Sensors of Mechanical Stresses and Deformations Based on Magnetic Phenomena

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***Abstract*—An overview of various sensors for mechanical stresses (or deformations) is provided within scope of the magnetic phenomena. The paper considers the latest achievements in the design of such sensors for the needs of smart digital devices in the area of Industrial Internet of Things applications. We specifically study the sensors based on single-domain wires, magneto-optical Kerr effect, and propagation of spin-polarized electrons.**

I. Introduction

The purpose of this overview is to present typical designs of sensors of mechanical stresses or deformations based on magnetic phenomena and the main achievements in the field of engineering of such sensors. This overview aims at further applying magnetic sensors in smart digital devices for Industrial Internet of Things (IIoT) [1]. In particular, an IIoT monitoring system would benefit from real-time measurements on deformation state of the observed construction [2].

One should note that, in contrast to the case of reviewing of methods used for solving some problem, when it is possible to compare how well different methods can solve this problem, in the case of reviewing of applications of some methods, the tasks to which these methods are applied can be so different that comparing these methods is meaningless. For example, typically for strain gauges key demands are the ability to detect small strains and high accuracy, but sometimes key demand can be another. For example, for sensors based on magnetic wires, valuable feature is the possibility of non-contact measurement, and for sensors based on the magneto-optical Kerr effect, key features are the possibility of non-contact measurement, and the possibility to observe a signal from a very small area.

In the branch standards ([3, 4]), for characterization of strain gauges, the notions of maximum capacity are introduced, sensitivity of a measuring system, and accuracy class. The analysis of these notions, however, shows that maximum capacity can be improved by adding springs, sensitivities of a measuring system for different types of sensors have different dimensions and are not comparable, and the accuracy class can be determined by an external ADC. Practically more important are the sensitivity threshold (the minimal value of mechanical stress or relative strain which can be confidently detected with the sensor.) and the accuracy of measuring of strains (or loads). To describe the accuracy of the measurements with the use of strain gauges, the following quantities are introduced in [3], [4]: hysteresis, creep, repeatability, durability; the influence of extraneous factors (extraneous magnetic field, etc.) is introduced separately; for accuracy in the usual sense (the width of the interval around the measurement result into which the true value is likely to fall), in [3] the term "expanded uncertainty" is used. Therefore, when describing specific strain gauges, it is desirable to have their sensitivity threshold and expanded uncertainty values. Unfortunately, in fact the authors do not provide such data, and only sometimes these data can be estimated from the figures.

In this connection, we do not try to evaluate, for example, the sensitivity thresholds for all described sensors, but reproduce the characteristics which the developers themselves characterize as essential.

The rest of the paper is organized as follows. Section II describes the used below classification of the magnetic strain gauges. Section III describes main principles of functioning and design of such gauges. Section IV briefly summarizes the possibilities thereof. Section V summarizes the key achievements of this overview.

II. Proposed Classification of the Sensors Under Consideration

When considering sensors of mechanical stresses (or deformations) based on magnetic phenomena, several cases can be distinguished.

The simplest cases are when magnetism plays only an auxiliary role and is not directly related to deformation (e.g., the effects of the magnetic field of a moving magnet are used).

If the signal is formed precisely due to the coupling of magnetic and elastic phenomena, then it is possible to distinguish cases when only magnetoelastic phenomena are used, and when there are used phenomena associated with magnetoelastic ones only indirectly (e.g. magnetooptical).

And, finally, one should consider separately the case when propagation of spin-polarized electrons is used.

Below we select the cases for which there exist described in the literature examples of implementation of sensors of mechanical stresses (or displacements) with the use of magnetic phenomena.

1. Magnetism plays only an auxiliary role, or only trivial magnetic effects are used.

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1.1. Changes in device characteristics during mechanical movement of a magnetic sample (e.g., core of a coil).

1.2. Changes in characteristics of the device when bringing the magnet closer (e.g., due to magnetization of the core of the coil).

1.3. Changes in the parameters of LC circuits; magnetic field pulse is used only for their excitation.

2. Magnetoelastic phenomena are used.

2.1. Changes in the parameters of the hysteresis loop.

2.2. As a special case of a change in the parameters of the hysteresis loop - the change of the critical field which causes giant Barkhausen jumps in single-domain wires.

