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Magnetoelastic resonance sensor for remote strain measurements

Thomas Huber,[1,2,a)] Bernhard Bergmair,[1,2] Christoph Vogler,[1] Florian Bruckner,[1] Gino Hrkac,[2] and Dieter Suess[1]
[1]*Institute of Solid State Physics, Vienna University of Technology, Wiedner Hauptstr. 8-10, 1040 Vienna, Austria*
[2]*Institute of Analysis and Scientific Computing, Vienna University of Technology, Wiedner Hauptstr. 8-10, 1040 Vienna, Austria*

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A low cost passive wireless strain sensor is proposed. The basis of the sensor is formed by two softmagnetic magnetostrictive ribbons. The first magnetostrictive ribbon transforms mechanical stress into a stress dependent magnetic field. The second ribbon senses this field by magnetoacoustic oscillations. The resonance frequency directly depends on the applied mechanical stress. For the proposed sensor, a gauge factor G_f, which is defined as the relative change of the resonance frequency divided by the strain ε, of $G_f = 380$ is obtained. This is significantly higher than the gauge factor of standard metal foil strain gages. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4735340]

Today's most widely used sensors for stress/strain measurements are strain gages, which are for example used in load cells. Strain gages contribute with 97.1% to the total stress/strain measurement equipment market (total market [dollar]3,240.1 million), whereas 2.9% are shared by fibre optics. In order to measure strain/stress, strain gages have to be wired to the electronic control unit. An alternative to strain gage sensor which is based on magnetostrictive materials was proposed by Mitchell *et al.*[1] and Shin *et al.*[2] A magnetostrictive ribbon was bonded to a base material and used as the core material in a coil. The stress was measured by the change of the induction of a coil. The results demonstrated that the sensor does not require sophisticated amplifiers as resistance-type strain gages do.

Remotely interrogated stress sensors based on standard, commercially available magnetoelastic materials were proposed by Wun-Fogle *et al.*[3] and Ong.[4,5] These sensors comprise magnetic layers which have a harmonic spectrum that varies with the applied stress/strain. Upon excitation by a magnetic field impulse, a magneto-elastic material emits an electromagnetic field. By measuring the change in the amplitudes of the higher order harmonics generated by the magnetic element stress can be monitored. The frequency spectrum of these sensors can be detected over a distance of about 15–18 cm. One disadvantage of magneto-elastic sensors on the basis of second harmonics is that the measured stress/strain varies with the relative orientation between sensor and the excitation coils.

Kouzoudis and Grimes proposed a pressure sensor which relies on magnetoacoustic resonators.[6] Pressure is transformed into a displacement of a hard magnetic material which then changes the magnetic bias field, which acts on an additional magneto elastic ribbon (resonator). This resonator is excited by an external field to mechanical oscillations. The resonance frequency is related to the pressure. In contrast to the work of Kouzoudis and Grimes, here we propose a strain sensor with significantly increased accuracy by using a magnetoelastic ribbon instead of permanent magnets to transform mechanical stress into a stress dependent external field.[7]

The proposed sensor consists of 3 main parts (i) the transducer, (ii) the resonator, and (iii) a bias-magnet, which are shown in Figure 1. The magnetoelastic ribbon (transducer) is bonded to the specimen whose stress is measured. A second ribbon (resonator) is positioned next to the transducer. In order to allow free mechanical oscillations of the resonator, it is put into a plastic casing (Figure 1). The magnetic field (and thus the resonance frequency) at the location of the resonator is defined by the stray field of the bias-magnet and by the magnetic properties of the transducer. When the stress state of the transducer changes, in turn its magnetic properties are altered according to the Villari effect.[8] Therefore, the share of the flux between the transducer and the resonator changes. As a consequence, the effective field acting on the resonator becomes a function of the stress applied to the transducer.

