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MAGNETOSTRICTIVE FORCE AND DISPLACEMENT SENSOR

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Abstract: The present work concerns the application of magnetostrictive soft magnetic amorphous ribbons for the detection of displacements or weak forces. The principle of signal generation is based on permeability changes as a result of mechanical stress acting in band direction. The elastic band is fixed at one end while the second one is displaced or loaded normal to the band axis. For high sensitivity, a bimetal band is used which comprises a non-magnetic carrier ribbon in addition to the magnetic ribbon. The sensitivity can be increased by increased thickness of the carrier ribbon. Further it can be optimized by pre-magnetization and by specifically adjusted measurement frequency. The low-cost, low-mass sensor allows to detect forces down to about 1 mN.

Keywords: magnetic materials, magnetostriction, force sensors, displacement sensors.

1   INTRODUCTION

The present work concerns the application of soft magnetic amorphous ribbons for the detection of displacements or weak forces. The principle of signal generation is based on the well known magneto-mechanical effect, i.e. changes of permeability μ due to mechanical stress. The large variety of amorphous ribbons offers several types (Fe-based and FeNi-based bands) that exhibit strong magnetostriction thus being attractive for magneto-mechanical sensors. The ribbons show favorable elastic properties. Further they show low thickness d_{AR} (typically 30 μm) which favors applications for sensors of small size designed for the detection of low forces.
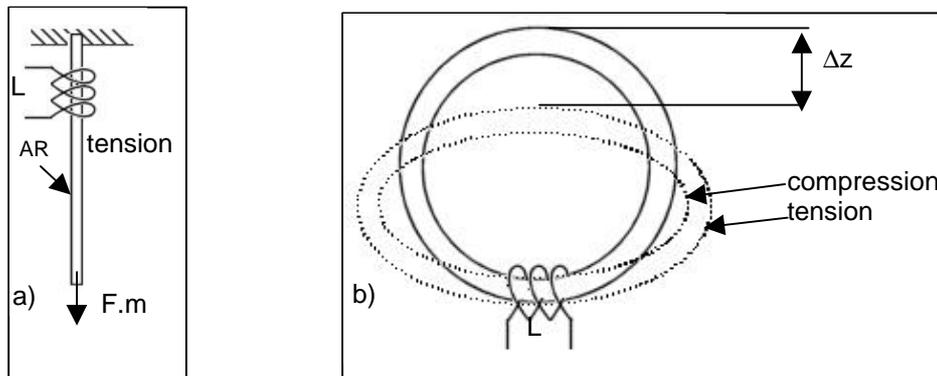

Figure 1. Common amorphous sensor designs, (a) for forces F, (b) for displacements Δz.

During the last 20 years, several types of amorphous sensors have been described in literature. Fig.1 shows two common designs. Fig.1a shows the most simple arrangement for the detection of a force F, or for the corresponding load mass m. A strip of material is used which carries a winding the AC inductance L of which increases with increasing axial stress s due to increasing permeability μ.

A rough estimation of the sensitivity can be based on the condition that the amorphous ribbon should show a minimum width w of some millimeters due to the fact that magnetostrictive bands tend to exhibit very wide magnetic domains. Assuming $w_{min} = 3$ mm and assuming that distinct changes of μ arise at stress levels σ_{min} close to 1 MPa, we find a resolution according to a minimum force of the order

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$$F_{min} = w_{min} \cdot d_{AR} \cdot s_{min} = 3mm \cdot 30 \ \mu m \cdot 1 \ MPa \ \approx \ 0{,}1 \ N \ . \tag{1}$$

For the corresponding resolution with respect to the mass we find the order of magnitude

$$m_{min} = F_{min} / g \ \approx \ 10 \ g \ . \tag{2}$$

Due to the material´s high elasticity modulus E, the strip sensor cannot be used as a displacement sensor.

Fig.1b shows an effective displacement sensor which consists of a ring of amorphous material. Vertical compression of the ring corresponding to a displacement Δz yields changes of local bending curvatures. There result changed volume ratios of ring regions which are under tensile stress or compression, respectively. Finally, this yields a change of the AC inductance L of a winding which can be arranged in different regions of the ring. As closer described in [1], rings of 10 mm diameter yield a resolution well below 1 mm, the corresponding force F being of the order 0.1 N for $\Delta z = 1$ mm. A possible application is given in the field of keyboards.