2.3. Changes in the characteristics of magnetoelastic resonators.

2.4. The appearance of EMF as a result of violation of the compensation of signals from several coils.

2.5. The appearance of EMF or other effects due to the connection of magnetization and twisting.

2.6. The appearance of the second harmonic signal due to the geometry of the system (small-angle magnetization rotation).

3. Other effects associated with magnetic phenomena are used.

3.1. Changes in the optical characteristics of a sample during magnetization (magneto-optical Kerr effect).

3.2. Changes in the characteristics of wires in a matrix or their ensemble in the radio-frequency or microwave region.

4. Tunneling of spin-polarized electrons.

4.1. Influence of mechanical stresses in the scheme of observation of giant magneto-impedance.

III. Review of the sensors

Now let us proceed to considering the examples of the implementation of sensors of the above mentioned types.

A. Magnetism plays only an auxiliary role

1) Changes in device characteristics during mechanical movement of a magnetic sample: In [5], the simplest design of a displacement or deformation sensor is described, which uses a change in the inductance of a coil when moving its magnetic core. The use of this design to determine mutual movements of various objects is patented, including movements of individual sections of deformable bodies.

2) Changes in characteristics of the device when bringing the magnet closer: The reviews [6] and [7] describe a displacement sensor based on bringing a magnet close to the core of the coil. In this case, there is used the fact that bringing the magnet close to the core changes the effective permeability of the core for a small signal. It is noted that usually two coils are used to linearize the signal with respect to displacement.

The construction described in [8] belongs to the same type – here the authors used the possibility to estimate the distance to the magnet with the use of the giant magnetoresistance effect.

3) Changes in the parameters of LC circuits; magnetic field pulse is used only for their excitation: This type of sensors includes strain gauge patented in [9] based on monitoring the frequency of the oscillatory circuit, in which the inductance and capacitance depend on strain. The inductance and capacitance themselves can be realized in the form of films on piezoelectric, magnetostrictive, or purely dielectric materials, and the resonant frequency is determined by non-contact excitation of the coil of the specified circuit by magnetic field.

B. Magnetoelastic phenomena are used

1) Changes in the parameters of the hysteresis loop: Some issues related to the design of sensors based on magnetoelastic phenomena were considered as early as in [10]. A consistent theory of such sensors is discussed in [11] and in [12].

The theory of sensors based on magnetoelastic phenomena is also the subject of [7]. Among other things, in this work, the authors consider the gauge factor of such sensors (i.e., the ratio of the relative change in the sensor signal to the relative change in the measured value). In the specific case, when the change in the magnetic permeability μ caused by deformation is measured, it is expressed through the characteristics of the sensor material as follows:

$$F = \frac{(\Delta\mu/\mu_0)}{\Delta\varepsilon} = \frac{3\lambda_S Y}{2K}, \quad (1)$$

where $\Delta\varepsilon$ is the relative deformation, λ_s is the saturation magnetostriction, Y is Young modulus, and K is the anisotropy parameter (with dimension of energy density). It is noted that for metal glasses it reaches 10^5, which provides three orders of magnitude higher sensitivity to mechanical stresses than in the case of semiconductors, and that, therefore, metal glasses as a material for strain sensors are much superior to all other known materials.

In [6], typical sensor circuits of the indicated type are given. In the simplest scheme of this type, one directly measures the mechanical force (see Fig. 1 (a)), or one transforms the displacement of the object into mechanical force.

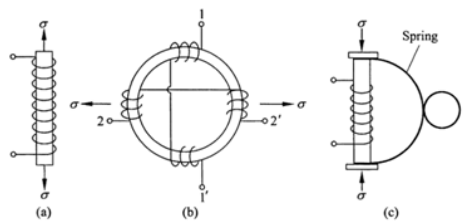

Fig. 1. (a) and (b) are two typical schemes for mounting ribbons as tensile sensors; (c) - design of the compressive force sensor with pre-tensioning spring [6]

A more complex bridge-like design, shown in Fig. 1 (b), eliminates the influence of zero drift of the sensor.

When using ferromagnetic ribbon as a sensing element, if it is necessary to measure the compressive force, the scheme shown in Fig. 1, (c); it is also presented in [7].

