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POSITION SENSORS BASED ON THE DELAY LINE PRINCIPLE

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In this paper, we present a position sensor based on the magnetostrictive delay line principle. The sensor is accompanied by its electronic circuitry and packaging. We analyze the sensor working principle, electronics, calibration procedure as well as its evaluation with respect to the state of the art, showing its advantages and applications.

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1. Introduction

The primary standards in measuring length are governed by the definition of the meter, which is the path traveled by light in vacuum during a time interval of 1/299,792,458 of a second. The experimental realization of this definition with respect to the uncertainties of the modern atomic clocks and the sharp Gaussian frequency response of lasers, offer an uncertainty of measurement of the order of parts per billion (ppb).

The secondary methods in measuring position are mainly referring to interferometric techniques, with corresponding uncertainty of the order of 1 part per million (ppm). The laser interferometers are currently used not only as secondary standards but also as sensing elements in given applications. Nevertheless, in cases where the use of interferometers is not appropriate, other kinds of position sensors are used.

Many physical effects have been employed in the past to develop such position sensors, based on the electrical, magnetic and optical properties of materials. In our days, these sensors should be contactless devices with built-in electronic circuitry including electronic auto-calibration algorithms, with sensitivities and uncertainties better than 1 μm and 10 μm/m, respectively. In some cases, where the environmental conditions do not allow the use of optic or capacitive techniques, magnetic phenomena and techniques are the only solution for more trustful measurements. Modern magnetic materials have enhanced the properties of sensors based on magnetic effects and have also initiated new sensing elements and applications, so that magnetic materials are competitive with respect to other sensing principles[1-4].

There is a wide variety of industrial applications requiring position measurement where the position sensor should have cross section area smaller than 2 mm x 5 mm, uncertainty of measurement better than 0.1 mm per meter and a speed of sensing head displacement faster than 10 m/s. Most importantly it should be able to perform measurement in mechanically harsh environments [5-12].

We used the magnetostrictive delay line (MDL) technique [13] by using some new materials, which enhance the properties of this technique, in order to develop a position sensor that should meet the above mentioned specifications. The specific application we have had in mind was the realization of a position sensor able to detect the position, speed and acceleration of a hydraulic piston. This sensor is to be presented hereinafter.

2. The sensor

The sensor is illustrated in Fig. 1. The sensing element (1) is a magnetostrictive delay line (MDL) in the form of ribbon or wire. A short excitation coil (2) is set around the one end of the MDL. An array of short, single layer coils (3), connected in series and named hereinafter “search coils”, is set around the MDL along its length, used as the sensor output. A moving hard magnet (4), able to be displaced parallel to the sensing material, is the active core of the sensor. Without any loss of the generality, in our specific application the moving magnet was the end part of the hydraulic piston, having a magnetic pole orientation parallel to the length of the MDL. It is mentioned that the magnetic pole orientation of the active core of the sensor can also be vertical with respect to the MDL, as it can be seen from the description of the operation of the sensor. The serial output of the search coils is driven to an Application Specific Circuit – ASC (5), including the analog and digital electronics for sensor excitation, signal conditioning and data acquisition & processing. The analog part of the ASC includes the pulsed current circuit for the sensor excitation (6) and the amplification circuit of the output voltage pulse train (7). The digital part includes a digital oscillator/counter (8) for delay time detection and a fast analog to digital converter – ADC (9) for the digitization of the output waveform and a microprocessor based circuit for data acquisition and processing. The data processing concerns the determination of the exact position of the moving magnet. Finally, the velocity and acceleration of the moving magnet can be determined by hardware or software calculation of the fist and second derivatives of the moving magnet position. The excitation part of the sensor is packed up together with the ASC at the sensor termination, whereas the excitation coil is covered by a soft magnetic tube, for example permalloy, in order to properly shield the coil against ambient magnetic fields. The length of the sensor can vary by changing the number of search coils, thus allowing a variable sensor length, in a relatively inexpensive production technique.

