated a considerable interest because of their potential to satisfy many of these requirements [3, 4]. These sensors utilise a very large change in ac impedance, which can reach up to 600 %/Oe in Co-based amorphous wires for a driving current frequency of a few tens of MHz [5]. The sensing element can be as small as 10-30 µm in diameter and a few mm in length without compromising on sensitivity which is in the range of 10-20 µOe for detecting an ac magnetic field.

In general, when an ac current is passing through a magnetic wire, the voltage signal is generated across the wire terminals and also in a pickup coil wound on it. These voltages are related to the diagonal and off-diagonal impedances, respectively [6, 7]. The off-diagonal impedance is determined by the tensor form of the permeability. These impedances have a different behaviour as functions of axial magnetic field: the former is symmetrical whereas the latter is antisymmetrical with a near-linear portion within a certain field interval. A linear response is preferable for sensor operation but to realise the off-diagonal configuration, the wire should be magnetised in a circular direction which is typically done by applying a dc bias current.

To a certain extent, the off-diagonal MI sensor configuration is similar to that for perpendicular fluxgate [8-10]. However, the excitation and detection principles of fluxgates are different and are based on non-linear magnetisation and generation of higher harmonics (typically a deep saturation into both polarities and the second harmonic mode are utilised). In the case of MI sensors, the response signal is generated by linear magnetisation dynamics, preferably, in a saturated state. Offset signal which influences the second harmonic mode is not a problem in this case.

The MI sensor element is excited by an alternating current which may have a complex waveform, but characteristic frequencies should be in the range of tens MHz. Employing a highly-stable sine excitation circuit such as that based on a crystal oscillator has the potential to improve the field resolution of the MI sensor [11, 12]. With optimised carrier suppressing circuit, a field resolution down to 10 nOe for ac external fields with a frequency higher than 100 kHz was achieved [11]. However, the resolution for low frequency signals is limited by the phase noise. The pulse excitation [13-15] has a number of advantages: relatively simple sensor circuitry, combination of high frequency and low frequency harmonics, possibility of using pulse width modulation options of microcontrollers. In the case of off-diagonal configuration, low frequency components of pulse excitation play a role of self bias which eliminates the magnetic domain structure, so increasing the coil response and reducing the magnetic noise related with domain wall displacements. In this configuration with differential detection scheme the root mean square noise of an amorphous wire pulse-MI sensor is reduced down to 30 nOe/Hz$^{1/2}$ at 1 Hz, which is sufficient for bio-magnetic field measurements including magnetic cardiography [16]. Micro-sized MI chips utilizing a pulse driven amorphous wire with a coil have been in mass production of electronic compasses by Aichi Steel Corp for smart phones [17].

Pulse excitation in MI sensors is typically realised with the help of CMOS inverter IC chip. It was also proposed in [15] to employ a microcontroller for pulse current driven MI element. This concept of controllable and tunable pulse excitation was adopted and further developed in the present work. We used a multiple wire

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element excited by a waveform close to a positive half sine-waveform with a frequency of 8 MHz and achieved a linear response with a resolution of 60 mV/Oe.

2. OFF-DIAGONAL MI SENSOR ELEMENT

Generally, magnetoimpedance in a wire is understood as a ratio of voltage V_w measured across it to a passing ac current i in the presence of an external magnetic field H_{ex}, as shown in Fig. 1. In wires with a circumferential anisotropy this quantity is very sensitive to H_{ex}, as a result of the skin effect and ac transverse magnetization. In the megahertz range, the real and imaginary parts of the impedance are symmetrical with respect to H_{ex} having two identical peaks at $H_{ex} \cong H_K$, where H_K is the characteristic anisotropy field. The sensitivity could be very high but the shape of the MI characteristics is such that the operation near zero field point could be a problem. For a helical static magnetization, the ac current induces also a voltage V_C in the coil wound on the wire, since the current flow gives rise to ac axial magnetization. The ratio $Z_C = V_C/i$ may be referred to as "the off-diagonal impedance".
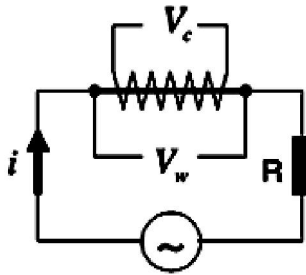

