Proceedings of the 21st International Conference on Global Research and Education (Inter-Academia 2024)

Modeling the Matteucci Effect in Non-uniform DC Magnetic Field Sensor

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This paper presents a quantitative model for magnetic field sensors based on the Matteucci effect in non-uniform magnetic fields. The Matteucci effect, observed in twisted amorphous wires, generates voltage pulses due to magnetization changes. The model describes non-uniformities by analyzing the effect of spatial gradients in the magnetic field and enables magnetic field gradient measurement. Experimental validation shows that the field gradient introduces an additional delay in re-magnetization, reflected as distinct forked voltage pulses. The proposed model allows for the improvement of sensor performance and extends the application of Matteucci-effect-based sensors to magnetic field mapping and non-destructive testing.

topics: Matteucci effect (ME), magnetic field sensor

1. Introduction

The *Matteucci effect* (ME) is a magnetomechanical phenomenon in which the circumferential magnetization changes under an axial magnetic field, inducing a sharp voltage pulse, known as Matteucci voltage, at the sample ends during magnetization jumps.

The Matteucci effect is observed in twisted wires with helical anisotropy, where the axial field induces the sharp voltage pulses [1, 2]. Although first discovered by Carlo Matteucci in 1858, ME has recently gained interest due to the stronger effects in twisted amorphous wires and tapes [3]. ME-based magnetic sensors offer a promising alternative to other existing sensors. These sensors are applied in rotational speed sensors, current measurements, and fast pulse generators [4–7]. Despite this potential, the physical processes of ME in non-uniform magnetic fields remain poorly understood.

This paper addresses this knowledge gap by analyzing the behavior of ME-based sensors in magnetic fields with spatial gradients. Describing the sensor's characteristics in a field with a specific spatial gradient allows for compensating the gradient influence on the sensor performance and measuring the gradient itself. This approach can improve the performance of ME-based sensors and enable their use in new applications, such as magnetic field gradient measurements. Development of a proper model for this phenomenon is thus necessary.

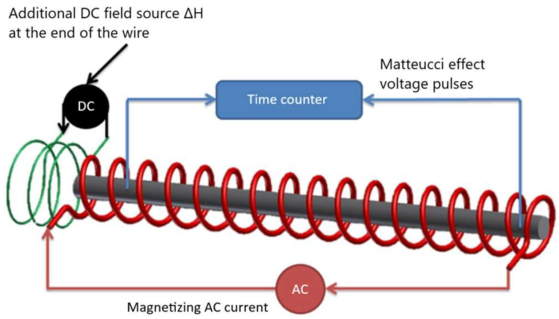

Fig. 1. Schematic of measuring ME voltage pulses and applying field non-uniformity.

2. Sensor setup

Constant magnetic field sensor based on the time-shift measurement process is presented. To develop the sensor, a bistable amorphous wire made of an iron–cobalt-based alloy with a diameter of 101 μm,

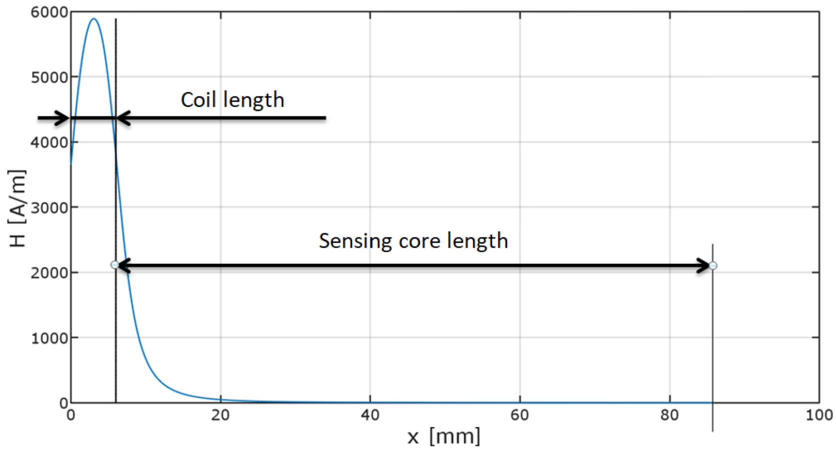

Fig. 2. Generated by an additional coil magnetic field's distribution in the sensor's core length.