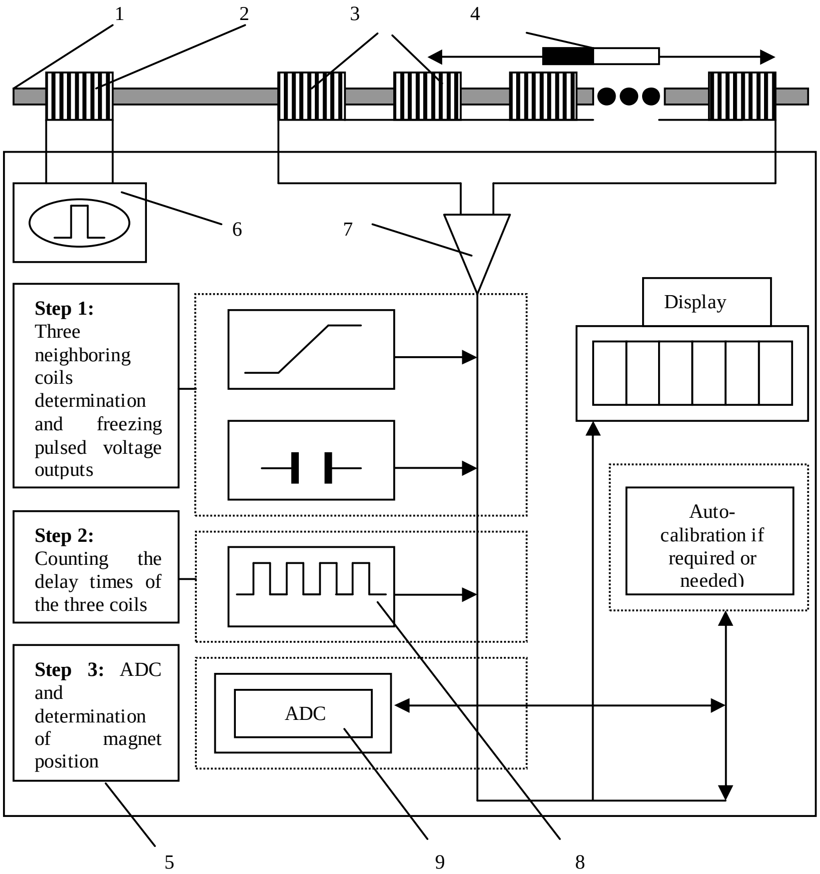

Fig. 1. The position sensor: (1) magnetostrictive delay line, (2) excitation coil, (3) array of search coils, (4) moving magnet, (5) application specific circuit, (6) excitation circuit, (7) analog amplifier, (8) oscillator/counter, (9), analog to digital converter.

The sensor operates as follows: Pulsed current of 1 μs duration and 1 ms period is transmitted through the excitation coil. Then, the pulsed magnetic field along the length of the MDL generates an elastic pulse, propagating along the MDL length. As the elastic pulse propagates along the length of the MDL, it causes changes of magnetic flux at the intersections of MDL and search coils, thus inducing a voltage pulse train with pulse intervals corresponding to the distance between consequent coils. In the absence of the moving magnet and low ambient field along the array of the short search coils, these voltage pulses are small in amplitude. In the presence of the moving magnet the ambient biasing field at the MDL intersection changes, resulting in a corresponding change of the pulsed voltage output.

These pulsed voltage outputs should be monotonically proportional to the ambient field along the axis of the search coils, in order to allow the use of the arrangement as sensing element. Thus, the determination of the regions of field where such statement is correct is the most significant problem in designing the sensing element. Observing the λ(H) and its first derivative d(λ(H))/dH, as illustrated in Figs. 2 (a) and (b) respectively, it can be seen that the field regions (-Hs, Hs) are determined by the maxima of d(λ(H))/dH. Since λ(H) is proportional to the dependence of the magnetoelastic response on the biasing field, the limits of the field for monotonic response are the maxima of this dependence.

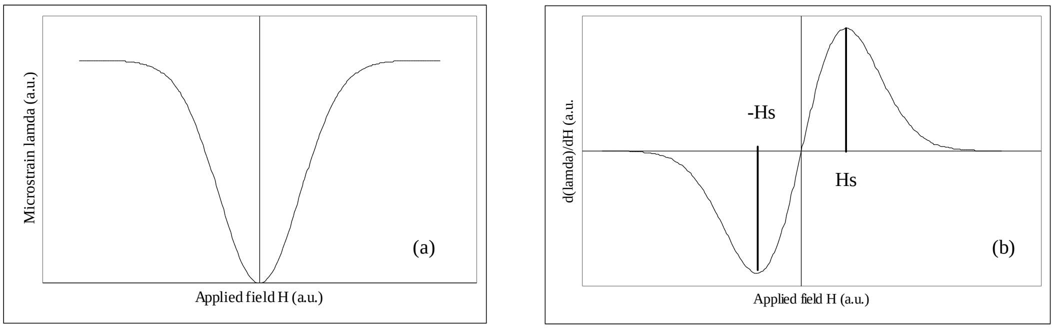

Fig. 2. (a) The magnetostriction function λ(H). (b) The first derivative of λ(H). The amplitudes of field (Hs, -Hs) correspond to the monotonic region of the biasing field dependence.