A sensor of this type is patented in [13]. To fabricate the sensor, several layers are deposited: the central layer is a strip of amorphous metal with negative magnetostriction (the example reported by the authors is 85% Co, 10% Zr, 5% Fe by mass), on which grooves are applied in the direction of the CO_2 laser beam to create anisotropy perpendicular to the axis of elongation of the strip; around it are insulator layers; further - the layers formed by oblique directional strips of the conductor, which together form a spiral coil; and then again insulator layers. One measures the impedance of the obtained coil (determined by the magnetic susceptibility of the coil's core) and its change when applying mechanical stress.

In [14], the authors consider the design of a similar sensor, but assembled from a separate ribbon made of amorphous alloy and separate exciting and receiving coils around it; the sensor is attached to the controlled object by means of two holders at the ends of the ribbon, and the ribbon is stretched parallel to the surface of the object. One measures the voltage at the receiving coil.

Standing apart in this series is the patent application [15], in which the idea is patented, to evaluate the mechanical stress in a ferromagnetic material by the magnetization reversal time, or practically by the response to a high-frequency signal. In this case, the recorded changes are associated not with a stationary magnetization curve, but with non-stationary effects which cause its distortion.

In [16] and [17], the magnetization reversal of the sensitive element (in the case of [17] - an amorphous magnetic tape) is performed with the use of alternating longitudinal magnetic field. One measures the magnetization reversal signal of this tape, which is induced as EMF in a differential receiving coil and monitors the changes in its shape under the action of an applied mechanical load.

In [18], an alternating current is passed through a sensitive element, which is an amorphous magnetic ribbon, the voltage is recorded at the same element, and one monitors the changes in the impedance of this element caused by the applying mechanical load.

In [10], the author considers constructions of sensors based on the propagation of ultrasound in the ribbons made of amorphous magnetic alloys which manifest magnetostriction, for example, on imbalance in the propagation of ultrasound from two ends of the ribbon to its middle point, when one of the halves of this ribbon is subjected to lateral deformation.

To the same type belongs the work [19], in which a prototype of sensor is described. The sensor is able to distinguish between tension and torsion. In this sensor, there is used a ribbon made of metal glass $Fe_{48}Co_{32}P_{14}B_6$. For various combinations of tension (up to 346 MPa) and twisting (up to 21 deg / cm), magnetization curves $M(H)$ were taken and parameters describing them were extracted, including values of remnant magnetization M_{rem} and coercive field H_C. It was shown that an increase in tension leads to a significant increase of M_{rem} and a slight increase of H_C, while twisting, vice versa, leads to a significant increase of H_C and a slight increase of M_{rem} (see Fig. 2). As a result, knowing M_{rem} and H_C, one can obtain magnitudes of both tension and twisting. The minimal detectable values of tension and twisting are 0.19 MPa and 0.13 deg/cm, respectively.

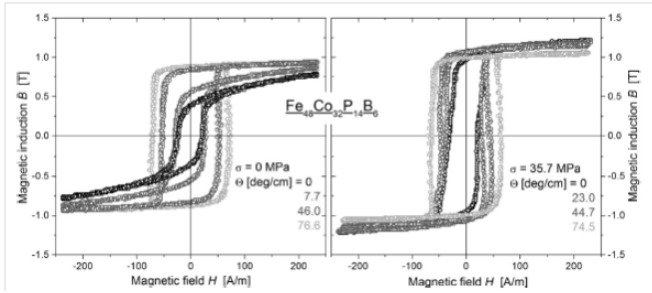

Fig. 2. Dominance of changes of M_{rem} и H_C when applying to the $Fe_{48}Co_{32}P_{14}B_6$ ribbon tension and twisting, respectively [19]

2) As a special case of a change in the parameters of the hysteresis loop - the change of the critical field which causes giant Barkhausen jumps in single-domain wires: It is worth to consider separately the use of single-domain magnetic microwires with a glass shell. Their applications are reviewed by [20], [21], [22], [23], [24].

