Characterization of a TMR Sensor for EC-NDT Applications

Andrea Bernieri, Giovanni Betta, Luigi Ferrigno, Marco Laracca and Antonio Rasile

Abstract Non-destructive tests based on eddy currents (EC-NDT) are one of the inspection techniques used to detect and characterize defects in conductive structures. The EC-NDT technique is based on the induction of eddy currents in the material under test and on the analysis of the reaction magnetic field that is generated. In this way, it is possible to detect the presence of a defect and evaluate its geometric characteristics. Generally, magnetic sensors such as AMR or GMR can be used to detect the reaction magnetic field. Recently, magnetic field sensors based on the Tunnel effect (TMR) have been introduced, which seem to have better performances than previous solutions. In this context, the article illustrates the metrological characterization of a TMR sensor for EC-NDT applications, as the information provided by the manufacturer is not complete and sufficient for this type of use. The results obtained show that the TMR sensor is able to provide a higher sensitivity than the AMR and GMR sensors, with a limited measurement uncertainty. This makes it possible to assume that the TMR sensors can be usefully used in EC-NDT applications.

Keywords TMR sensor · Tunneling Magneto-Resistance · Magnetic sensor Eddy current test · Non destructive test

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A. Bernieri (✉) · G. Betta · L. Ferrigno · M. Laracca · A. Rasile
Department of Electrical and Information Engineering, University of Cassino
and Southern Lazio, Via G. Di Biasio, 43, 03043 Cassino, Italy
e-mail: bernieri@unicas.it

G. Betta
e-mail: betta@unicas.it

L. Ferrigno
e-mail: ferrigno@unicas.it

M. Laracca
e-mail: m.laracca@unicas.it

A. Rasile
e-mail: a.rasile@unicas.it

B. Andò et al. (eds.), *Sensors*, Lecture Notes in Electrical Engineering 539,
https://doi.org/10.1007/978-3-030-04324-7_30

1 Introduction

The Eddy Current Non-Destructive Testing (EC-NDT) technique is actually widely used in the industrial applications in order to detect the presence of defects in conductive structures. As it is known, the EC-NDT technique is based on the induction of currents in the material under test through a suitable excitation system; these currents generate a reaction magnetic field which changes in presence of defects in the material; by means of an appropriate magnetic field sensor and suitable processing procedures, it is possible to detect the presence of a defect and evaluate its geometric characteristics (length, width, depth) [1–9].

With reference to magnetic field detection systems, many solutions are provided in the literature, based on both magnetic pickups [1] and magnetic field sensors [2–5, 10]. Among the latter, magnetoresistive sensors are among the most used, thanks to their characteristics of limited size, good spatial resolution and adequate sensitivity for EC-NDT applications.

To this category belong the Giant MagnetoResistive sensors (GMR), formed by a multilayer metallic structure with alternating ferromagnetic and non-magnetic layers. In presence of an external magnetic field, the GMR sensors provide changes in electrical resistance that ranges from 10 to 20% up to 70% [11]. However, for optimal use as magnetic field sensors, the GMR sensors require an external control circuitry able to constantly ensure a proper reference magnetization axis and an output signal offset compensation.

Another class of magnetic field sensors based on the magnetoresistive effect is the AMR (Anisotropic MagnetoResistive) sensors. The sensor structure is composed of a thin film of a ferromagnetic material (nickel-iron, permalloy) deposited on a silicon wafer. In presence of an external magnetic field, the AMR sensor resistance changes up to 2–3% [12–15]. Although they exhibit less sensitivity than GMR sensors, AMR sensors are built with internal circuits to compensate for magnetization and offset effects, allowing much easier development of magnetic field measurement applications [12–15].

Recently, magnetic field sensors based on the Tunnel effect (TMR—Tunneling Magneto-Resistance) have been introduced. The TMR sensors are based on a particular multi-layer junction (TMJ—Tunneling Magnetic Junction) composed of two ferromagnetic layers separated by a non-magnetic tunnel barrier. The first ferromagnetic layer is characterized by a "free" magnetic direction, in the sense that it can assume a magnetic polarization with direction depending on the external magnetic field. The second ferromagnetic layer, instead, is "pinned", i.e. the polarization direction is fixed and does not depend, within certain limits, on the external magnetic field. Applying an external magnetic field, the polarization of the free layer is modified according the external magnetic field direction and intensity, determining a variation of overall junction resistance. Figure 1 shows the TMJ resistance against the polarizations of the ferromagnetic layers.

