Journal of ELECTRICAL ENGINEERING, VOL 55. NO 10/S, 2004, 62-65

LINEARIZATION OF TWO-COIL MAGNETOELASTIC SENSOR TRANSFER CHARACTERISTIC

Jan Bydžovský* — Mojmír Kollár* — Luděk Kraus ** — Peter Švec***

Magnetoelastic sensors of elongation, or acting force, are currently based on the change of core permeability, caused by mechanical stress, while altering its magnetization. The sensor, like an "open transformer" works either in the constant current or constant secondary voltage mode. The linear relationship between mechanic stress or strain (bound as $\sigma = \varepsilon E$, through the Young modulus) is preserved only if the amplitude of voltage induced in the secondary winding is constant and determined by the changes of magnetic polarization J of the core. If the susceptibility of the sensors changes from 1850 to 90 (when the applied stress changes up to 600 MPa) the unfavorable influence of the secondary coil window filling leads to a noticeable loss of the transducer linearity. Inclusion of an additional coil of mutual induction into the driving circuitry of the two-coil sensor and its influence on the linearity of the transducer characteristic are described in the paper. The improved performance not only allows easier calibration, it also widens the possible applications of magneto-elastic sensors with build-in affordable measuring electronics.

Keywords: susceptibility, magneto-elastic sensors,

1 INTRODUCTION

The main advantage of magnetoelastic sensors of elongation or acting force, in comparison with the classic wire one or semiconductor ones, is their marked sensitivity and higher resistance to environmental moisture. These their properties predestinating them for use in civil engineering and geo-technological applications [1,2]. They are mostly designed to work as unloaded transformer with the open magnetic core. If an amorphous/nanocrystalline magnetic materials with the optimal magnetoelastic parameters are as the transformer core used, the ideal shape of open core is a thin ribbon with width several millimeters. We used as magnetic core of sensor the cobalt-rich amorphous alloy $Fe_2Co_{69}Cr_7Si_8B_{15}$ with relatively low negative magnetostriction [$\lambda_S = -(0.9\div1.1)\mathrm{x}10^{-6}$] to ensure the wide measuring range of sensor. Ribbons 3 and 6 mm wide were prepared by planar flow casting and afterwards continuously stress-annealed in a radiation furnace (1h at temperature 380°C) [3]. By annealing with currently applied stress σ_A one can introduced perpendicular (to the ribbon axis) magnetic anisotropy, with anisotropy field $H_{K\sigma A}$ practically linear dependent on applied stress σ_A. Magnetization reversal then takes place by rotation mainly, that ensures negligible hysteresis and nearly linear magnetization characteristics (Fig. 1). If external stress σ is applied, the effective anisotropy field H_{Keff} is sum of effective fields induced anisotropy, magnetoelastic interaction and shape anisotropy [4]

$$H_{Keff} = H_{K\sigma A} - \frac{3\lambda_S\sigma}{J_S} + \frac{NJ_S}{\mu_0} \tag{1}$$

where N is the demagnetizing coefficient along the ribbon axis. The inverse magnetic susceptibility as function of applied stress σ is given (see Fig. 1.)

$$\chi^{-1}(\sigma) = \left(\frac{J_S}{\mu_0 H_{Keff}}\right)^{-1} = \chi^{-1}(0) - \frac{3\lambda_S}{J_S^2}\sigma \tag{2}$$

For materials with $\lambda_S<0$ if the measured strain σ is positive (tension) the dependence of inverse susceptibility on applied stress is illustrated in Fig. 1b.

The voltage U_2 induced in secondary winding as function of the applied stress σ, when a sinusoidal magnetizing current I_1 in primary winding with angular frequency ω is forced, can be expressed as

