

POSITION SENSORS BASED ON THE DELAY LINE PRINCIPLE

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Abstract - *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 present and analyze the sensor principle, electronics, calibration procedure as well as its evaluation with respect to the state of the art, showing its advantages and applications.*

Keywords - Magnetostrictive delay lines, Position sensors.

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. 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 sensing 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 $1 \mu\text{m}$ and $10 \mu\text{m/m}$ 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 solutions. 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.

There is a vast variety of industrial applications requiring position measurement where the position sensor should have cross section area smaller than to $2 \text{ mm} \times 5 \text{ mm}$, uncertainty of measurement better than 0.1 mm per meter and a speed of sensing head displacement faster than 10 m/s , and most importantly it should be able to perform measurement in

mechanically harsh environments. Having had the motivation to develop a position sensor to meet these specifications, we employed the magnetostrictive delay line (MDL) technique, using some new materials, which enhanced the properties of this technique. 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 Figure 1. The sensing element (1) is a magnetostrictive delay line (MDL) in the form of ribbon or fiber. A short excitation coil (2) is set around the one end of the MDL and an array of short, single layer coils (3), connected in series and named hereinafter "search coils", is spread around the MDL along its length, being 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 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 first 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.

The sensor operates as follows: Pulsed current of 1 μ second 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. These voltage pulses are proportional to the ambient field along the axis of the search 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 voltage pulses of the neighboring coils become larger. The closer the moving magnet is to a coil, the larger the corresponding voltage pulse, following the classical dependence of magnetostriction and inverse magnetostriction on the ambient field. 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. Having tailored the magnetostrictive element in a way to retain a uniform and monotonic output response with respect to the ambient field along its length, the amplitude of the voltage pulses can be the indication of the distance of the magnet with respect to the three coils. An algorithm, which can be used for the determination of the absolute position of the moving magnet, includes three steps. At the first step, a voltage threshold comparator determines and freezes the three consequent pulsed voltage outputs, which overcome a preset nominal value. At 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. At the third step, the three frozen pulsed voltage outputs are measured by using the fast analog to digital converter and the resulting digital words determine the relative position of the moving magnet with respect to the three coils, by using a EEPROM stored calibration look up table concerning the dependence of the pulsed voltage output on the magnet displacement is used to, corresponding to the three pulsed output voltages. 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 autocalibration procedures. It must be said at this point that, the recently developed amorphous magnetostrictive ribbons and fibers after proper treatment offered a uniform, sensitive and unhysteretic magnetoelastic performance along the length of the MDL, thus 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.