Thus, if the moving magnet core is approaching three consequent receiving coils, then the voltage output of these three coils overcomes a preset threshold and indicates that the magnet approaches the vicinity of these coils. The amplitude of the voltage pulses can be the indication of the distance of the magnet with respect to the three coils by tailoring the magnetostrictive element in a way to retain a uniform and monotonic output response with respect to the ambient field along its length. Then, the algorithm which can be used for the determination of the absolute position of the moving magnet includes three steps. In the first step, a voltage threshold comparator determines and freezes the three consequent pulsed voltage outputs, which overcome a preset nominal value. In the second step, an oscillator/counter circuitry is used to measure the delay time of these three pulsed voltages, with respect to the excitation signal. Bearing in mind that the two outer pulses ought to be always smaller in amplitude compared with the middle one, it is known that the moving magnet is somewhere between the three coils. In the third step, the three frozen pulsed voltage outputs are measured by using the fast analog to digital converter (ADC). The result determines the relative position of the moving magnet with respect to the three coils, by using an EEPROM stored calibration look up table concerning the dependence of the pulsed voltage output on the magnet displacement. Thus, the position of the magnet with respect to the excitation coil is determined. The three point measurement and the look up table are also the means for auto-calibration procedures. The recently developed amorphous magnetostrictive ribbons and wires after proper treatment offered a uniform, sensitive and un-hysteretic magnetoelastic response along the length of the MDL, allowing the use of a unique look up table for all the search coils. Without such a unique look up table the sensor could not measure position and displacement in real time conditions.

This sensing technique is not dependent on time delay measurement, which is practically limited to uncertainties of 0.1 mm/m. Instead, it is dependent on ADC measurements, which allow uncertainties of the order of 1 p.p.m.

3. Experiments and discussion

3.1. Testing the material

We have developed the above described position sensor using FeSiB amorphous ribbons and wires. The sensor manufacturing process followed three independent procedures: the manufacture and tailor of the magnetostrictive element, the sensing element construction and finally the electronic circuit development. The magnetostrictive elements were 1 mm wide and 25 μm thick $Fe_{75}Si_8B_{15}C_2$ amorphous ribbons and $Fe_{77}Si_8B_{15}$ amorphous wires, annealed at 350°C in argon atmosphere under an applied stress of 400 MPa. We annealed the magnetostrictive elements in order to optimize the sensitivity and the uniformity of the magnetoelastic response. We tested the dependence of the magnetostrictive elements on the applied biasing field along their axis, as well as their uniformity response, which determine their magnetoelastic behavior. The field dependence and the uniformity response of the annealed ribbons and wires are illustrated in Figures 3 and 4, respectively.

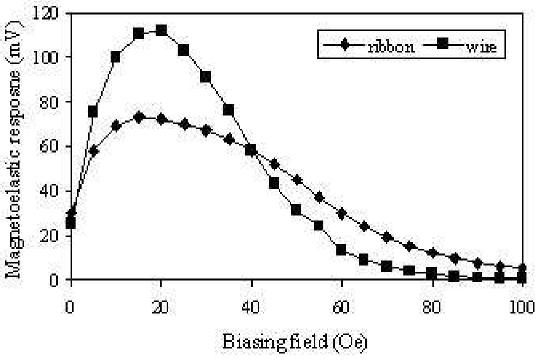

Fig. 3. The dependence of the magnetoelastic response of the annealed amorphous ribbons and wires on the bias field along their length.

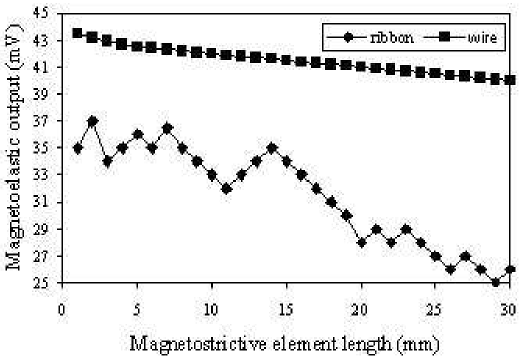

Fig. 4. Magnetoelastic uniformity response of the annealed amorphous ribbons and wires.