For the resonator, a softmagnetic, magnetostrictive ribbon is used, which is placed inside a casing where it allows for free longitudinal mechanical oscillations. The resonance frequency of the oscillation depends on the Young's modulus. The Young's modulus depends on the magnetic field, which acts on the resonator according to the (ΔE effect) given by Livingston as[9]

$$\frac{\Delta E}{E_H} = \frac{E_M - E_H}{E_H} = \frac{9\lambda_s^2 E_M H^2}{J_s H_{A\sigma}{}^3}, \tag{1}$$

where E_M describes the pure elastic Young's modulus at fixed magnetization, λ_s is the magnetostrictive constant, J_s

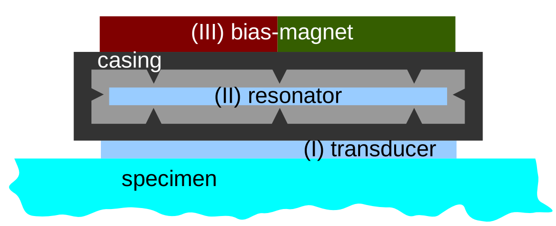

FIG. 1. Main components of the strain sensor.

[a)]E-mail: thuber@ifp.tuwien.ac.at.

TABLE I. Summary of used materials.

Name of sample	Material of sample	J_s [T]	H_A [A/m]	λ_s [ppm]	l [mm]	w [mm]	t [μm]
VC7600F-13	$Fe_{65}Co_{18}Si_1B_{16}$	1.74	260	42	38.0	12.3	22.1
VC7600F-14	$Fe_{65}Co_{18}Si_1B_{16}$	1.74	380	42	37.9	12.3	22.1
MG2705-M	$Co_{69}Fe_4Ni_1Mo_2B_{12}Si_{12}$	0.77	—	<0.5	37.3	12.6	19.3
MG2826-MB3	$Fe_{40}Ni_{40}P_{14}B_6$	0.88	—	12	37.9	6.0	28.7

the magnetic saturation polarization, $H_{A\sigma}$ the stress dependent anisotropy field of the material, and H the external field. According to Eq. (1), a large ΔE effect for materials with a large magnetostriction and a low anisotropy field can be expected.

Mechanical oscillations of the resonator are excited is to by an alternating (AC) external magnetic field. The frequency of the field is similar to the resonant frequency. In order to measure the eigenfrequency of the resonator, the excitation field is switched off and the field emitted by the resonator is detected by a pickup-coil. Due to the weak damping of the resonator, the mechanical oscillations can be still detected about 1 ms after the AC field is switched off. The detected signal is analysed using a Fast Fourier transform, which yields the resonance frequency.

The accuracy of the sensor is limited by the resonator being not only sensitive to the bias field but also to unavowed external magnetic fields (e.g., the earth's magnetic field). Recently, a design to overcome this restriction by using sensors with antisymmetric bias fields was suggested by Bergmair *et al.*[10]

For a suitable transducer material, it is essential that its magnetization strongly depend on its strain state. To select optimal materials, the stress dependent magnetization of different alloys was investigated. Four ribbons consisting of different alloys were glued each on an aluminum-beam. On the other side of the aluminum-beam opposite to the ribbon, a standard strain gage was fixed to measure the stress. The aluminum-beam was bent in both directions to produce either compressive or tensile stress. A hysteresograph was used to measure the magnetization of the transducer. The hysteresograph consists of a field-coil and a compensated concentric pickup system. The pickup system was located within the field-coil. The field-coil is 200 mm long, has a diameter of 40 mm, and about 380 windings in two layers of an insulated copper wire with 0.75 mm^2. For the pick up system, two concentrically winded coils were used. The aluminum-beam was mounted to a bending device.

This experimental setup allowed to measure hysteresis-loops of magnetic ribbons as function of compressive or tensile stress. The hysteresis-loops were measured with a sinusoidal field oscillating with a frequency of 8 Hz and with a peak-value of $\pm$17 mT.

The magnetic properties of the investigated samples are summarized in Table I. There J_s describes the magnetic saturation polarization, H_A the anisotropy field, λ_s the saturation magnetostriction, and the size of the used ribbon is given as length l, width w, and thickness t.