According to [24], these wires are obtained by the Taylor-Ulitovsky method, i.e. by exhaust hood of a glass capillary with molten metal inside. The typical diameter of the metal core is 1..30 µm, the glass shell - 2..20 µm. In the center of the wire a domain lies which stretches through the wire, occupies a large part of its volume, and has magnetization along the wire; near the surface there are small domains with magnetization perpendicular to the surface; and at the ends there are closing domains (see Fig. 3).

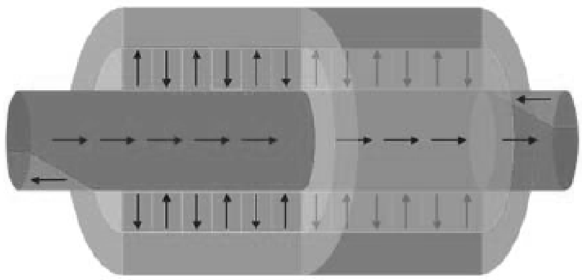

Fig. 3. Domain structure of a magnetic microwire with a dominant central domain (from [24])

According to theory, when magnetostriction coefficient is negative, the re-magnetization of the central domain caused by changing longitudinal field proceeds smoothly, but when it is positive, we have bistability, and the re-magnetization proceeds jump-wise (as giant Barkhausen jump).

In consequent, we denote the field which causes the magnetization reversal as H_{sw} (from "switching").

It is convenient to use not sinusoidal, but linear sweep of the magnetizing field, to measure the time from the moment of the change of the sign of the current which generates this field to the moment of the Barkhausen jump (this time is proportional to H_{sw}), and to monitor the change of this time under external influences (temperature change or application of mechanical stress). Such a measurement scheme is illustrated in Fig. 4 from [25].

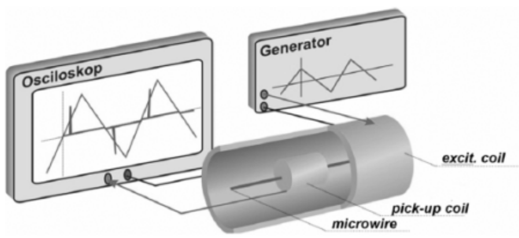

Fig. 4. The scheme for measuring the field of domain switching in a magnetic wire (from [25])

When designing sensors, the dependence of H_{sw} on temperature and on mechanical stress is important. In [23], a theory is described that describes such a dependence and its change with varying scanning frequencies.

An example of the dependence of H_{sw} on the applied stretching stress is presented in [26]. The composition of the wires is $Fe_{38.5}Ni_{39}Si_{7.5}B_{15}$, the diameter with the glass shell is 35 µm, of the wire itself – ca. 15 µm, and the length is 20 mm. The wires were embedded in the composite material during its manufacturing. The dependence, within noise, is linear, and tensile stresses 0 and 35 MPa correspond to H_{sw} = 218 and 228 A/m, respectively.

Examples of testing the method for measuring the deformations of various materials (concrete, fiberglass, etc.) into which such wires can be introduced at the stage of their manufacture are described in many works - see, for example, [25], [27], [28], [29]. Moreover, in [25], [26], [28] and [29] the authors propose some schemes for contactless measuring of stresses in the materials under monitoring.

One should note that, according to [30], the pyrex glass shell is biocompatible, and this makes it possible to use such sensors in medical applications.

3) Changes in the characteristics of magnetoelastic resonators: An example of the use of magnetoelastic resonators to control deformations is given in [31]. In this work, a doubly-anchored suspended structure is used as a sensor - a magnetoelastic plate connected by thin jumpers at the ends with thick anchors attached to the controlled part near the surface or in the cavity inside this part. For querying such a sensor, the resonance oscillations of the plate are excited by a pulse of an alternating magnetic field generated by the excitation coil, whose frequency is operatively tuned, with subsequent registration of the alternating magnetic field generated by such oscillations. In this case, the excitation and response of the sensor are separated in time. The method was tested on sensors with resonant frequencies in the range 120..240 kHz. Deformations reached 3.5 mstrain (1 strain corresponds to $dl/l = 1$), sensitivity was 14300 ppm/mstrain, response times were of the order of 0.5 s, and the frequency measurement accuracy was better than 0.1%.