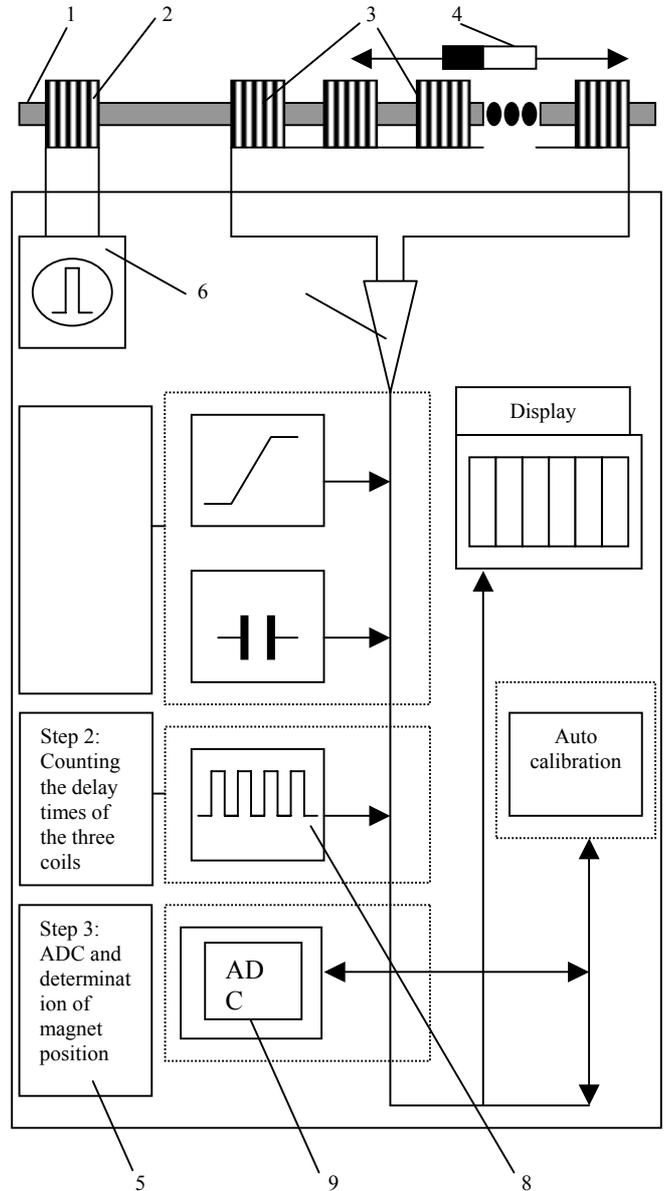


Figure 1. The position sensor. (1) Magnetostrictive delay line, (2) Excitation coil, (3) Array of search coils, (4) Moving magnet, (5) Application specific circuit, (6) Excitation circuit, (7) Analog amplifier, (8) Oscillator/counter, (9), Analog to digital converter.

3. EXPERIMENTS

We have realized the above described position sensor using FeSiB amorphous ribbons and fibers. The sensor manufacturing process was realized following three independent procedures: the manufacturing and tailoring of the magnetostrictive element, the of the sensing element construction and finally the electronic circuit development. The magnetostrictive element was a 1 mm wide and 25 μ m thick Fe₇₅Si₈B₁₅C₂ amorphous ribbon and a Fe₇₇Si₈B₁₅

amorphous fiber, annealed in 350°C in Argon atmosphere under 400 MPa stress and 250 mA dc current. We annealed the magnetostrictive elements in order to optimize the sensitivity and the uniformity of magnetoelastic response. Indeed, 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 ribbon and fiber are illustrated in Figures 2 and 3 respectively.

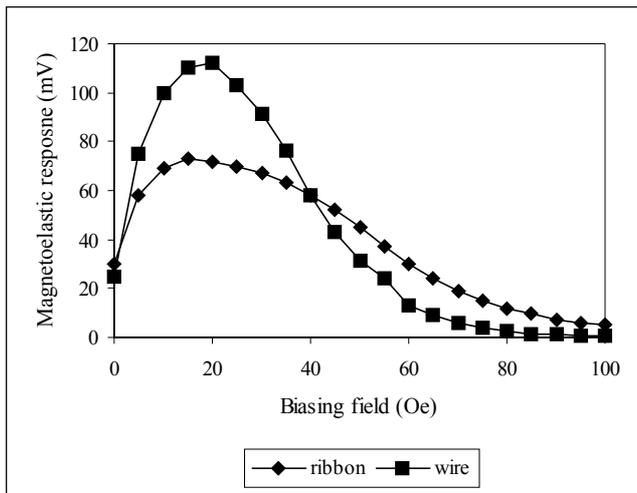


Figure 2. The dependence of the magnetoelastic response of the annealed amorphous ribbons and wires on the bias field along their length.

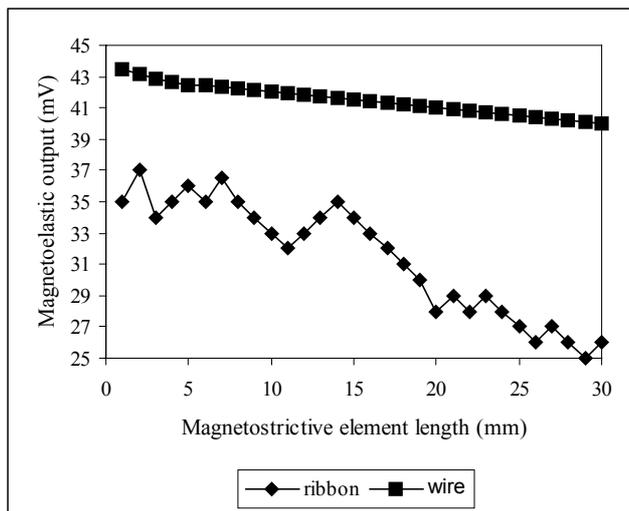


Figure 3. Magnetoelastic uniformity response of the annealed amorphous ribbon and wire.

For the sensing element manufacturing, we used a flexible plastic substrate tube, where we wound 10 search coils in a pitch of 30 mm, allowing an measuring effective length of 300 mm. The magnetostrictive element was inserted and fixed into this tube manually, afterwards.

Finally, the ASC was developed following the specifications described in the previous chapter.

