Sensors and Actuators A 269 (2018) 269–275

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Giant stress-impedance (GSI) sensor for diameter evaluation in cylindrical elements

J.J. Beato-López [a,b], G. Vargas-Silva [c], J.I. Pérez-Landazábal [a,b], C. Gómez-Polo [a,b,*]

[a] Departmento de Física, Universidad Pública de Navarra, 31006 Pamplona, Spain
[b] Institute for Advanced Materials (INAMAT), Universidad Pública de Navarra, 31006 Pamplona, Spain
[c] Materials + Technologies Group, Department of Mechanical Engineering, Universidad del País Vasco/Euskal Herriko Unibertsitatea (UPV/EHU), Plaza de Europa 1, 20018, Donostia-San Sebastian, Spain

ARTICLE INFO

Article history:
Received 19 July 2017
Received in revised form
22 November 2017
Accepted 22 November 2017

Keywords:
Magnetoelastic sensor
Magnetoimpedance
Giant stress-impedance
Cross section characterization
Bending stresses

ABSTRACT

In this work, a magnetoelastic sensor to detect the micrometer diameter variations of cylindrical elements is analyzed. A nearly zero magnetostrictive amorphous ribbon with nominal composition $(Co_{0.93}Fe_{0.07})_{75}Si_{12.5}B_{12.5}$ was selected as sensor nucleus. The sensor, based on Giant Stress-Impedance (GSI), is attached (glued) along the external perimeter of the cylindrical element. Changes in the cylindrical diameter, D_M, induce effective tensile stresses, σ_S, on the ribbon, giving rise to sensitive changes in the high frequency impedance, Z. The sensor response is analyzed in terms of the relationship between the induced strains and the diameter variations, where the effect of geometrical factors (cylinder diameter and sample length) is taken into account. The results indicate that although the maximum GSI ratio depends on the pre-induced bending stresses associated to the cylindrical configuration, the sample length plays the dominant role in the sensor sensitivity. The proposed device enables to monitor the micrometric diameter variation in cylindrical elements, with a maximum strain gauge factor (GF ≈ −80) for low induced strains.

1. Introduction

Giant Magnetoimpedance (GMI) effect has been extensively studied during the last decades due to its technological perspectives in the sensor field [1–3]. The effect consists of huge variations of the high frequency electrical impedance, Z, of a ferromagnetic conductor under the application of external stimuli, mainly dc magnetic field. Within the classical electro dynamical theory, the impedance variations can be correlated to the changes in the characteristic skin depth: $\delta = \sqrt{\frac{\rho}{\pi f \mu}}$ (exciting frequency, f, magnetic permeability, μ, and the resistivity, ρ, of the conductor). Those agents (i.e. magnetic field, applied stresses or temperature) promoting changes in μ leads to measurable changes in Z. Thus, highly sensitive sensor devices can be designed based on this magnetoinductive effect [4], namely, magnetic field and non-contact position sensors [5–7] current sensors [8], temperature detectors [9], biolabel detection devices [10,11] and stress sensors [12].

Regarding stress devices, the so-called Giant stress-impedance (GSI) effect have been widely analyzed in the literature since the first report in 1997 by Shen et al. [13]. Since then, different magnetoimpedance elements have been analyzed regarding the stress (σ) impedance response, Z(σ), including rapidly quenched wires [14,15], glass coated microwires [16,17], ribbons [18,19] and multilayer and composite structures [20–22]. As previously outlined, Z(σ) reflects the dependence of the transverse magnetic permeability on the effective applied stresses. For instance, the stress dependence of the GMI effect can be used to accurately determine the magnetostriction constant, λ_S, in nearly zero magnetostrictive samples [23–25].

Since the pioneer work of Shen, GSI effect has been employed in the design and development of highly sensitive strain sensors for different technological purposes: (i) design of biomedical detectors for the control of blood vessel pulsations, mechanoencephalogram or breathing activity [26–28] or tactile and pressure sensors [29,30]. In particular, strain gauge configuration devices are proposed in the literature [31–33] with strain gauge factor, GF, around 2000, notably higher than in conventional metal strain gauges (≈2) and semiconductor strain gauges (≈200).

Recently, we have reported the design of a highly sensitive magnetoelastic sensor to determine the periodic variation of the

* Corresponding author at: Departamento de Física, Edificio de los Acebos, Universidad Pública de Navarra, Campus de Arrosadia, 31006 Pamplona, Spain.
E-mail address: gpolo@unavarra.es (C. Gómez-Polo).

