Removal of earth's magnetic field effect on magnetoelastic resonance sensors by an antisymmetric bias field

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A B S T R A C T

Magnetoelastic sensors are used in a wide field of wireless sensing applications. The sensing element is a low-cost magnetostrictive ribbon whose resonant frequency depends on the measured quantity. The accuracy of magnetoelastic sensors is limited by the fact that the resonant frequency is also affected by the earth’s magnetic field. In this paper we present a technique to minimize this effect by applying an antisymmetric magnetic bias field to the ribbon. The ribbon’s response to external perturbation fields was measured and compared to a conventional sensor design. Our results show that the influence of the earth’s magnetic field could be reduced by 77%.

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1. Introduction

The principle of magnetoelastic resonance sensors is long known and in its simplest form used millionfold in electronic article surveillance (EAS) [1]. In recent years there has been an increasing interest in magnetoelastic sensors, as they provide an opportunity to remotely monitor a variety of quantities [2,3]. The sensors are passive and material costs are so low that it is possible to use them on a disposable basis. They are applicable for measuring temperature [4], pressure and mass [5], fluid flow velocity and density [6–8], humidity [9,10], pH [11,12], concentration of ammonia [13], glucose [14], carbon dioxide [15], \textit{Escherichia coli} [16], etc.

The basic sensing element of magnetoelastic resonance sensors is a low-cost amorphous ferromagnetic ribbon. As a consequence of the magnetoelastic effect mechanical vibrations of the ribbon can be generated remotely by applying a time varying magnetic field. After turning off this excitation field the ribbon mechanically oscillates at its resonant frequency. It thereby produces a time varying magnetic moment (inverse magnetoelastic or Villari effect), which can be detected remotely again.

The ribbon’s resonant frequency depends on its Young’s modulus which in turn depends on the ribbon’s pre-magnetization, due to the $\Delta E$-effect [17,18]. The pre-magnetization also determines the sensor’s signal strength [19] and the resonant frequency’s temperature dependence [20] and thus constitutes the ribbon’s operating point. The pre-magnetization is obtained by a constant magnetic field (bias field). The bias field can be generated by a coil or the stray field of an adjacent permanent magnet which can be included in the housing of the sensor. The bias field is commonly homogeneous or at least its longitudinal component is of constant sign along the ribbon’s long axis.

Depending on the specific sensing application magnetoelastic resonance sensors are designed to transduce a change of the measured quantity to a change of the resonant frequency with respect to the set operating point. Unfortunately this operating point is shifted by external magnetic fields like the earth’s magnetic field. In general it could not be distinguished if changes of the resonant frequency are due to such perturbations or due to changes of the measured quantity indeed. This significantly reduces the accuracy and reliability of magnetoelastic sensors.

To eliminate this influence of external fields on the resonant frequency in first order one can choose the operating point to be at an extremum of the $\Delta E$–$H$-curve [9], but thereby compromising signal strength and temperature dependence. Another way is to use ribbons with higher anisotropy fields and/or higher demagnetizing factors which need large bias fields and thus reduce the relative influence of external field perturbations. The first concept is not practicable when it comes to sensor designs where the measured quantities are transformed to changes in the ribbon’s effective bias field [21–23], because in those cases the resonant frequency has
to be sensitive to changes of the $H$-field. Application of the second concept makes it difficult to cause the ribbon to vibrate by means of an external AC field.

Some other efforts to solve the problem have been made recently by Ong et al. [24]. When analyzing non-linearities of the ribbon’s permeability one could estimate and therefore consider ambient conditions like temperature and external magnetic DC fields. This technique yields large error reductions but restricts the possibility to read out the sensor remotely, as it requires to generate a controllable and well defined magnetic DC field at least of the magnitude of the perturbing magnetic field (i.e. earth’s field) at the ribbon’s position.

Besides this a method for increasing the accuracy of magnetoelastic resonance mass sensors has been developed when mass changing is not uniformly distributed along the ribbon. The method considers the frequency of the second harmonic resonance mode, thereby overcoming the lack of sensitivity of the first harmonic frequency against certain types of mass changes [25].

This article presents a method of minimizing the effect of external magnetic fields on magnetoelastic sensors which is also based on measuring a higher resonance mode. The technique only marginally restricts the possibility to optimize the sensor characteristics by means of pre-magnetization.

2. Underlying principle

The perturbing influence of the longitudinal (parallel to the $x$-axis, see Fig. 1) external field component on the ribbon is predominant over the influence of the perpendicular components, due to following reasons: First, due to the ribbon’s geometry its longitudinal demagnetizing factor is much smaller than those of the other directions. Second, the ribbon’s magnetic easy axis is perpendicular to the long axis. The perpendicular magnetization components of neighboring domains are thus antiparallel [1]. Therefore, effects of the external field component parallel to the easy axis are of opposite sign for neighboring domains and do not influence the macroscopic average of the Young’s modulus in first order.