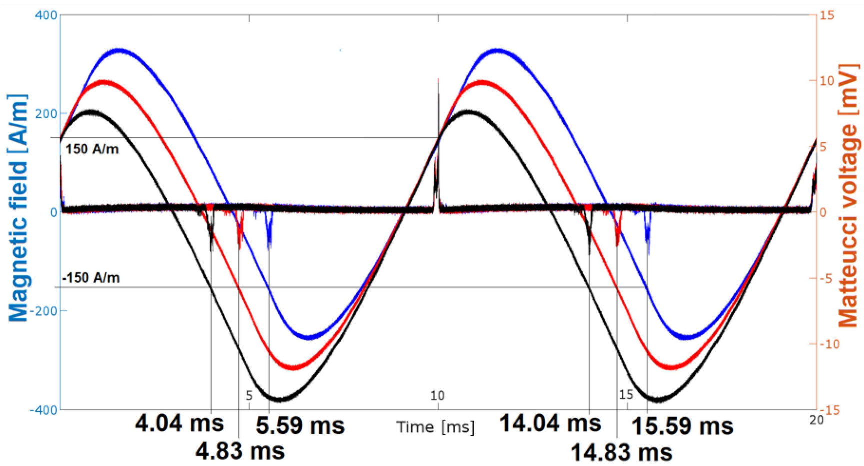

Fig. 3. The DC magnetic field sensor's voltage pulses and applied AC uniform magnetic field vs time. The plots are triggered on the rising slope of positive ME pulses.

manufactured by AICHI Steel (formerly UNITIKA, Japan), commercially available under the name 101DC5T, has been selected. The twisted amorphous wire is placed inside an *alternating current* (AC) magnetizing coil, and the Matteucci voltage is measured by a timer counter with an amplifier. An additional coil is placed at the tip of the wire to add non-uniformity to the field. The setup is presented in Fig. 1.

Figure 2 presents how the additional coil influences the distribution of magnetic field along the length of the wire. The non-uniformity occurs only at the tip of the wire, diminishing rapidly.

Figure 3 presents how the sensor works in a uniform field. The visible sinusoidal-like plots are the magnetic fields applied by the AC coil along the entire length of the wire. The color of the magnetic field plot corresponds to the color of the voltage pulse plot. By changing the *direct current* (DC) offset of the magnetizing field, an external DC magnetic field is simulated, and a resulting change in time delay between the positive and negative ME pulses is visible. This is because the sensor's core, which is an amorphous wire, has a constant value of the magnetic field, which is needed to trigger a change in the magnetization direction — in this case, 150 A/m. After reaching the field, the wire re-magnetizes, generating a voltage pulse.

The timer shows varying times between rising and falling slopes, which depends on the external DC magnetic field.

3. Non-uniform field measurements

When the sensor is subjected to a non-uniform magnetic field, the ME pulses split into two positive and two negative pulses. Depending on the value of nonuniformity, they can separate from each other or still be attached to one another. This is presented in Fig. 4.

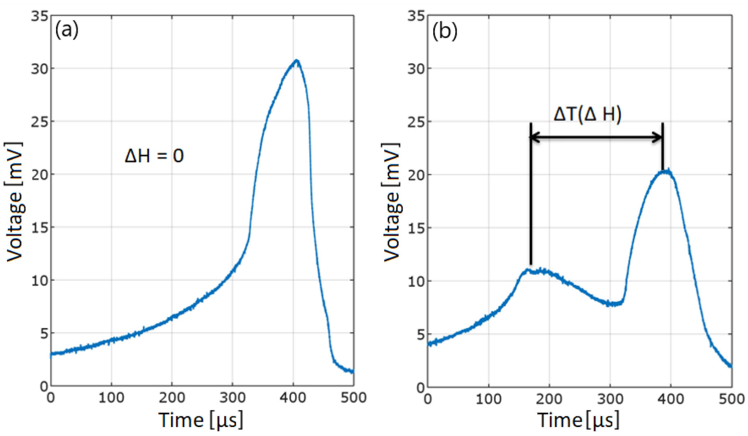

Fig. 4. Shape of ME pulses in (a) uniform and (b) non-uniform fields.

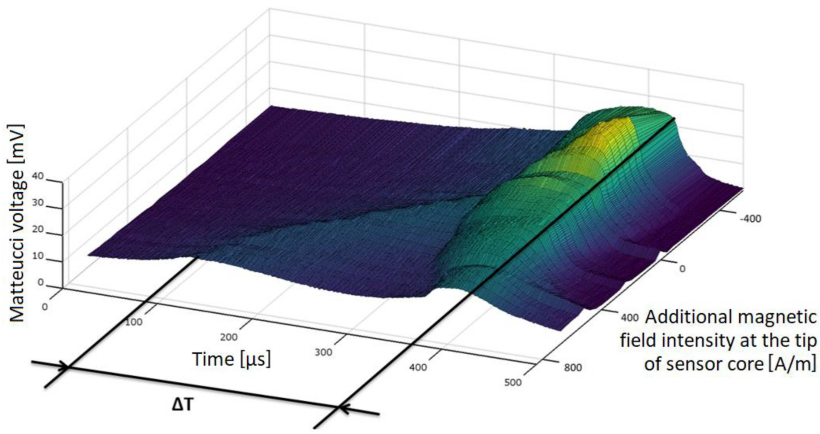

Fig. 5. 3D plot of ME positive pulses' voltage vs time and field non-uniformity.