This paper presents an alternative sensor version. It is based on the consideration that the sensitivity of ring sensors is restricted due to the fact that all band regions are subject of both tension and compression, i.e., effects on the permeability are partly balanced. The novel idea is to improve the sensitivity through a bimetal arrangement which transfers bending into pure compression (or tension). Short descriptions have already been given in [2,3].

2   METHOD

The basic principle of the novel sensor is illustrated by Fig.2. A bimetal is used which comprises an amorphous ribbon (AR) of type VAC4040, the thickness d_{AR} being close to 30µm. The second component is given by a non-ferromagnetic Al-carrier ribbon (CR) of thickness d_{CR}. One end of this sandwich – which carries a winding - is fixed. The second end can be displaced by a defined distance Δz or through a defined force F. Alternatively it can be loaded by a mass m. After calibration, this arrangement yields a very simple sensor for these three quantities.
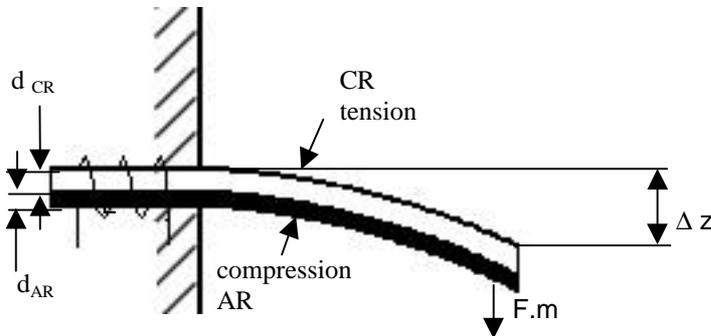

Figure 2. Schematic outline of the bimetal sensor.

As a specific advantage, the sensitivity can simply be adjusted to the given task by adjustment of the thickness ratio

$$r_d = d_{CR} / d_{AR} \qquad , \tag{3}$$

which represents a key quantity of the sensor. Lowest sensitivity is given for $r_d = 0$, i.e. a pure AR, due to the fact that the neutral area ($\sigma = 0$) falls into the center of the AR. Thus its upper half shows tension while the lower one shows compression (equivalent to the case of ring sensors). Still, restricted sensitivity results from the fact that the decrease of μ due to compression tends to be more pronounced than the increase of μ due to tension (see Fig.3).
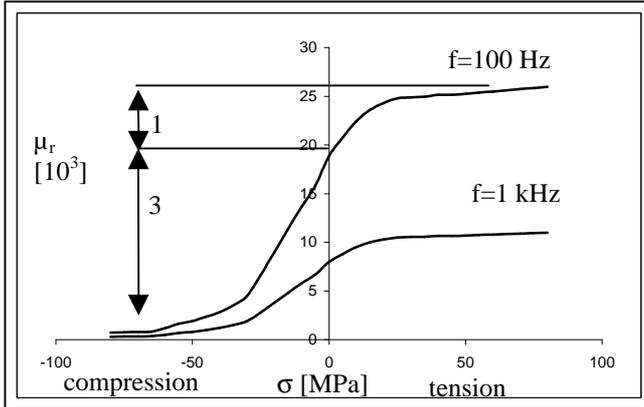
Fig. 3. Typical changes of permeability μ as a function of stress σ (after [2].

Increasing the ratio r_d means that the neutral area is gradually shifted upwards. Assuming $E_{CR}= E_{AR}$, it falls into the contact area between AR and CR which means that the whole AR volume is compressed while the whole CR volume is under tension. For a given displacement Δz, the compression level in AR – and thus the drop of μ - can be increased even more from $r_d > 1$. Theoretically, no limit is given. However, the stiffness of the sandwich increases as well, and thus also the force which has to be provided in order to attain the given displacement Δz. As a compromise, we use r_d close to 3 (d_{CR} close to 100 µm) for most sensor prototypes.