In an earlier work by the same authors [32], frequency adjustment was not used, instead a plate of the same alloy as the main sensor is used, but fixed only on one side and not subjected to mechanical stress; the frequency difference between the stressed and unstressed plates is controlled, which allows one to realize compensation for temperature changes.

4) The appearance of EMF as a result of violation of the compensation of signals from several coils: This type includes a sensor, the design of which was illustrated above - see Fig. 1, (b).

5) The appearance of EMF or other effects due to the connection of magnetization and twisting: In [33] and [7], there are considered effects, which make it possible to create twisting sensors, and which connect three values to each other: (1) a longitudinal magnetic field in a rod (and associated circular currents); (2) the longitudinal current in the rod (and the associated circular field); (3) mechanical twisting of the rod. The following effects can be distinguished: direct Wiedemann effect: 1 + 2 → 3; Wiedemann's first inverse effect: 2 + 3 → 1; the second inverse Wiedemann effect: 1 + 3 → 2. The Matteucci effect ([34], [35]) stands out separately, and in this scheme it can be written as 1 + 3 → 1' (longitudinal magnetic field + twisting → change in longitudinal magnetization). A special feature of this effect is that it is accompanied by the running of a re-magnetization wave along a twisted sample and the formation of a voltage jump similar to the giant Barkhausen jump.

In Fig. 5, there are shown two designs of a twist sensor (from [6]).

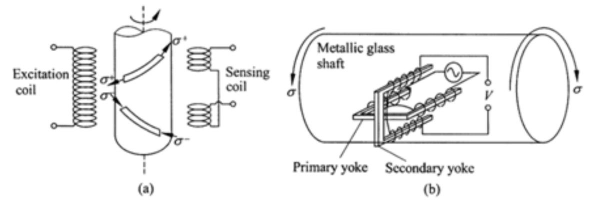

Fig. 5. Designs of the sensors of twisting

In the case (a), in the absence of twisting, the signals of the receiving coil halves are compensated, and in the presence of it, one of the ribbons works in tension, the other in compression, and the deviations are summed up. In the case (b), the shaft is covered with a layer of metal glass, and the primary yoke is supplied with direct current; twisting distorts the flow lines, and a voltage arises at the secondary yoke. (Case (a) is also considered in [7]).

In [36], there was investigated the possibility of the use of the Matteucci effect in a ferromagnetic wire (an amorphous alloy based on Co+Fe, composition not specified, diameter 101 μm, length 60 mm) for creating torsion strain sensors. Shear deformation ε_{shear} reached $12 \cdot 10^{-3}$ (in both directions). It is shown that the switching field and the width of the voltage peak in the receiving coil are unsuitable for measuring small torsions, because they are not monotonic functions of ε_{shear} (near $\varepsilon_{shear} = 10^{-3}$, the switching field passes through a minimum, and the peak width passes through a maximum), while the peak amplitude is a monotonic function (it is close to zero at $\varepsilon_{shear} = 0$, grows and reaches a limit near $\varepsilon_{shear} = 10^{-3}$), and in the range $0.1 \cdot 10^{-3}..1.5 \cdot 10^{-3}$ it is quasilinear.

In [7], the design of a twist sensor based on the 2nd inverse Wiedemann effect is described.

To the same type belongs the sensor described in [37]: a NiFe alloy layer is electrochemically deposited on a non-magnetic steel shaft; an alternating magnetic field is applied (the amplitude of which corresponds to region of bending on the $M(H)$ curve, and differential longitudinal susceptibility is measured. Due to the coupling of the circular current generated by the alternating longitudinal field and the twisting, an additional longitudinal magnetic field arises, and the differential susceptibility changes, which is registered.

6) The appearance of the second harmonic signal due to the geometry of the system (small-angle magnetization rotation): This type includes a sensor, the design of which is patented in [38]. An amorphous ferromagnetic ribbon is used as a magnetic material. Two coils are used, the axes of which coincide with the axis of elongation of the ribbon. Through one of them, one passes electric current to magnetize the tape to saturation, the other serves as a receiving one. Then, in the same way as in one of the variants of the Narita method for measuring magnetostriction (small-angle rotation of the magnetization vector – SAMR) [39], a constant longitudinal magnetic field is applied to the ribbon to magnetize it up to saturation, an alternating current of frequency f is passed through the ribbon, and the amplitude of signal at double frequency $2f$ in receiving coil is recorded.