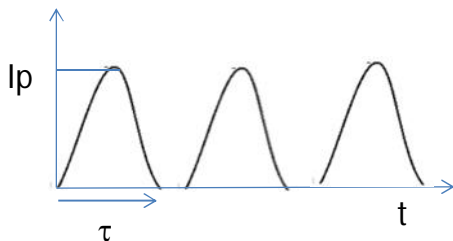Fig. 1 – Voltage responses in a wire produced by current excitation

Fig. 2 – Pulse width modulation output from the microprocessor. The pulse duration τ is about 60 ns, and the pulse repetition is almost twice of that. Note the exponential nature of the pulse, which is caused by the internal capacitance on the pins of the microcontroller

In single-domain wires with a circumferential anisotropy, the real and imaginary parts of the function $Z_C(Hex)$ are antisymmetrical with a near-linear region around zero field point [18]. These field characteristics are very useful for linear sensing.

3. EXPERIMENTAL: SENSING ELEMENT AND CIRCUITRY

A microcontroller was used for producing a complex ac excitation as shown in Fig. 2. The controllable elements include a shape of an individual pulse and a pulse repetition. The pulse width (and pulse rising / falling time) determines the characteristic

frequency of excitation and the repetition frequency affects the dc component (and hence, dc bias) of pulse excitation. The both parameters are important for sensor performance. The pulse duration was about 60 ns and the period of repetition was about 120 ns that corresponds to the characteristic frequency of 8 MHz which was measured with the help of a resonance circuit. As it is apparent in Fig. 2 the pulse is exponential in nature, resembling that of a capacitive charge and discharge curves which is determined by the internal capacitances of the input / output pins, this gives the pulse a sinusoidal structure. The width of the pulse can be adjusted using a combination of fine tuning the oscillator and configuring the scaling factors associated with the oscillator, also the period of the pulse repetitions can be adjusted by changing the internal timer period value.

Schematic of sensor design is shown in Fig. 3. The voltage signal produced by the microcontroller is amplified and applied to the MI wire. The current pulse peak value is estimated to be about 10 mA. The output signal from the coil mounted on MI wire is supplied to a fast switch through a capacitor to cut the dc signal.
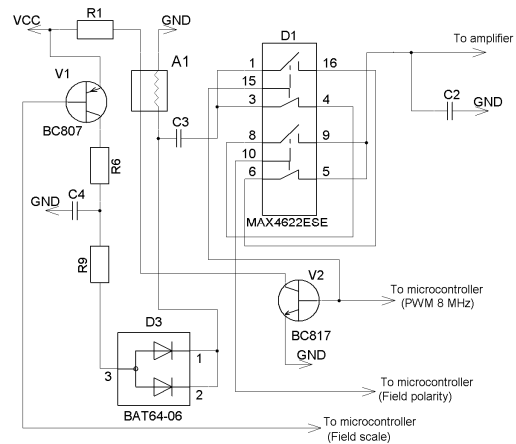

Fig. 3 – Schematics of sensor circuitry showing the main blocks

In comparison with a diode operation, the use of the switch is preferable to avoid temperature variations and nonlinearity. The switch operation is controlled by the microcontroller: the switch is on at the moment of a peak signal from the coil supplying a voltage to the accumulating capacitor. The amount of charge on the capacitor corresponds to the output signal amplitude from the sensor coil which depends on the external magnetic field. The signal from the capacitor is amplified and digitised by the microcontroller. The controller can adjust the full scale of sensor operation by changing the gain of the output signal amplifier and providing this information to the sensor through the feedback loop.