A measurement series was carried out in which the ME pulse was observed during the change in an additional non-uniform magnetic field. The uniform AC magnetic field was big enough not to affect the Matteucci effect's occurrence, while the DC non-uniform field was changed from 0 to 850 A/m (peak) in the middle of the additional coil. The resulting ME voltage pulse split is presented in Fig. 5.

4. Model

Concerning the measurements of the magnetic field inhomogeneity, a quantitative model is proposed in the paper that explains the occurrence of an additional Matteucci voltage peak as a result of the field gradient at the end of the amorphous wire. It results from the phenomenon of the occurrence of an additional domain at the tip of the amorphous wire [8]. The reverse domain has a magnetizing field direction opposing the magnetization of the wire. As a result, to re-magnetize the final fragment of the wire, the critical intensity of the magnetizing field H^* must be reached. In the case of uniform magnetization with a sinusoidal field, the re-magnetization moment T^* is given by the relationship

$$H_m \sin\left(2\pi f\, T^* + \varphi\right) = H^*, \tag{1}$$

where H_m is the amplitude of the sinusoidal magnetizing field, f — frequency of the sinusoidal magnetizing field, ϕ — phase shift of the magnetizing field.

In the presence of an additional field H_d associated with the occurring gradient of the measured field δ [A/m^2], the re-magnetization of the end of the wire will occur with a delay of time Δt,

$$H_m \sin\left(2\pi f\,(T^* + \Delta t) + \varphi\right) = H^* + \delta L = H^* + H_d, \tag{2}$$

where L is the length of the wire over which the magnetic field gradient δ is given, resulting in the appearance of the magnetizing field difference H_d.

To solve the system of equations, let us assume that $\phi = 0$. The resulting Δt is given by

$$\Delta t = \frac{1}{2\pi f}\left[\arcsin\left(\frac{H^* + H_d}{H_m}\right) - 2\pi f\, T^*\right], \tag{3}$$

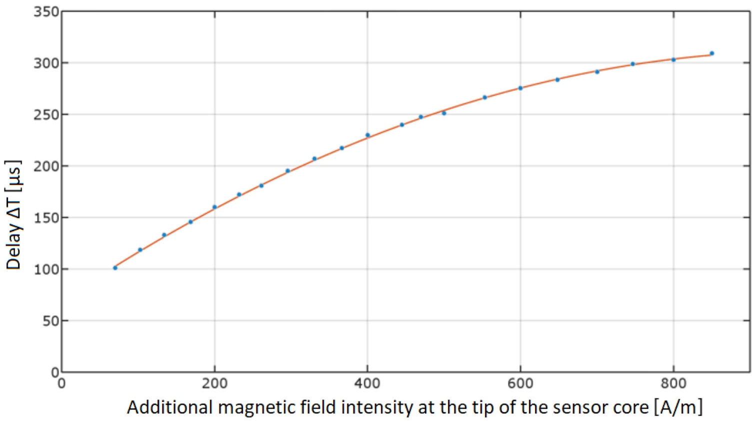

Fig. 6. Characteristic of time delay between ME pulses vs field non-uniformity.

and

$$\Delta t = \frac{1}{2\pi f}\left[\pi - \arcsin\left(\frac{H^* + H_d}{H_m}\right) - 2\pi f\, T^*\right], \tag{4}$$

The relationship describing the time delay of the additional pulse determined from the proposed model is difficult to apply in practice. Therefore, in practice, polynomial interpolation was used to describe the processing characteristics of the sensor for measuring the magnetic field gradient using a second-degree polynomial

$$\Delta t = a\, H_d^2 + b\, H_d + c. \tag{5}$$

The polynomial parameters a, b, and c should be selected experimentally, depending on the physical parameters of the measurement system used.

Based on the results in Fig. 5, a plot of the time delay Δt between two positive pulses vs the additional non-uniform magnetic field ΔH generated by the coil is presented in Fig. 6.

The second-degree polynomial fits the data with a parameter R^2 of 0.993, which indicates that the fit is of very good quality and accordingly approximates the real data.

5. Conclusions

This study addresses the gap in the understanding the Matteucci effect (ME) in non-uniform magnetic fields by developing a quantitative model for ME-based sensors. Through experimental validation, we demonstrated that the presence of a magnetic field gradient introduces an additional delay in the re-magnetization process, manifesting as a distinct voltage pulse. The model accurately describes this behavior and provides a practical means of compensating for field non-uniformity through polynomial interpolation.

Beyond improving sensor performance, ME-based sensors could now be used for direct measurements of magnetic field gradient, opening up new applications in magnetic field mapping and non-destructive testing. Future work should focus on refining the model for more complex magnetic environments and integrating it into multi-sensor systems for enhanced spatial resolution.

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