Journal of ELECTRICAL ENGINEERING, VOL 59. NO 7/s, 2008, 55-57

ON UNCERTAINTY OF SENSORS BASED ON MAGNETIC EFFECTS

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The contribution of magnetic hysteresis to the response of sensors based on magnetic phenomena and materials is investigated. Two different types of MDL based sensors, namely a displacement sensor and a load cell, were examined. The sensing cores used are based on amorphous FeSiB and polycrystalline Fe, Ni, FeNi wires. Hysteresis is lower in the case of amorphous materials even at low pulse fields or stress levels which lead to sensors with lower uncertainty levels.

Keywords: magnetic sensors, hysteresis modelling, MDL sensors, load sensors, position sensors

1 INTRODUCTION

Magnetic sensors are important in many fields of engineering [1]. They can be mainly used in the measurement of physical sizes, such as position, stress and field [2]. Their characteristics and range of measurement make them attractive for applications where other kinds of sensors cannot operate. They can be manufactured using hybrid or micromechanic techniques and can be easily packaged in miniaturized set-ups. Many of them have the intrinsic property of self-calibration, allowing accurate and repeatable measurements.

Hysteresis is an intrinsic property of magnetic materials responsible for the memory properties of magnetic materials used in energy applications, data storage or security applications. It is also the property which is highly undesirable in materials used for sensing applications since, along with the material nonuniformity, it contributes to the uncertainty of the sensor [3].

This work investigates the effect of magnetic hysteresis on sensor response, and more specifically on the response of magnetostrictive delay lines (MDLs), a family of magnetic sensors used, among others, for stress and position measurements. MDLs (Fig. 1) consist of the sensing core that can be a magnetostrictive ribbon or wire around which excitation and sense coils are wound at a distance from each other. When a DC bias magnetic field is applied along the sensing material, magnetic domain walls are set to motion, during which Barkhausen jumps take place, followed by domain rotations tending to align the domains with the applied field. The angle of rotation is related to the magnitude of this field. The domain wall displacement is related to the hysteretic part of the sensor's response while the domain rotation accounts largely for the anhysteretic response.

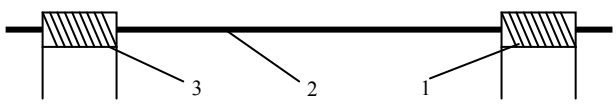

Fig. 1. The basic MDL arrangement: (1) Excitation coil, (2) Magnetostrictive delay line, (3) Search coil

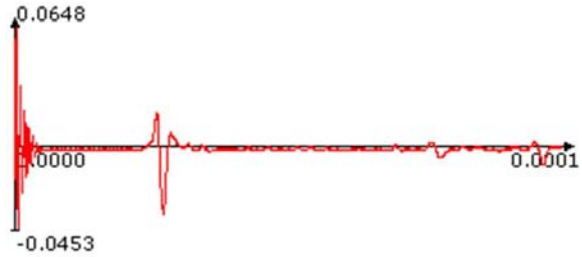

Fig. 2. The detected MDL pulsed voltage output. The first impulse response is due to the pulsed excitation field. The main pulsed voltage output follows, with characteristic amplitude V_0. The small waveforms following the main pulsed output are reflections of the propagating elastic pulse at the ends of the magnetostrictive medium (Time units in seconds and voltage amplitude in volts).

The domain rotation sets off the magnetostriction mechanism leading to the shrinkage (elongation) of the negatively (positively) magnetostrictive sensing element. When a pulsed field is applied on top of the dc bias field, a dynamic component of elongation will be superimposed on the dc elongation. This part of the response takes the form of an elastic Lamb wave propagating along the sensing core. The deformation is picked up by the sensing coil which yields an output voltage pulse. The response of an MDL is shown on Fig. 2.

2 EXPERIMENTAL RESULTS AND DISCUSSION

The first type of sensor examined is a moving magnet displacement sensor [4]. A moving hard magnet (fig. 3) is displaced parallel to the sensing material and acts as the active core of the sensor. Pulsed current is transmitted through the excitation coil, generating an elastic pulse, which propagates along the MDL length. The propagating elastic pulse induces a pulsed voltage in the search coil whose amplitude is proportional to the ambient field along the axis of the search coils and therefore, the closer the moving magnet is to the coil, the larger the corresponding voltage pulse is. The sensor utilizes a look-up table to determine the displacement.

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ISSN 1335-3632 © 2008 FEI STU

Typical response curves of this sensor are shown in Fig. 4 and 5. Figure 4 illustrates the hysteretic response of polycrystalline Fe, Ni and FeNi wires used as sensing cores in the arrangement of Fig. 3. The voltage output is measured with respect to the pulsed excitation field amplitude. The highest sensitivity is exhibited by the FeNi wire while the Ni wire is the material with the strongest hysteresis in the high sensitivity region. The uncertainty introduced by the hysteresis can be as high as 10 %.