3   SENSOR OPTIMIZATION

According to the above, the basic adjustment of sensitivity is attained by an optimum thickness ratio r_d. Further procedures of optimization concern the establishment of a reliable electric sensor signal u which should be maximum for a given change of μ.   The corresponding electrical impedance measurement circuit has been described in detail in [3]. The following considerations and results concern sandwiches of 7 mm width and 70 mm length with $r_d \approx 3$. In this case, we use a 15 mm long winding of about 300 turns ($R \approx 20\ \Omega$, $L \approx 1$ mH). The coil signal is demodulated by a diode and integrated by a capacitor.
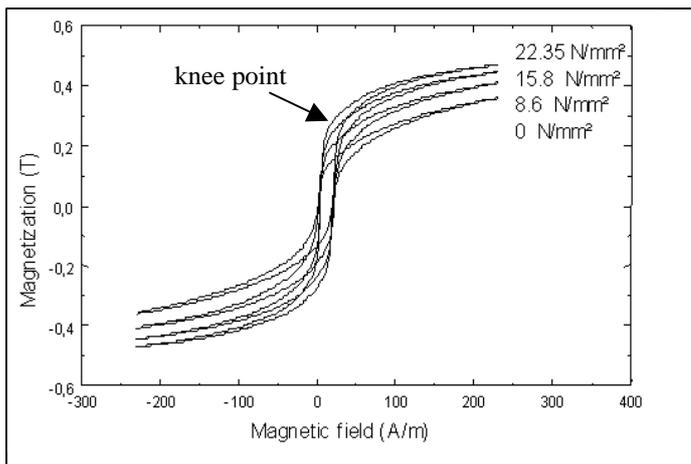

Figure 4. Hysteresis loops for the here applied AR type for different values of tensile stress.

In order to establish a strong signal, the sensor´s operation point should be adjusted according to a compromise between maximum differential permeability and maximum stress sensitivity. The corresponding interdependencies are illustrated by the hysteresis loops in Fig.4 which were established by means of the so-called SAMR method (small angle magnetization rotation). The optimum was adjusted by means of an offset current corresponding to pre-magnetization. An example for an optimization

procedure is given in Fig.5, a case where the highest voltage win Δu resulted for 45 A/m (corresponding to a DC current of about 3 mA). However, experience showed that it is advantageous to choose somewhat higher pre-magnetization levels in order to reduce artifacts caused by the geomagnetic field.

A further quantity which should be optimized is the measurement frequency f. Fig.6 shows a typical result of f-scanning (usually performed between 10 and 25kHz) which indicates maximum sensitivity for frequency values between 15 and 17 kHz.
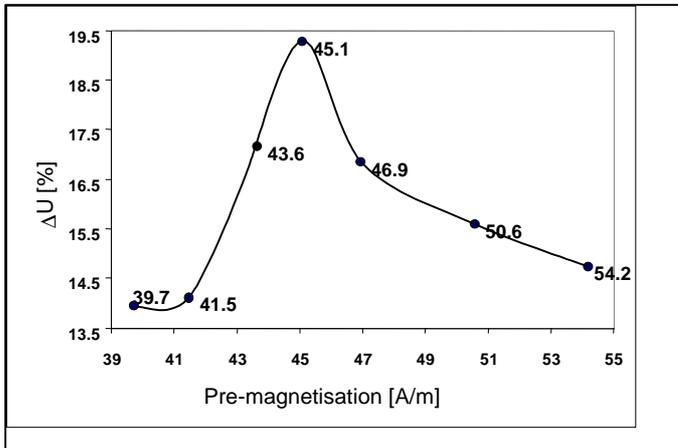

Figure 5. Data as used for sensor optimization:
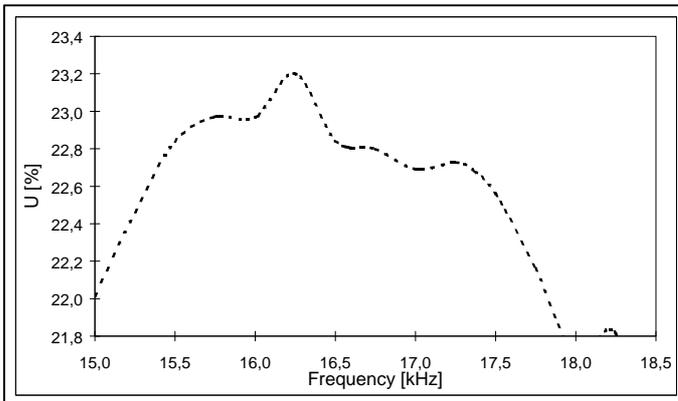Win of sensor signal amplitude as a function of pre-magnetization.