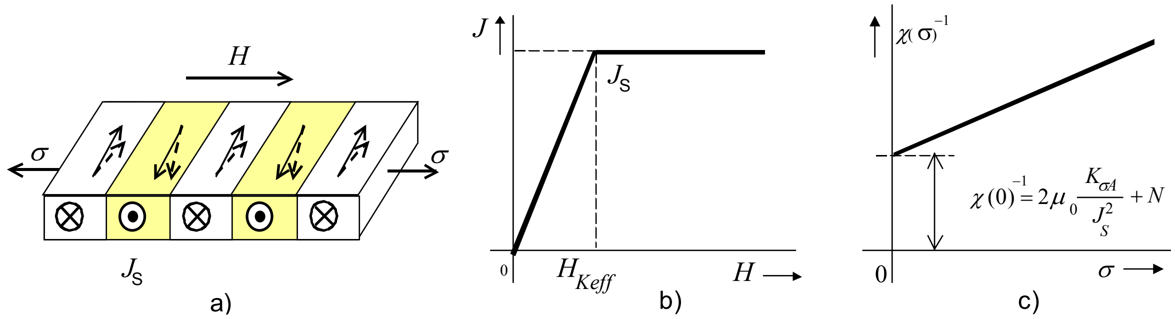

Fig. 1. Stress-annealing induced domain structure a), Ideal anhysteretic *J-H* characteristic b), and $\chi^{-1}(\sigma)$ dependence c)

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ISSN 1335-3632

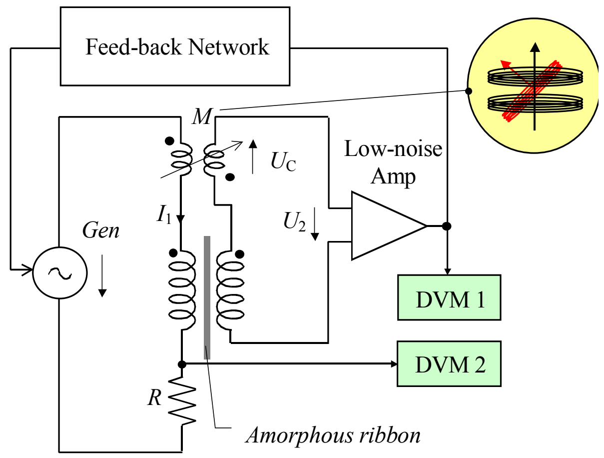


Fig. 2. Block diagram of the set-up with mutual induction

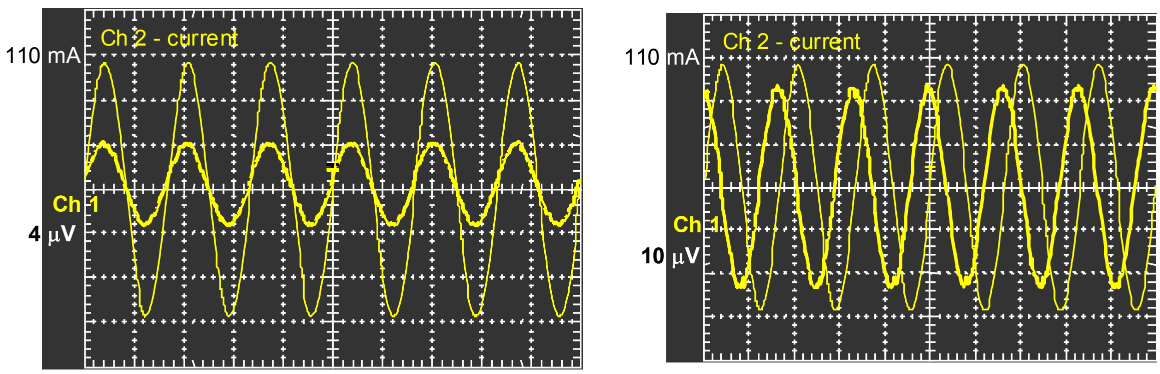
$$U_2 = n_2 k_1 \omega \mu_0 I_1 \left(S_C + \chi(\sigma) S_{Fe}\right) \tag{3}$$

where S_{Fe} is the cross-section of the amorphous magnetic ribbon, n_2 and S_C are secondary winding and the cross-section of the secondary coil, respectively. Constant k_1 takes into account parameters of the magnetizing coil with primary winding n_1 in relation $H(t) = k_1 i_1(t)$. If product $\chi(\sigma).S_{Fe} >> S_C$, and the amplitude of induced voltage U_2 is kept constant, than

$$I_1(\sigma) = \frac{U_2 \chi^{-1}(\sigma)}{\mu_0 n_2 S_{Fe} k_1 \omega} = I_1(0) + A_1 \sigma \tag{4}$$

as follows from equation (2). The amplitude of primary current at $\sigma = 0$ is proportional to $H_{K\sigma A}$ and N whilst A_1 is proportional to the magnetostriction constant λ_S. If the above condition is not met, what is in the case of higher values of applied stress σ when magnetic susceptibility decreases, the equation (4) is not valid and sensor linearity is decreased.