3.2. Testing the sensor

For the sensing element manufacturing, we used a flexible plastic substrate tube, where we wound 10 search coils in a pitch of 30 mm, the measuring effective length being of 300 mm. The magnetostrictive element was inserted and fixed into this tube manually, afterwards. Finally, the ASC was developed following the specifications described previously.

The sensor as a whole was attached on a commercially available hydraulic piston, having attached the Nd-Fe-B permanent magnet at the end of its moving part. The piston was moved manually by using a linear spacer of 10 nanometers sensitivity. We calibrated the sensor using the manual displacement of the piston as the sensor input and the output of the ASC as the sensor output. Consequently, we determined the dependence of the magnetic field component along the MDL axis upon the position of the moving magnet. For this reason we used a three dimensional Hall magnetic field sensor with sensitivity of 100 nT and uncertainty of 10 mT. This dependence is illustrated in Fig. 5. These results show a good agreement with the biasing field response of both the ribbons and wires.

Consequently, we performed the characterization of the position sensor. The dependence of the pulsed voltage output of a single search coil on the displacement of the moving magnet, which corresponds directly to the position of the moving piston, is illustrated in Fig. 6. The uncertainty of measurement concerning all search coils is illustrated in Fig. 7. Sensitivities of 1 μm and uncertainties of 10 μm were determined for the case of the annealed amorphous wire. These characteristics improve the position sensing methods based on MDL's [14] competing the current state of art in magnetic and optical tapes.

Reproducibility of the sensor is mainly affected by the so-called MDL non-uniformity response, defined as the fluctuation of the amplitude of readings along the length of the line [15].

Although such fluctuation is large for the case of ribbons, it is eliminated in amorphous wires even in the as-cast state, while thermal and magnetic annealing greatly improves their sensitivity and magneto-elastic uniformity. Additionally, the sensor reproducibility is also assisted by the almost non-hysteretic behavior of the λ(H) function of the annealed amorphous wires.

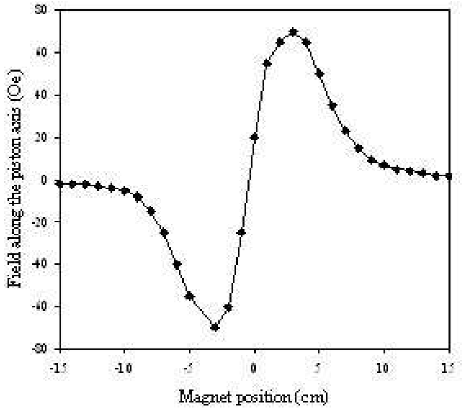

Fig. 5. The dependence of the magnetic field component on the position of the moving magnet attached to the hydraulic piston.

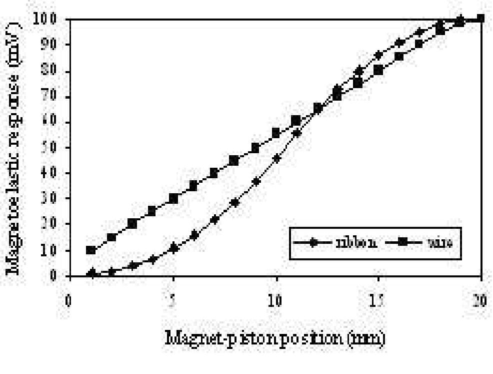

Fig. 6. The dependence of the sensor output of a single search coil on the displacement of the moving magnet.

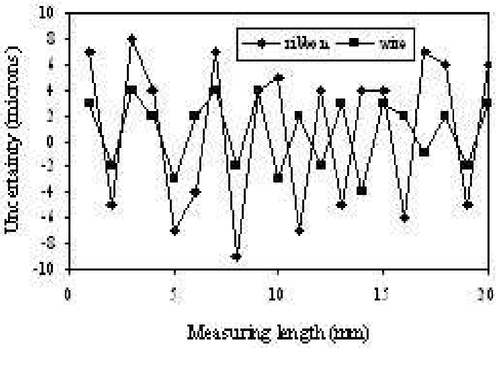

Fig. 7. The uncertainty of measurement concerning all search coils.

In order to use such sensors at industrial scale, some problems should be solved to optimize the sensor characteristics, namely the linearity and repeatability of the sensor response. Regarding the problem of the sensor linearity, one has to tailor the λ(H) function to obtain a linear response of the voltage output with respect to the applied field. From the experimental results, a linear region of the sensor response can be determined for amorphous wires after annealing. Considering the problem of the noise elimination, which can further improve the sensor uncertainty, one approach is the use of low pass filtering. Research work is under way to develop such a signal conditioning system.

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