Figure 6. Data as used for sensor optimization:
Signal win as a function of measurement frequency.

4   RESULTS

Fig.7 shows typical results for the performance of a sensor prototype for the registration of forces F. The graph illustrates that the bimetal principle can be utilized to attain very high sensitivity. F = 10 mN yields as much as 20% shift of voltage. This indicates a sensitivity close to 1 mN, corresponding to a mass detection threshold close to $m \approx 0.1$ g. The zero region exhibits distinct non-linearity which, however, was caused by insufficiencies of the load system in the present case. On the other hand, pronounced non-linearity of the sensor arises for high intensities, i.e. for F exceeding 20 mN. In cases where even higher forces are to be registered, a bimetal of lower thickness ratio r_d has to be applied (e.g., $r_d = 1$). As an alternative, software correction can be used in the range of moderate non-linearity.

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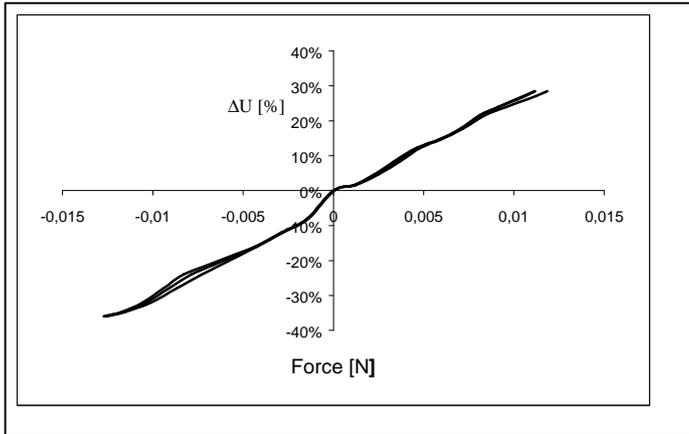Vienna, AUSTRIA, 2000, September 25-28

Figure 7. Typical results of measurement for a 70 mm long bimetal with $r_d \approx 3$. The percentage voltage shift is given as a function of force F of both signs (three times applied).

Fig.8 shows the performance of the above mentioned sensor prototype for the registration of displacements Δz. The figure indicates approximate over-all linearity up to displacement levels of about 5 mm. Regional non-linearity and restricted reproducibility can be attributed mainly to the deflection system also here. Additional studies concerned the dynamic behavior of the sensor. For a displacement amplitude $\Delta z = 1$ mm, adequate resolution was attained for sinusoidal excitations up to about 100Hz. At higher frequencies, the inert mass of the sensor – but also the vibration exciter - started to cause considerable signal distortions.
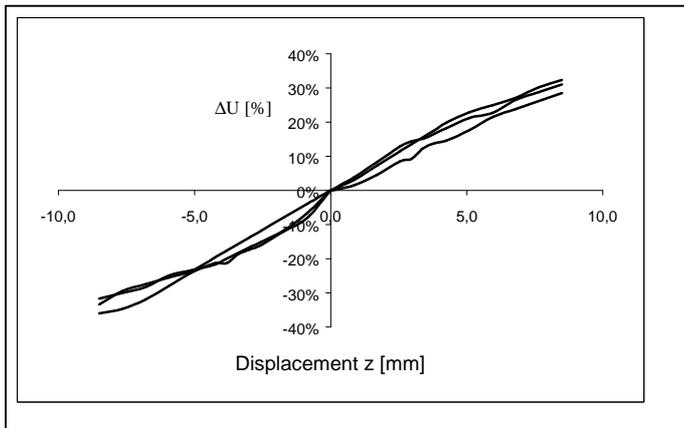

Figure 8. Typical results for the registration of deflections Δz (3 courses).

Summing up, we conclude that the novel sensor type offers effective applications especially in those fields where simplicity, low mass and cheapness are of higher relevance than precision. Especially, the prototypes indicate the following advantages:
(1) The sensors can be simply used for different quantities including the registration of displacements and very low forces (or masses).
(2) The sensitivity can easily be adjusted by the thickness ratio r_d as well as by the width and the length of the bimetal.
(3) The low sensor mass allows for dynamic measurements.
(4) The sensor components are extremely cheap thus being attractive for mass production.

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