Figure 2 shows the magnetization at a constant field of $H_{bias} = 0.4$ mT as a function of the strain of the sample. The largest change of magnetization as function of stress is obtained for the material VC7600F-13, but material VC7600F-14 shows a more symmetrical curve with respect to the zero strain axis. So, the latter material was identified as optimal transducer material for the proposed sensor.

For the resonator magnetostrictive materials were investigated that show a large change of Young's modulus E as function of field induced stress (ΔE effect). The ΔE effect was investigated experimentally by repeatedly exciting the ribbons with an 58 kHz-signal with an excitation coil while varying the homogeneous bias field. Figure 3 shows the resonance frequency as a function of the bias field for three different samples. Sample MG2705-M is not plotted as it is not a suitable resonator material. Due to its low magnetostriction, there is no possibility to induce mechanical oscillations.

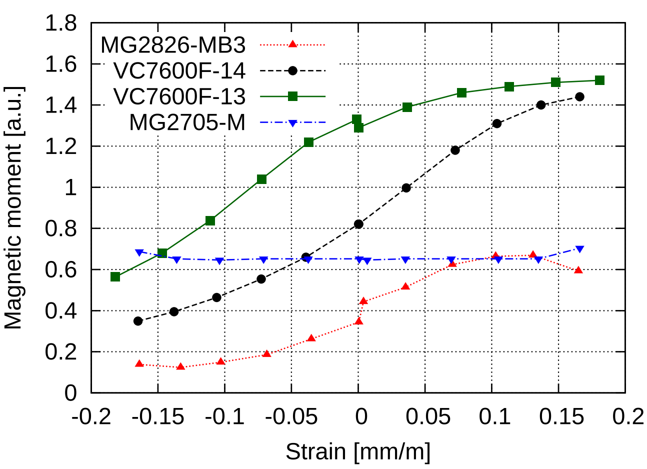

FIG. 2. Magnetization as a function of strain for several materials at $H_{bias} = 0.4$ mT.

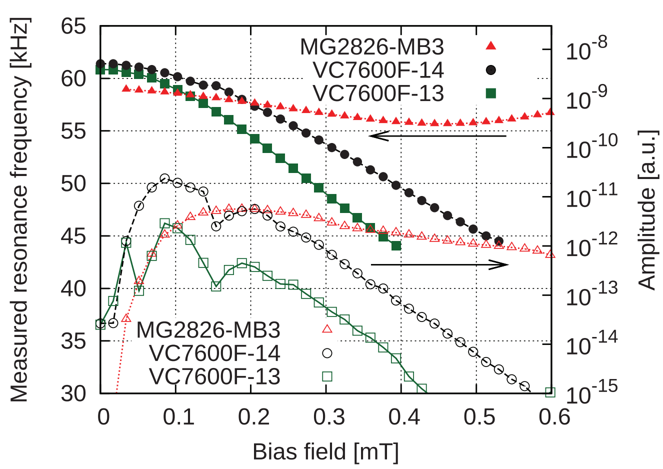

FIG. 3. Resonance frequency as a function of the magnetic bias field for freely oscillation ribbons.

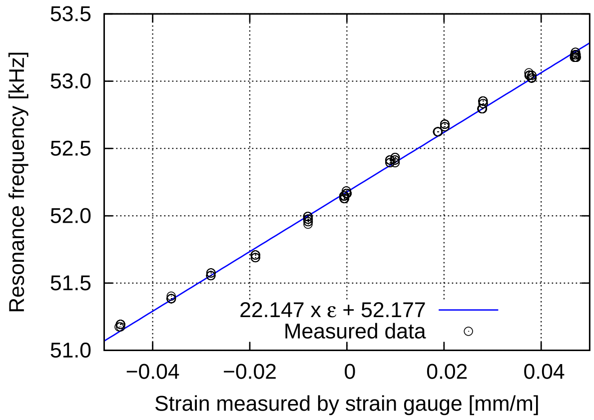

FIG. 4. Measured strain from a distance of 100 mm between sensor and excitation- and pickup-coil.