The suggested technique is based on a related principle and is able to eliminate also the influence of the longitudinal component of an external $H$-field on the resonant frequency in first order. The profile of the sensor’s bias field along the ribbon’s long axis ($x$-axis) was designed completely antisymmetric with respect to its central cross section:

$$H_x(-x) = -H_x(x).$$

We used a field which is basically constant negative for negative $x$-values and constant positive for positive $x$-values.

As the mechanical properties of the ribbon depend only on the absolute value of the magnetization, the profile of the Young’s modulus of an antisymmetrically biased ribbon is symmetric. An longitudinal external field would now decrease the absolute value of the effective bias field in one half of the ribbon (e.g. for $x<0$) and increase it in the other half (e.g. $x>0$), independent of the sign of this external field. Thus, also the Young’s modulus will increase in one half and simultaneously decrease in the other half of the ribbon. Effects on the ribbon’s resonant frequency due to these deviations of the Young’s modulus on both sides cancel each other out in first order.

The described antisymmetric nature of the bias field also affects the excited oscillation modes of the ribbon. In most cases the external magnetic AC field, by which the ribbon’s vibrations are excited, is predominantly homogeneous. The field vector of the homogeneous AC field adds to the vector of the antisymmetric bias field. This yields a time varying change in magnetization which is symmetric for small AC fields. Therefore the magnetic AC signals of both halves of the ribbon interfere constructively. The absolute value of the total magnetization (= pre-magnetization + AC change in magnetization) on the other hand increases in one half of the ribbon and decreases in the other half simultaneously. Due to the magnetoelastic effect this yields tensile stress in one half and compressive stress in the other half of the ribbon. Therefore antisymmetric mechanical oscillation modes are excited, whereof only the second harmonic was considered.

3. Experimental

To test the effectiveness of the proposed compensation the experiment setup shown in Fig. 1 was used to compare an antisymmetrically biased ribbon to a conventional symmetrically biased one. The ribbon geometry was adopted from those of acoustomagnetic EAS tags. EAS tags use ribbons with a typical length of 40 mm and can be read out from a distance of about one meter therewith. With decreasing ribbon length the signal strength will decrease quadratically due to increased damping and decreased volume [1].

Setup for antisymmetric biasing: To set the operation point the ribbon (dimensions $76.6 \text{ mm} \times 12.1 \text{ mm} \times 22 \mu\text{m}$) is magnetically biased by the antisymmetric field of the ‘as-coil’. Therefore the ribbon has to be precisely ($\pm 0.5 \text{ mm}$) positioned in the middle of the as-coil. This was done by searching for the position where the ribbon’s signal is at its maximum. Homogeneous perturbation fields are generated by the ‘h-coil’. The field profiles of both coils are shown in Fig. 2. From the profile of the as-coil one can also estimate the influence of the actual position of the ribbon along the coil axis on the resonant frequency: The transition from the negative to the positive section of the bias field in the center of the as-coil shows a slope of approximately $35 \text{ A/m} \text{ per mm}$ at a typically used coil current of $0.2 \text{ A}$. Thus for the affected middle section of the ribbon a displacement of $\pm 1.3 \text{ mm}$ would have the same effect as a $180^\circ$ rotation in the earth’s magnetic field with a field.

Fig. 1. Schematic of experiment setup.

Fig. 2. Axial magnetic field of h-coil and as-coil at a coil current of 1 A.
strength of ±44 A/m. The resonant frequency of the second harmonic was measured while varying the strength of both the bias and the perturbation field independently.

Setup for symmetric biasing: the ribbon (dimensions 38.4 mm × 12.1 mm × 22 µm) is biased homogeneously by the ‘h-coil’ to set the operation point. As external field perturbations are likewise homogeneous they lead only to a constant offset in the bias field. The dependency of the first harmonic frequency on the strength of the homogeneous field was measured. The as-coil was disconnected to avoid any interferences.

Both ribbons are cut from a FeCo-based melt-spun amorphous alloy, provided by G. Herzer from VACUUMSCHMELZE, with following properties: easy-axis transverse to long axis, anisotropy field: 380 A/m, saturation magnetization: 1.74 T, saturation magnetostriction: 42 ppm, mass density: 7.5 g/cm³. The double length of the antisymmetrically biased ribbon was chosen for better comparability of the resonant frequencies as the second harmonic is excited in this case. In both cases the ribbon’s vibrations could therefore be excited by an 65 kHz magnetic AC field of the ‘ac-coil’. This frequency lies slightly above the first harmonic of the short ribbon and slightly above the second harmonic of the ribbon with double length. After sending the AC signals the ribbon vibrates for about 1 ms in its self-oscillation modes, thereby inducing a response signal in the ‘pickup-coil’. A fast Fourier transform was performed on the signal. The resonant frequency was defined as the position of the spectral peak maximum, the signal amplitude as the height of this maximum.