This problem is more critical if 3mm double-coil system is used, because the ratio S_C/S_{Fe} for 3 mm wide flat secondary coil is higher compared to 6 mm one. On the other hand, 3mm wide magnetoelastic sensors have many advantages from application point of view, because narrower sensing element (amorphous ribbon) should be as small as possible providing a negligible own influence on measured object.



a) b)

Fig. 3. Oscilograms of waveforms (*cf* Fig.2) of *secondary voltage* *without a ribbon* U_{20} – Ch1 *and primary current* I_1 – Ch2; a) compensated state (I_1 and U_{20} are in-phase), and b) small perturbance from the compensated state.

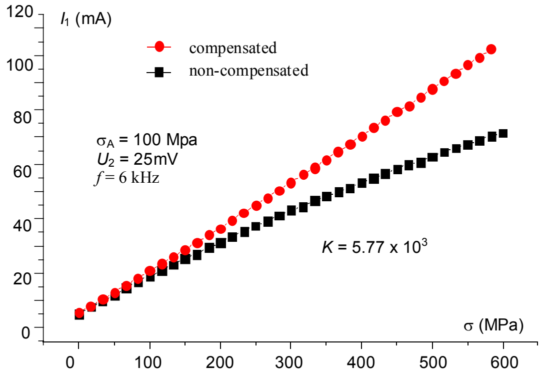
2 EXPERIMENTAL

Elimination of influence of parasitic magnetic flux coupled by sensing secondary winding by software control is too a CPU time consuming [2]. But the problem of secondary coil window filling can be easy successively solved by inclusion of an additional mechanically tunable mutual inductance into the driving circuitry. Afterwards the relation (4) holds again also at elevated strain and effect of "saturation" of the sensor transfer characteristic is overcome.

The two-coil systems were designed for 6 and 3 mm wide amorphous ribbons, continually stress-annealed at tension stresses 100 and 150 MPa, respectively. Both two-coil systems have the same of primary winding $n_1 = 240$ and different secondary winding $n_2 = 120$ or 200 for 6 mm or 3 mm wide ribbon, respectively. If the working amplitude of flux density is approximately 100 mT (limited by influence of DC-disturbing external field [5]) and working frequency is 5 or 6 kHz for 6 mm or 3 mm coil systems, the induced voltage $U_2 = 30$ mV is the same for both two-coil systems. The block diagram of the testing set-up is shown in Fig. 2, where the compensation voltage $U_C = \omega \mu_0 n_2 S_C I_1$ is adjusted to assure the minimal measured voltage U_{20} while the measuring double-coil system is empty. The tuning part of mutual inductance was realized by small turning coil, see inset in Fig.2

The compensated state for 3 mm double coil system is illustrated in Fig. 3a, where small (in-phase with primary current) voltage U_{20} due-to parasitic capacitance of the coil system is shown. The small perturbance from ideal compensation state (turning of the free coil of mutual inductance a few degs) is illustrated in Fig. 3b. Both of oscilograms were taken at the same primary current I_1 = 110 mA, which corresponds to maximum applied tensile stress 600 MPa. Without compensation the voltage U_{20} for 3mm double-coil system at working frequency f = 6 kHz and I_1 = 110 mA is typically more than 10 mV, while the minimum in-phase voltage in compensated state is about of 4 μV.

The transfer characteristics of 3 mm wide magneto-elastic sensors, dependences of primary current on applied tensile stress, with and without compensation by mutual inductance, are illustrated in Fig. 4. We can see in both cases of stress-annealing a small non-linearity of transfer characteristics, when compensation was used. The slope of transfer characteristics changes when applied stress exceeds the value of 300 MPa. We suppose this change of slope is due to small influence of surface domains motion on magnetization process at low stresses.