As expected from Eq. (1), VC7600F-13 shows the largest ΔE effect due to its small anisotropy field and its large magnetostriction. The ΔE effect of VC7600F-14 is almost the same and additionally shows larger signal amplitudes in a wider range of bias fields. Hence, this material was selected for the resonator.

Using the results of the previously presented experiments, the optimum materials for the transducer and resonator could be selected and a fully functional prototype of the strain sensor could be fabricated. For the prototype, the resonator (VC7600F-14) was placed in a plastic casing. The transducer (also VC7600F-14) was glued to an aluminum-beam (600 mm long, 20 mm wide, and 3 mm thick), which was used to realize different stress states. The casing was attached to the beam with the resonator being next to the transducer. In addition, a permanent magnet was fixed next to the resonator to set the operation point. Strain was applied by bending the beam. The strain was measured using a standard strain gage on the opposite site of the beam. The strain at this opposing position has the same absolute value with reversed signs, as the influence of the very thin transducer and strain gage do only marginally influence the stress profile in the aluminum beam. The resonance frequency was measured remotely over a distance of about 100 mm by a ferrite core pickup-coil (diameter of 10 mm and length of 80 mm) and an excitation-coil (diameter approx. 200 mm). The excitation coil is powered by a resonant circuit.

Figure 4 shows the resonance frequency of the sensor as a function of the applied strain. It shows 241 measured points with an almost linear relation between the applied strain and the measured frequency. The transfer-function from strain to resonance frequency is described by the linear fit function

$$f(\varepsilon) = 22147(\pm 82.3)[Hz \times m/mm] \times \varepsilon[mm/m] + 52176.9(\pm 2.2)[Hz]. \quad (2)$$

This is equal to 22 Hz/ppm in a range of ± 50 ppm. The gauge factor G_f can be used to characterise sensors. It is defined as the relative change of the mapping value (i.e., the resonance frequency) divided by the relative change of the measured variable (i.e., the applied strain $\varepsilon = \Delta l/l$).

The gauge factor is thus defined as

$$G_f = (\Delta f/f)/(\varepsilon). \quad (3)$$

Inserting Eq. (3), one obtains a gauge factor G_f of about 380 in the range between ± 50 ppm. The gauge factor of standard metal foil strain gages is typical in a range between 2 and 5.

To conclude, the presented magnetoacoustic strain sensor provides a low cost and easy to use device to measure strain. For the investigated materials, a gauge factor which is 80 to 200 times higher than those of standard strain gages was obtained in the strain range of ± 50 ppm. The sensor can be read out remotely, which is especially advantageous when measuring strain of moving or vibrating parts where wire connections are not feasible. The sensor does not need any source of energy, which makes it suitable for long term structural health monitoring. Due to its low manufacturing costs, an extensive use is affordable.

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[1] E. E. Mitchell, R. DeMoyer and J. Vranish, IEEE Trans. Ind. Electron. **33**, 166171 (1986).
[2] K.-H. Shin, M. Inoue and K.-I. Ari, J. Appl. Phys. **85**, 5465 (1999).
[3] M. Wun-Fogle,H. T. Savage, and A. E. Clark, Sens. Actuators **12**, 323–331 (1987).
[4] K. G. Ong and C. A. Grimes, Sens. Actuators, A **101**, 49–61 (2002).
[5] K. G. Ong, D. M. Grimes, and C. A. Grimes, Appl. Phys. Lett. **80**, 3856 (2002).
[6] D. Kouzoudis and C. A. Grimes, Smart Mater. Struct. **9**, 885–889 (2000).
[7] D. Suess, US patent 2011/0232392 (16 November 2009).
[8] I. Mihalca, A. Ercuta, and C. Ionascu, Sens. Actuators, A **106**, 61–64 (2003).
[9] J. D. Livingston, Phys. Status Solidi A **70**, 591596 (1982).
[10] B. Bergmair, T. Huber, F. Bruckner, C. Vogler, and D. Suess, Sens. Actuators, A **183**, 11–15 (2012).