C. Other effects associated with magnetic phenomena are used.

1) Changes in the optical characteristics of a sample during magnetization (magneto-optical Kerr effect): In [21] and [40], there was demonstrated the possibility to use the magneto-optical Kerr effect (MOEC) to monitor mechanical stresses in a sample. In both cases, a change in the domain structure was observed upon application of the load, which complicates the use of the effect to create sensors.

In [41], there is described an approach which solves this problem, namely, as a sensitive element, the authors used the layered structure SiO_2(40 nm)/Fe(30 nm)/Mn-Ir(10 nm)/Fe(10 нм)/Ru(1 nm). Due to exchange coupling between the antiferromagnetic and ferromagnetic layers, it was found possible to obtain a domain size exceeding the size of the light spot from the laser beam. The aim of the development was to increase the accuracy of the control of mechanical stress in the processing of parts. The authors note that the disadvantage of resistive and semiconductor sensors is the need for wiring and sensitivity to inductive pickups, and the disadvantage of sensors based on fiber Bragg gratings and a Fabry-Perot interferometer is their high volume; the MOKE-based sensor is free from these drawbacks. The sensor constructed by the authors is attached to the part with tensometric glue. Two photodiodes detect the radiation of two polarizations, and the difference in their signals is amplified; in the absence of mechanical stress, the difference is zero, and in the presence of the latter, it reaches several volts. The results are consistent with those obtained using a resistive strain gauge. The sensor allows one to measure strain up to about 7 ppm. The sensor hysteresis effect is small and reversible.

2) Changes in the characteristics of wires in a matrix or their ensemble in the radio-frequency or microwave region: For a single wire, one can evaluate the change in surface impedance (magneto-impedance and stress-impedance effect) caused by a magnetic field or mechanical stress, and for a medium containing such wires, one can the change in the complex permittivity of such a medium. Examples of prototypes of stress sensors based on these effects are described in [22] and [42]. The authors note that for creation of sensors specifically for mechanical stresses, it is preferable to create spiral anisotropy in the wire, which can be achieved by annealing of the wires with small negative magnetostriction coefficient and cooling them under load. In [22], the authors used amorphous wires of the composition $Co_{69}Fe_3Cr_3Si_{10}B_{15}$ in a glass shell (core diameter - 10 μm, with a shell - 14 μm) and frequencies of the order of GHz, in [42] - wires $(Co_{94}Fe_6)_{72.5}Si_{12.5}B_{15}$ with a diameter of 120 μm without shell and frequency of 1 MHz. The model calculations performed by the authors of [22] gave good agreement with the experiment.

D. Propagation of spin-polarized electrons

1) Influence of mechanical stresses in the scheme of observation of giant magneto-impedance: In consequent, we use the expressions “giant magneto-impedance” and “giant magneto-resistance” (GMR) as synonyms, and use the term “giant stress-impedance” for the change of the resistance of structures which manifest giant magneto-impedance when they are subjected to mechanical load. Recollect that this refers to the effect of a sharp decrease the resistance of the structures in a magnetic field. Such the structures consist a series of alternate magnetic and non-magnetic layers. Electrons move perpendicularly to these layers and the resistance depends on whether the spins of the electrons in the magnetic layers are aligned with the magnetic field or not. An example of a structure that manifests the GMR effect is described in [43], where it is used as a magnetic field sensor.

The sensor is made of several alternating layers of permalloy $Ni_{81}Fe_{19}$ and copper and in sectional view has a form of meander with a layer thickness of 20 μm and a total area of 4.5 mm^2. The number of layers was several hundred and was fitted to achieve the desired resistance. As the field increases from zero to 10 mT, it changes its resistance from 26 to 22 kOhm, i.e., the relative change is ca. 10-13%.

In [44], the authors report the creation of a highly sensitive micron-sized mechanical stress sensor based on a magnetic tunnel junction with magnetostrictive $Fe_{50}Co_{50}$ layers. The ratio of the values of tunnel magnetoresistance reaches 48%, and the tensile deformation $\Delta\varepsilon$ of the order of $0.4 \cdot 10^{-3}$ causes the change in resistance by 24%, i.e., gauge factor $(\Delta R / R)/\Delta\varepsilon$ is about 600, while for metal sensors it is 2..4, and for piezoresistive semiconductor sensors it is 40..180.