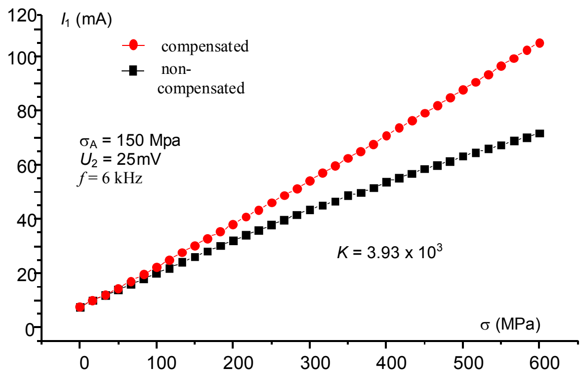


Fig. 4. Transfer characteristics of 3mm wide two-coil magnetoelastic sensors with different stress-annealed amorphous ribbons as cores. The length of the amorphous ribbon was 85 mm.

The efficiency or "quality coefficient" K, generally characterizing the sensor sensitivity to mechanical stress, is define as the relative change of the measured quantity to the strain

$$K = \frac{(\Delta M)_{rel}}{\varepsilon} = \frac{A_1\sigma}{I_1(0)\varepsilon} = \frac{A_1 E}{I_1(0)}$$

where E is Young modulus of magnetic ribbon [2]. After substitution to this relation for case of continuous stress-annealing at 100 MPa, when the value of induced anisotropy field $H_{K\sigma A} \cong 175$ A/m, we receive theoretical value of quality coefficient $K = 6.570\times10^3$, if the influence of demagnetizing field was neglected. The shape anisotropy of the ribbon causes the decrease of this value to $K = 5.155\times10^3$ for length of sensor 85 mm. But the measured value of quality coefficient is higher (K = 5.77×10^3) than the theoretical one. This discrepancy can be explained by non-homogeneity of magnetizing field at a flat and narrow primary coil or invalidity simple relation for magnetoelastic interaction in equation (1), if magnetization process is not pure coherent rotation of magnetization. However, the quality coefficients of the two-coil sensors with 3mm wide ribbon core increase more than 40%, when a compensation of parasitic coupled magnetic flux was used.

4 CONCLUSIONS

Designed magnetoelastic strain sensors an the bases of used amorphous alloy $Co_{69}Fe_2Cr_7Si_8B_{15}$ are suitable for civil engineering and geotechnology in comparison with standard wire gauges have several advantages. Firstly, they have much higher "quality coefficient" K, reaching values more than $5x10^3$, in a deformation range up to 3500 ppm, if compensation mutual inductance is used. This allows using inexpensive devices for a long-term monitoring and one-shot in field measurement. The sensitivity of the sensor, at given composition of the sensor alloy, can be tailored by choosing the stress-annealing in quite a range according to specific demands. Second, significant advantage is the possibility to use them in environment with long-lasting moisture, where the wire gauges fail to operate properly. Utilizing software control, calibration, diagnoses and data acquisition after connecting the measuring system a PC trough RS232/RS485 one obtains an intelligent system for recording the actual mechanical forces and deformations in objects under investigation. Higher linearity of the transfer characteristic of the whole device will remove the present need to adjust (calibrate) each sensor individually and keep the correction curve in controlling computer memory

Acknowledgement

This work was supported partly by Grant VEGA 1/0143/03 and partly by Grant VEGA 1/0142/03.

REFERENCES

[1] J. Bydžovský et al: International Workshop on Advancing Technological Frontiers for Feasibility of Smart Structures, Strasbourg, 2003, 158-162

[2] J. Bydžovský et.al: Sensors and Actuators A Physical, 110, 2004, 82-86

[3] L. Kraus et.al: Sensors and Actuators A Physical, 106, 2003, 117-120

[4] J. Bydžovský et.al: International Workshop on Applied Physics of Condensed Matter, Liptovský Mikuláš, 2002, 159-162

[5] J. Paľa et.al: Journal of Electrical Engineering, 53, 2002, 103-106

Received 28 June 2004

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