https://doi.org/10.1016/j.sna.2017.11.040
0924-4247/

trunk diameter in plants (daily periodic micrometric trunk shrinkage and growth as a result of changes in transpiration process and in within-plant water balance) [34]. The measurement of the daily stem or trunk variations provides valuable information about the plant water status and can be employed as an efficient technique for irrigation scheduling. Thus, these simple and low cost magnetoleastic devices are proposed to replace the LVDT displacement sensors currently employed in the agronomic field for plant water monitoring. Other applications requiring the determination of micrometric diameter variations can also be designed based on these magnetoelastic devices (i.e. pressure flow evaluation in cylindrical tubes or pipes). The sensor basis is a nearly zero magnetostrictive amorphous ribbon glued to a cylindrical element along the external perimeter (i.e. the plant's trunk or stem). The diameter variations induce stresses on the attached amorphous ribbon, giving rise to a measurable GSI effect. In the previous work [34], the calibration of the sensor response was performed by gluing the sensing ribbon radially along the external perimeter of a methacrylate cylinder. The application of controlled compression tests to the cylinder gives rise to micrometric changes in the cylinder diameter. A sensor length of 11 cm was chosen to cover a diameter of 40 mm. This diameter was regarded as the mean trunk diameter of the chosen application (grapevine plant). Nevertheless, only this diameter (40 mm) and sensor length (11 cm) were studied. Therefore, in the present work, the effect in the sensor response of both parameters is analyzed. Accordingly, a further investigation on the detection principle and sensitivity optimization of these GSI based sensors for the determination of diameter variations in cylindrical elements is performed. In particular, the dependence of the sensor response on the strain resistivity is analyzed as a function of the cylinder diameter. A nearly non-magnetostrictive amorphous ribbon ($(Co_{0.93}Fe_{0.07})_{75}Si_{12.5}B_{12.5}$) is employed as sensor nucleus. An unexpected optimum response is found for 20 mm diameter. This fact cannot be explained just in terms of the effect of the initial bending stresses induced in sensing ribbons. Therefore, additional factors must affect sensorís performanceleading to a study of the influence of ribbon's length on GSI effect. Results reported in this work, clearly show how sensors can exhibit different sensitivities when different diameters and lengths are involved. While the response and sensitivity of the sensor is determined by the initial bending configuration, the dependence on the sample length plays the dominant role. Furthermore, the definition of an equivalent gauge factor GF (around −80 for low applied strains) is introduced that supports the interest of the proposed magnetoelastic device for different applications where the cross section evaluation is required. These applications include not only the determination of daily trunk diameter variations in plants, but also other practical purposes where the employ of the traditional strain gauges could not be competitive (evaluation of mean changes around the perimetric dimensions or small diameters).

2. Experimental

2.1. GMI: optimization and length dependence

Melt spun ribbons with nominal composition $(Co_{0.93}Fe_{0.07})_{75}Si_{12.5}B_{12.5}$, 66 μm thickness (t) and 530 μm width, were employed as magnetoelastic sensor nucleus. The first step was the optimization of GMI effect. In axial configuration (unstressed state), the ribbon was excited, employing a voltage divider configuration, by an ac current, I, under the action of a dc axial magnetic field, *H* (generated by a home-made solenoid). The output voltage ($V_S = ZI$)was measured with a Tektronix MDO 3024 Oscilloscope. The whole system was controlled by LABVIEW 2014. Dependence of relative impedance, $Z = (R + iX)$ on H was calculated using the usual GMI ratio:

$$\frac{\Delta Z}{Z}(\%) = \frac{Z(H) - Z(R_{DC})}{Z(R_{DC})} x100 \quad (1)$$

where Z(H) is the impedance value at different H values and Z(R_{DC}) corresponding to the impedance under a saturating dc magnetic field ($Z \approx R_{DC}$ and X = 0). Frequency, f = 600 kHz and peak to peak current amplitude, I_{pp} = 69 mA, were found as the optimum measuring conditions (maximum GMI ratio). These conditions were kept constant for subsequent impedance characterizations. Nevertheless, since different parameters (magnetic fields, diameters, stresses, length) are analyzed in the present work, the evolution of impedance with each parameter is evaluated through different GMI ratios as shown below.

2.2. Giant stress impedance effect (GSI). Mechanical tests

2.2.1. Mechanical tests under methacrylate cylinder compressions cylindrical configuration

Mechanical tests were performed on straight and homogeneous methacrylate cylindrical probes (see Fig. 1a). The following subscripts were employed to describe the mechanical parameters of the system: M, methacrylate cylinders, and S, for ribbons; The additional subscript 0 is introduced to describe the initial values under zero strain.

Different diameters D_{M0} (D_{M0} = 15, 20 and 40 mm) of circular uniform cross section were employed. Their short length (L_{M0} = 5 cm) prevents lateral buckling. Subsequently ribbons of lengths L_{S0} = 3, 5 and 11 cm were glued with epoxy along the external perimeter of each cylinder. These lengths were chosen to cover the whole cylinder perimeter length ($L_S \approx \pi D_M$). The adhesive layer does not introduce additional stresses that could affect the accuracy of the measurement because the epoxy resin does not undergo significant volumetric changes during the cure. Consequently, there are not dimensional variations on the magnetostrictive amorphous ribbon due to its adhesion. Besides, impedance of sensors was not modified before and after applying glue. The cylinders were subjected to a compression parallel to the load, σ_0, by a MTS – Insight 10 universal testing machine with a 10 kN load cell. As a result, a shorten on cylinderís length (ΔL_M) was produced. Variations in length were monitored by an optical video-extensometer. Finally longitudinal unit strain ε_M, induced in the system can be calculated according to Hookeís law as follows [35]:

$$\varepsilon_M = \frac{\Delta L_M}{L_M} = \frac{\sigma_0}{E_M} \quad (2)$$

where E_M is the methacrylate Young Modulus (E_M = 3.2 GPa).

At right angles to the load, the cylinder expands under compression uniformly in all transverse directions. The induced unit lateral strain, $\varepsilon'_{M,}$ is related to longitudinal unit strain by means of material Poisson's ratio ν_M:

$$\varepsilon'_M = -\upsilon_M \varepsilon_M = -\upsilon_M \frac{\sigma_0}{E_M} \quad (3)$$

The total lateral deflection (ΔD_M) in any direction is proportional to the lateral dimension (D_{M0}) and can be expressed taking into account Eqs. (2) and (3):

$$\varepsilon'_M = \frac{\Delta D_M}{D_{M0}} = -\upsilon_M \frac{\Delta L_M}{L_{M0}} \quad (4)$$

It is assumed that the variations of ΔD_M are uniformly transmitted as tensile stresses along the ribbon axis, ε_S, giving rise to measurable changes in Z. Assuming that ε_S is equal to the relative changes in the cylinder diameter, ε'_M, and taking into account the