A glass-coated amorphous wire of a composition $Co_{66.94}Fe_{3.93}Ni_{1.44}Mo_{1.69}B_{11.51}Si_{14.59}$, with a total diameter of 22.8 μm and a glass-metal core ratio of 0.19 was used. At 20 MHz, the wire impedance change ratio against the field is more than 100 %/Oe as measured with the help of a network analyser. The sensor element with the detection coil is shown in Fig. 4. Three wires connected in parallel were used as a sensing element and the detection coil had 40 turns of copper wire with a diameter of 60 μm.
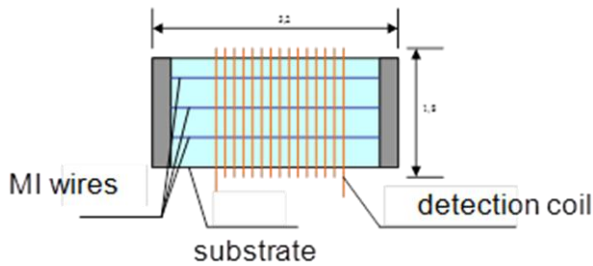
Fig. 4 – Sensing element comprising three MI wires connected in parallel and a detection coil with 40 turns

4. RESULTS AND DISCUSSION

The sensor response is based on the dependence of the coil voltage on the external magnetic field. The voltage signal from the coil for two values of the magnetic field is shown in Fig. 5. It is seen that the voltage pulse increases almost twice when the field is increased from 0.2 Oe to 1 Oe. There is also change in the waveform shape.
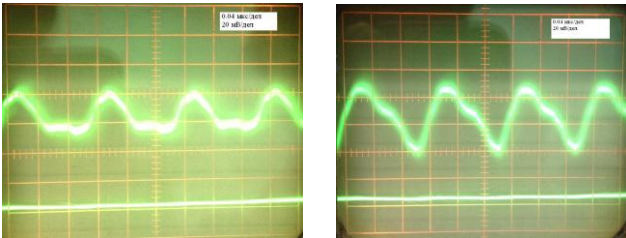
Fig. 5 – Voltage signal from the detection coil for two values of the magnetic field: 0.2 Oe (left) and 1 Oe (right). The scales are: 40 ns and 20 mV per division

In other off-diagonal MI sensor designs [13-15], the period of pulse train is much larger than the pulse duration which reduces the power consumption and produces a moderate dc bias.

It is considered that the dc bias should not be large in order not to increase the magnetic hardness. However, we found that a larger bias results in deeper circular saturation increasing the output signal and reducing the noise due to closure domains, thus, improving the sensor resolution.

A drawback of the off-diagonal sensor configuration could be a reduction in sensitivity due to a small cross-sectional area of the wire. Multiwire cores can solve this problem. The same approach to improve sensitivity was

used in designing orthogonal fluxgates [19, 20]. It is interesting to note that increase in sensitivity is non linear with respect to the number of wires when they are closely packed (the distance between the wires is less than 5 mm). It could be assumed that the increase in sensitivity is due to an additional effect of the currents from the adjusting wires. However, replacing some MI wires with copper wires does not improve the sensitivity. It means that the dynamic magnetic interaction between the wires is important. The exact nature of this interaction will be investigated elsewhere.

The output voltage signal as a function of the external magnetic field is shown in Fig. 6. The sensitivity is very high with resolution of 60 mV/Oe. There is also almost a linear behaviour for fields smaller than 3.5 Oe. This field corresponds to the sum of the anisotropy field (about 2 Oe) and the dc induced bias field (1.5 Oe).
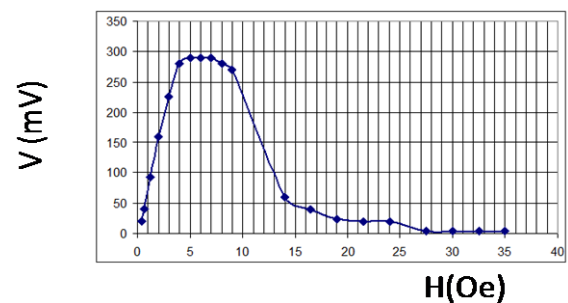
Fig. 6 – Sensor output as a function of the external magnetic field

5. CONCLUSIONS

We demonstrated that a complex waveform excitation from a microprocessor is an effective way of driving MI sensor elements. Using a microcontroller also provides additional functionality and a cost effective approach to producing controllable excitation for an MI sensor which is compatible with intelligent sensor design. In this work, by optimizing the pulse characteristics a resolution of 60 mV/Oe was realized with linearity in the field interval ± 3.5 Oe.

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