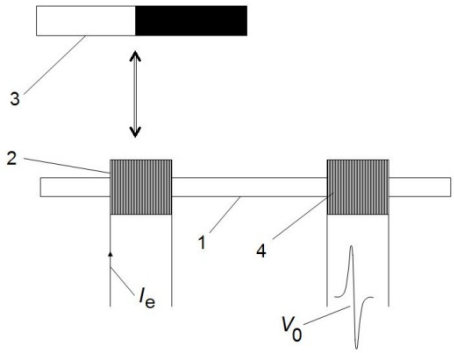

Fig. 3. Moving magnet displacement sensor causes change of the elastic pulse at the excitation region: 1 - MDL, 2 - Excitation coil, 3 - Search coil, 4 - Moving magnet

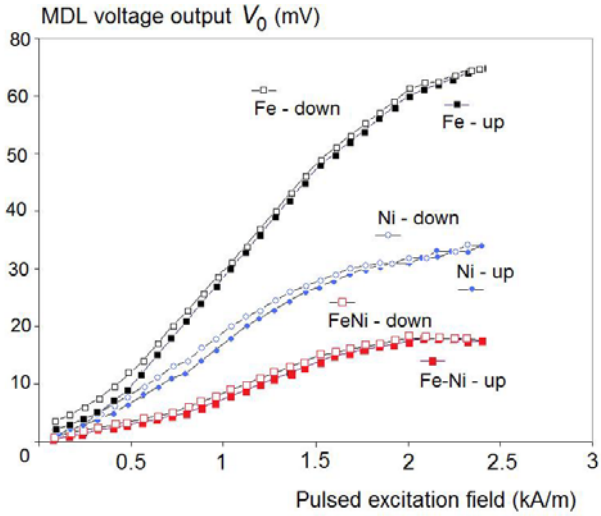

Fig. 4. Typical hysteretic MDL response of polycrystalline Fe, Ni and FeNi wires concerning Fig. 3 position sensor after the heat treatment

Figure 5 shows results from a FeSiB amorphous ribbon: a) as cast b) after heat treatment at 300°C in Ar atmosphere and c) after thermal and field annealing 300°C and 30 Oe in Ar atmosphere. Thermal and field annealing greatly enhance the response of the sensor, making it more sensitive, while in all cases, the response is anhysteretic even at low pulse fields.

The second type of investigated sensor is the MDL-based load cell arrangement shown in Fig. 6. In this case, the MDL itself is subject to load. Stressing the MDL results in a distortion of the magnetostriction curve λ(H) of the material with positive (negative) magnetostriction and consequently in a decrease (or increase) of the pulsed voltage output. Figure 7 shows the hysteretic stress dependence of the voltage output for Fe, Ni and Fe-Ni polycrystalline wires after flash annealing. Fe and FeNi wires have positive magnetostriction leading to a decrease of the signal with applied stress while Ni, as a negative magnetostrictive material, yields an increasing response. The highest sensitivity is exhibited by the FeNi wire, which also exhibits considerable hysteresis in the high sensitivity region.

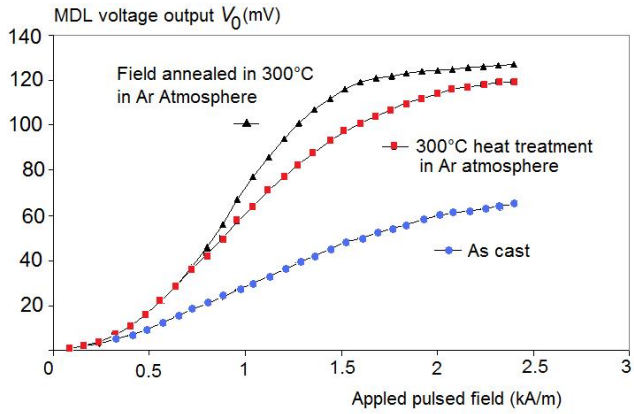

Fig. 5. Typical anhysteretic MDL response of FeSiB amorphous ribbon after thermal and field annealing concerning Fig. 3 position sensor