In [45] and [46], the change in the characteristics of the Co/Au/(Fe,Co) and similar pseudospin valves under the action of mechanical stresses was studied. It was shown that on silicon substrates, where the deformations are small ($-300 \cdot 10^{-6}..300 \cdot 10^{-6}$), the deviations of the magnetoresistance ratio $R(H)/R(0)$ from unity are of the order of 3%, and the change of these deviations under deformation are small (1..2% of the value of these deviations). At the same time, on a polyimide substrate, where the stresses at the same strain reach $1100 \cdot 10^{-5}$, these deviations are 2.5% at a strain of $-900 \cdot 10^{-5}$, pass through a value of 2.7% at zero deformation, and reach 2.9% at deformation $+1100 \cdot 10^{-5}$. That makes it possible to use such systems as strain sensors.

IV. Remarks on the possibilities of magnetic strain gauges

By analogy with the requirements of minimal resistance for an ammeter and maximal for a voltmeter, the stiffness of the sensor should be minimal when measuring strain, and maximal when measuring mechanical stress or force. It is possible to use single-domain wires of the minimal diameter and the thickest wires, respectively, but one can increase or decrease the stiffness by mounting sensors in parallel or in series with springs. It also allows one to increase the maximum allowable values of the measured strains and mechanical stresses.

And as for minimal detectable values of the measured mechanical stresses and strains, their estimates from the data available in the literature are as follows:

- for magnetoelastic effects: for stretching - σ=0.19 MPa ($\varepsilon = 10^{-6}$), for twisting – shear deformation *dl/l* = $4*10^{-3}$ [19];

- for measuring H_{sw}: σ=2 MPa ($\varepsilon = 2*10^{-5}$) ([20], [23]);

- for GMR: $\varepsilon = 2 \cdot 10^{-5}$ [44].

Recollect that in some cases essential demands for strain gauges are not sensitivity and accuracy but some other, and magnetic strain gauges are highly suitable for some specific demands. Namely, single-domain wires and magnetoelastic resonators are suitable for contactless sensing, moreover, they can be made biocompatible, which makes it possible to use them for monitoring the state of implants in medicine. Next, sensor on the basis of magneto-optical Kerr effect can be used when processing parts in industry, which allows one to perform contacless measurements from small area. And small size of such sensors can be used in robotics, for creation of manipulators which simulate human arm.

V. Prospective scopes of application

Below we outline prospective application spheres of strain sensors based on various principles with the use of magnetic phenomena.

TABLE I. Prospective scopes of application

Principle of functioning	Advantages and prospective application spheres
1. Magnetism plays only an auxiliary role	Simple in fabrication, usually robust sensor, but with low sensitivity; industrial process control
2.1. Changes in the parameters of the hysteresis loop	General-purpose devices; simultaneous measuring of tension and torsion
2.2. Single-domain wires	Contactless measurement; building and industrial equipment; biocompatibility, medicine
2.3.Magnetoelastic resonators	Contactless measurement
2.4. Violation of compensation of signals from several coils	General-purpose devices
2.5. Connection of magnetization and twisting	Measurement of twisting; industrial process and equipment control
2.6. Small-angle magnetization rotation.	Measurements for wire-shaped samples with increased sensitivity
3.1. Magneto-optical Kerr effect.	Contactless measurement; possibility to work with small areas
3.2. Characteristics of wires in the radio-frequency or microwave region	Contactless measurement
4. Tunneling of spin-polarized electrons	Small size, robototechnics

VI. Conclusion

Existing solutions for strain gauges based on magnetic phenomena make it possible to measure relative tensile strains from $1 \cdot 10^{-6}$ to $0.5 \cdot 10^{-3}$, and torsion-induced shear strains from $4 \cdot 10^{-3}$ to close to unity.

The described methods are applicable for solving a wide range of problems, including non-contact measurements based on sensors built into the controlled object at the stage of its manufacturing.

The developed designing solutions allow one to minimize the errors caused by the changes in temperature, external magnetic fields, etc.

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