In the presence of a magnetic field, the TMR sensors provide a greater resistance variation than that provided by the previously described AMR and GMR sensors

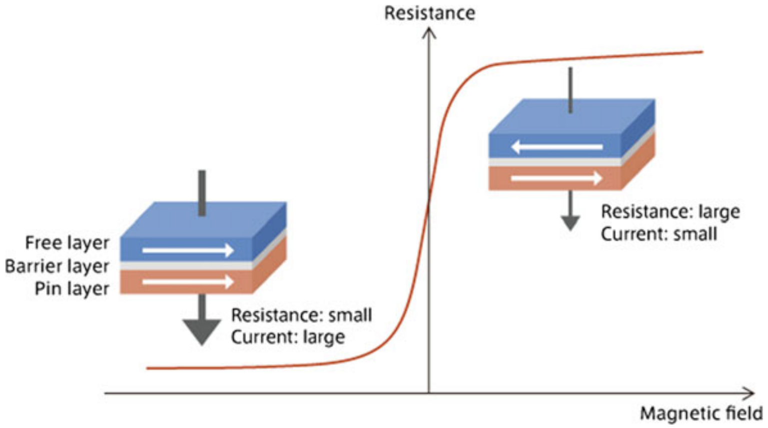

Fig. 1 TMJ resistance against the polarizations of the ferromagnetic layers

and do not require compensating circuits. Compared to a AMR sensitive element, a TMJ element has a higher sensitivity and a wider linear range. Compared to a GMR sensitive element, a TMJ element has a higher sensitivity, less energy consumption, and a wider linear range.

Because of its recent production, the TMR sensor is not well known in terms of metrology performance, and even manufacturers do not provide exhaustive information. For this reason, in order to efficiently use TMR sensors in an EC-NDT probe, the authors have made a preliminary metrological characterization of a TMR sensor by Multi Dimension Technology (model TMR2905D), following the same approach used for the previously characterization of a GMR sensor [10].

2 TMR Sensor Performance Evaluation

Figure 2 shows the measurement station developed to characterize the considered TMR sensor. It is composed by a signal generator coupled with a Kepco bipolar amplifier to feed a calibrated Helmholtz coil in order to generate a controlled excitation magnetic field; the TMR signal output is then amplified and measured by means of a digital multimeter. The TMR sensor is placed in the middle of the Helmholtz coil in order to assure a uniform excitation magnetic field.

The tests are performed applying both DC and AC magnetic fields. Figure 3 shows the obtained DC TMR transfer function in the magnetic field range of ±30 G and for a TMR supply voltage of 1 V. The analysis of the DC characteristic shows a saturation effect for magnetic field values of ±10 G, together with a noticeable linearity. Figure 4 shows the TMR sensitivity characteristic, with a mean value of 53.58 mV/G in the magnetic field range of ±4 G.