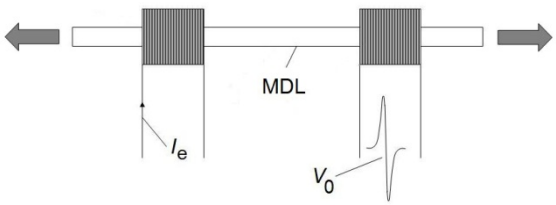

Fig. 6. Load cell principle based on direct MDL stressing

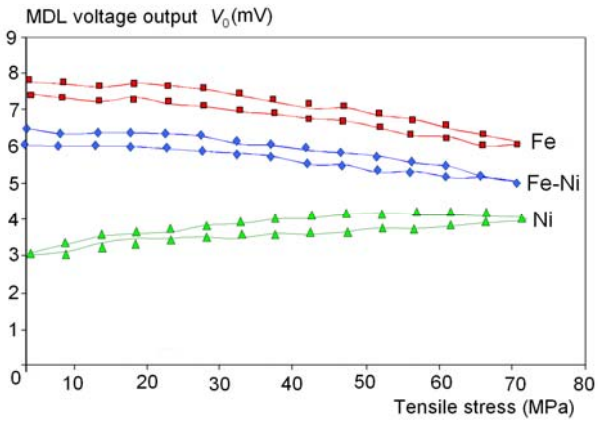

Fig. 7. Hysteretic stress dependence of Fe, Ni and Fe-Ni polycrystalline wires after flash annealing. Ni wire illustrated the expected increasing response, as negative magnetostrictive material

Finally, Fig. 8 illustrates the typical anhysteretic response of the sensor of Fig. 6 on applied load under various amplitudes of applied biasing field and for a FeSiB sensing core. The sensor response decreases with

increasing field and the sensitivity decreases with the applied load. The response is anhysteretic even at low bias fields and loads.

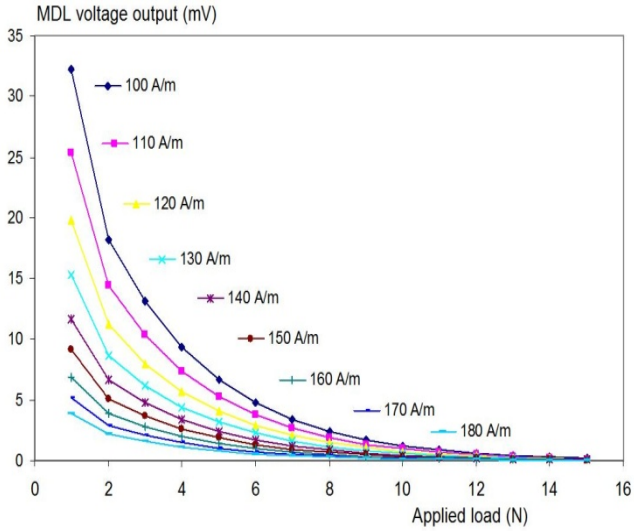

Fig. 8. Typical anhysteretic response of the MDL dependence on applied load under various amplitudes of simultaneously applied biasing field

The uncertainty of measurement of a sensor is defined as the total deviation of the measured value from the near true value of measurement and is a function of both the sensor sensitivity and the sensor hysteresis. In the two MDL sensor arrangements examined in this work, the sensor sensitivity is enhanced through heat treatment and/or field annealing (Fig. 5).

In both arrangements, amorphous materials like FeSiB wires exhibit lower or negligible hysteresis than polycrystalline materials. The explanation lies in the hysteresis characteristic of the sensing material. Hysteresis is the result of irreversible processes like Barkhausen jumps or the change in the orientation of local easy axes. Even though both types of materials undergo irreversible processes, hysteresis is more prominent in the case of polycrystalline materials because of their microstructure. The $B(H)$ or $\lambda(H)$ characteristic of polycrystalline materials is wider and more "square" with a small anhysteretic portion of the loop compared to the amorphous materials. Generally, it is desirable to operate the sensor at the more sensitive (and hysteretic) portion of the $\lambda(H)$ loop where the output signal is higher. In the case of amorphous materials it is possible to do that and still get a practically anhysteretic response even for low bias fields as Fig. 8 shows.

3 CONCLUSIONS

Good levels of uncertainty are achieved in the case of highly sensitive responses and in the case of high uniformity and low hysteresis of the sensing material and. In this work, the effect of hysteresis on the response is examined. Higher sensitivity is achieved when operating in the hysteretic part of the curves rather than in the reversible anhysteretic region, having though the disadvantage of higher uncertainty due to hysteresis. The sensitivity of magnetic materials used as sensing cores in MDL arrangements can be increased considerably by thermal and field annealing of the material. More importantly, amorphous materials offer themselves for such applications since their $\lambda(H)$ characteristic has small hysteresis and a big region of highly sensitive and reversible response compared to polycrystalline materials.

Acknowledgements

This work was partially supported by the Greek Ministry of Education, "Archimedes" project, TEI of Chalkis.

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Received 28 June 2008