To avoid perturbations due to the ‘real’ earth’s magnetic field the coils and the ribbon were placed inside a MuMetal-box, which shields magnetic fields.

In a second experiment setup (Fig. 6) the usability of the concept for the aimed application of remote monitoring was tested. Therefore the as-coil was replaced by two antiparallel permanent magnets adjacent to the longer ribbon (length: 76.6 mm). They, too, produce an antisymmetric bias field of similar although not equal shape compared to the field of the as-coil. This kind of bias field cannot be varied but constitutes a fixed operating point of the ribbon. Additionally homogeneous field perturbations were imposed by the h-coil. Their influence on the ribbon’s resonant frequency was measured. The permanent magnets (dimensions 43 mm × 13 mm × 1.1 mm) are taken from EAS hard tags of SENSORMATIC. The ribbon was positioned 14 mm above the permanent magnets.

4. Results and discussion

Fig. 3 (left) shows the behaviour of the antisymmetrically biased ribbon when varying both the strength of the bias field (i.e. operating point) and the homogeneous field (i.e. perturbation). The area which is relevant for perturbations due to the earth’s magnetic field is indicated by the white boxes and will be depicted in more detail in Fig. 5. One can learn from the figure that the resonant frequency is both symmetric with respect to the direction of the applied homogeneous perturbation field and that it is continuous. The elimination of the influence of small homogeneous fields in first order is the consequence thereof.

The following results demonstrate this for the specific problem of frequency shifts due to the earth’s magnetic field, which is of the magnitude 44 A/m, corresponding to 0.02 A in the h-coil. The resonant frequency of both a conventional (symmetrically) and the suggested antisymmetrically biased ribbon have been analyzed for varying operating points with and without additional homogeneous fields of 44 A/m.

The results for the conventional symmetric sensor design are shown in Fig. 4. As a consequence of the ΔE-effect the resonant frequency depends on the homogeneous bias field. The earth’s magnetic field changes the effective bias field by ±44 A/m when being parallel or antiparallel to the ribbon’s long axis, thus, varying the
resonant frequency within a range of 3.0 kHz. The maximum shift appears in the steepest part of the $f$-$H$-curve, which would otherwise be the optimal operating point for many sensor applications for already mentioned reasons (low temperature drift, maximal sensitivity).

The results for the antisymmetric sensor design are shown in Fig. 5. Due to the earth’s magnetic field the resonant frequency varies within a range of 0.7 kHz. The shift is even much smaller in the vicinity of the optimal operating point.

The proposed compensation technique reduces the maximum influence of the earth’s magnetic field by 77%. Additionally also the measured signal strength of the antisymmetric sensor is larger and less affected by the field perturbations compared to the conventional sensor design. Parts of this increase in signal strength can be explained by the double size of the antisymmetrically biased ribbon and other geometry aspects. But our results show that due to the special profile of the antisymmetric bias field the directly excited second harmonic oscillation is of at least similar strength as the first harmonic oscillation of the symmetrically biased ribbon. At least when assuming ideal conditions this is not surprising. Both halves of the antisymmetrically biased ribbon perform more or less an oscillation which is equal to a free first harmonic oscillation of a ribbon with half the size.

Together with the second harmonic also the first harmonic of the antisymmetrically biased ribbon is always co-excited (not plotted). Both harmonics have similar amplitudes, in contrast to symmetrically biased ribbons, where the higher harmonics usually have much smaller amplitudes than the fundamental. Thus an antisymmetric bias field is very beneficial for the mentioned method of nonuniform mass detection using higher harmonics [25].

As already described above the antisymmetric bias field can also be created by two opposing collinear permanent magnets positioned in parallel with the magnetoelastic ribbon. Fig. 7 shows the influence of external homogeneous field perturbations on the resonant frequency of a thus biased ribbon. One can clearly see the symmetry of this effect with respect to the sign of the external field. For the actual operating point, field perturbations of the strength of the earth’s magnetic field (±44 A/m) yield frequency fluctuations in a range of 0.29 kHz. These fluctuations are by a factor of ten smaller than the maximum deviation in the uncompensated design. The reason why the symmetry center of the figure is shifted to approximately −0.02 A is most probably an offset in the control of the bias-coil and not due to deviations in the strength of the permanent magnets as we conclude from reference measurements. If this would be taken into account the frequency deviations would even shrink to 0.09 kHz.

5. Conclusion

Thus, we conclude that the presented compensation technique brings forth outstanding reductions of the disturbing influence of the earth’s magnetic field. This allows for sensor applications with high accuracy. Assuming a sensor design for the presented ribbon material where the full measurement range of the measured quantity is transduced to a resonant frequency change of 10 kHz the noise due to the sensors orientation in the earth’s magnetic field would shrink down to 1% of this measurement range.

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