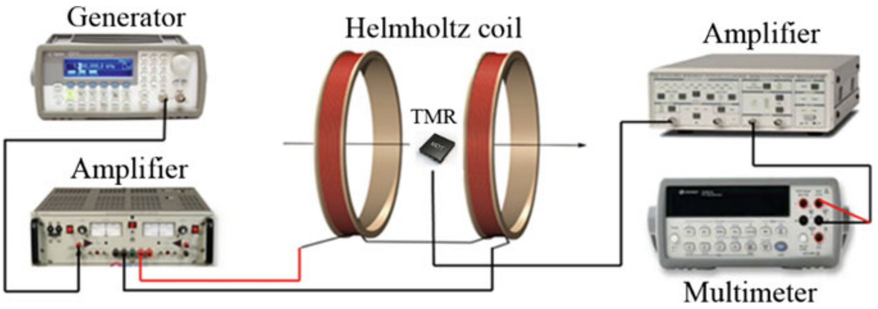

Fig. 2 Measurement station for the TMR characterization

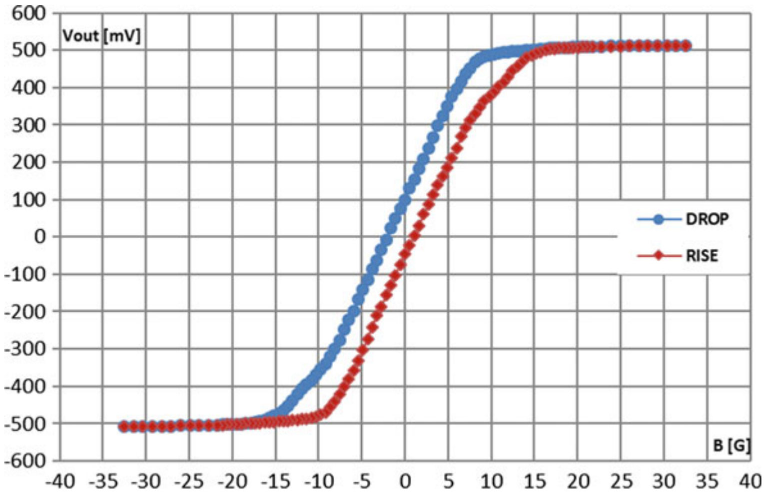

Fig. 3 TMR transfer function for DC magnetic fields in the range of ±30 G

Figure 5 shows the AC TMR transfer function obtained for magnetic field values from 0 to 4 G, in the frequency range from 1 kHz to 50 kHz and for a TMR supply voltage of 1 V. Figure 6 shows the corresponding AC TMR sensitivity characteristic. A mean sensitivity of about 39 mV/G was obtained, together with a good linearity with a maximum variability of 1.32 mV/G for the considered frequency range.

It should be pointed out that only some of these characteristics correspond to those supplied by the manufacturer (when available).

3 Uncertainty Evaluation

For the correct use of the TMR sensor in EC-NDT applications, the main uncertainty contributions that affect sensor performance were evaluated [16, 17], as the manufacturer did not provide any information about it. In particular, for the evaluation of

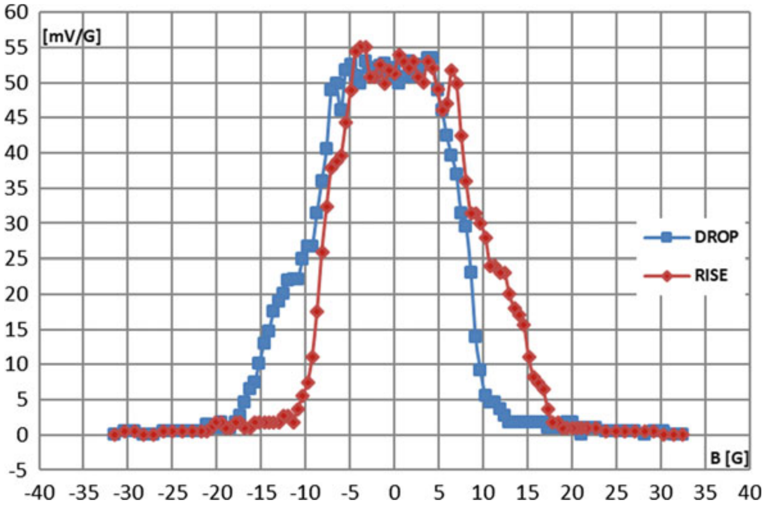

Fig. 4 TMR sensitivity for DC magnetic fields in the range of ±30 G

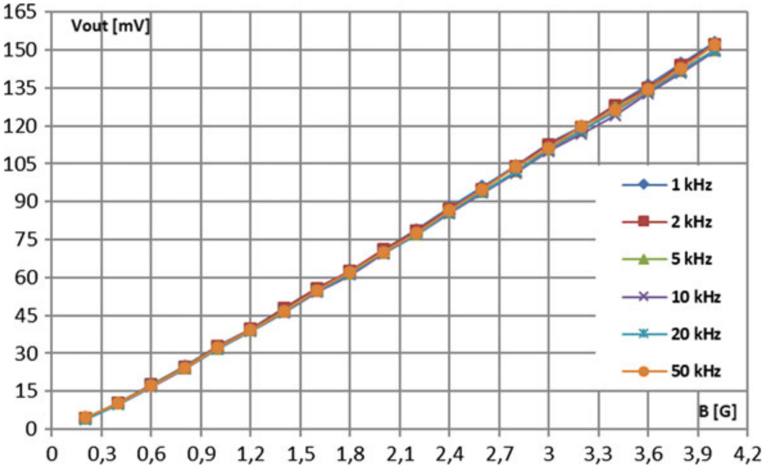

Fig. 5 TMR transfer function for AC magnetic fields (0–4 G) in the frequency range from 1 to 50 kHz

the uncertainty contributions, repeated tests were performed in the magnetic field range of ±4 G (where the considered sensor showed the best performances).

In detail, the uncertainty contributions due to repeatability (σ_{TMR}), sensitivity (μ_{SEN}), hysteresis (μ_{HYS}), non-linearity (μ_{NL}) and frequency variability (μ_{FREQ}) of the sensor response were examined.

The uncertainty due to the repeatability of the sensor response was calculated using the (1), that is, by means of the standard deviation of the sensor response

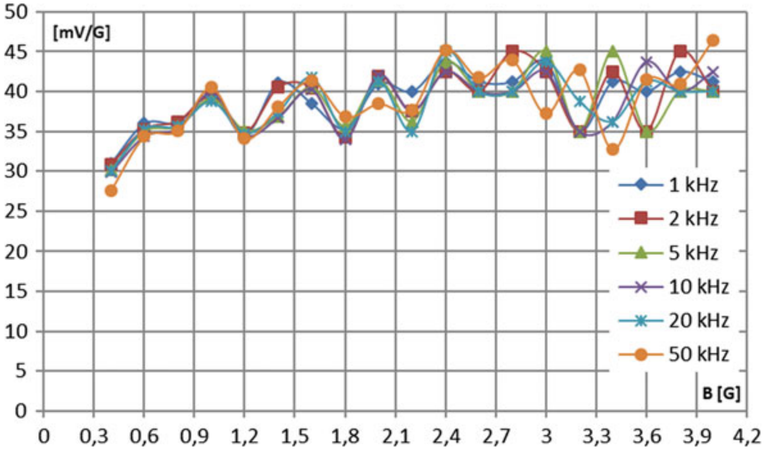

Fig. 6 TMR sensitivity for AC magnetic fields (0–4 G) in the frequency range from 1 to 50 kHz

(Vout) with respect to the applied magnetic field (G), evaluated on N repeated tests (N > 20):

$$\sigma_{TMR} = \frac{\sum_{i=0}^{N-1} Vout_i^2}{\sqrt{N}} = 0.02\text{mV} \tag{1}$$

The uncertainty due to the variability of the sensor sensitivity has been calculated by means of the (2), where $\Delta_{MAX}SEN$ is the difference between the maximum and the minimum value of the sensor output obtained to the same variation of the imposed magnetic field ΔG:

$$\dot{\mu}_{SEN} = \frac{\Delta_{MAX}SEN}{\sqrt{3}} = 0.20\,\text{mV/G} \tag{2}$$

The uncertainty due to the hysteresis of the sensor response was calculated using the (3), where ΔV_{MAX} and ΔV_{MIN} are the maximum and minimum output value of the sensor at the same imposed magnetic field value, with respect to the overall range of magnetic field ΔG in which the hysteresis cycle has been analyzed (±4G):

$$\mu_{HYS} = \frac{(\Delta V_{MAX} - \Delta V_{MIN})}{\sqrt{3}} = 0.43\,\text{mV} \tag{3}$$

The uncertainty due to the non-linearity of the sensor response was calculated using the (4), where $\Delta_{MAX}NL$ is the maximum deviation of the sensor response with respect to the ideal output characteristic, depending on the applied magnetic field ΔG:

$$\mu_{NL} = \frac{\Delta_{MAX} NL}{\sqrt{3}} = 1.01\,\text{mV} \tag{4}$$

The uncertainty due to the frequency variability of the sensor response has been calculated using the (5), where $MAX\_VAR\_FREQ(V_{OUT})$ is the maximum variation of the sensor response with the same applied magnetic field G, in the considered frequency range:

$$\mu_{FREQ} = \frac{MAX\_VAR\_FREQ(V_{OUT})}{\sqrt{3}} = 0.76\,\text{mV} \tag{5}$$

Finally, the overall uncertainty of the TMR sensor due to all the aforementioned contributions was assessed by (6):

$$\dot{\mu}_{TMR} = \sqrt{\dot{\mu}_{SEN}^2 + \dot{\mu}_{tot}^2} \tag{6}$$

where

$$\mu_{TOT}^2 = \sqrt{\sigma_{TMR}^2 + \mu_{HYS}^2 + \mu_{NL}^2 + \mu_{FREQ}^2} \tag{7}$$

4 Conclusions

The work reports a first characterization of a TMR sensor for EC-NDT applications. The experimental results obtained show that the considered TMR sensor can be usefully used for the measurement of continuous and variable magnetic fields. The characteristics of good sensitivity and linearity and ease of use with respect to the other types of magnetic field sensors (GMR and AMR) make it possible to develop methodologies for analyzing defects in conductive materials by means of eddy current which are more efficient and less critical from the implementation point of view. With this in mind, future research developments will concern the integration of the TMR sensor into an EC-NDT probe for the identification of defects on conductive elements in real operating conditions.

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