The sensor as a whole was attached on a commercially available hydraulic piston, having an 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. Using the manual displacement of the piston as the sensor input and the output of the ASC as the sensor output, we realized the calibration of our sensor.

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 effect magnetic field sensor with 100 nT and 10 mT sensitivity and uncertainty respectively. This dependence is illustrated in Figure 4. These results show a good agreement with the biasing field response of both ribbons and wires.

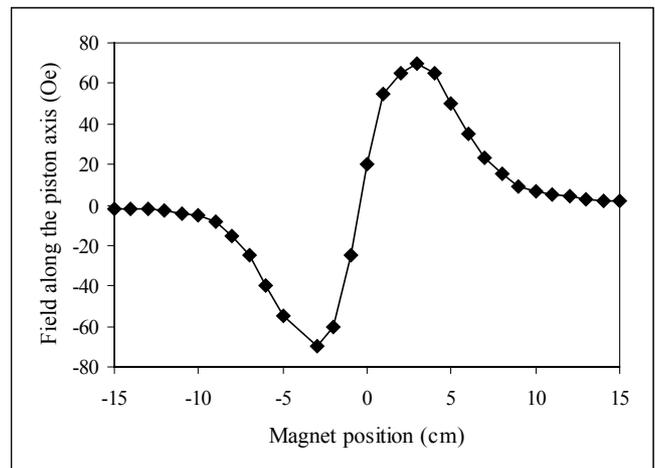


Figure 4. The dependence of the magnetic field component on the position of the moving magnet of the hydraulic piston.

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 Figure 5. The uncertainty of measurement concerning all search coils is illustrated in Figure 6. A sensitivity of 1 micrometer and an uncertainty of 10 micrometers was determined due to these measurements for the case of the annealed amorphous fiber. Apart from that it can be seen that the response of the amorphous fiber is more linear than the response of the amorphous ribbon. These results demonstrate that this sensor is quite competitive with respect to the given state of the art in this field of application.

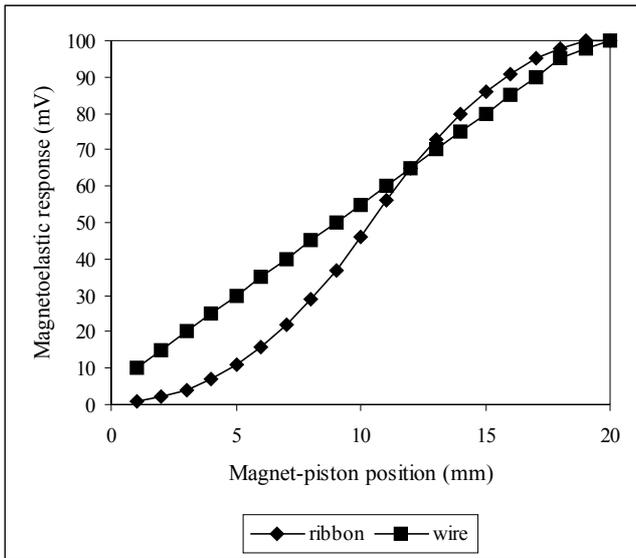


Figure 5. The dependence of the sensor output of a single search coil on the displacement of the moving magnet.

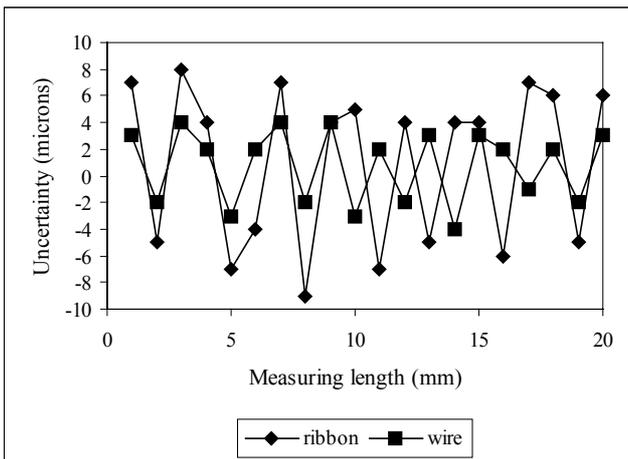


Figure 6. The uncertainty of measurement concerning all search coils.

4. DISCUSSION

In order to industrialize such sensor, a number of problems should be solved to optimize the sensor characteristics, namely being the linearity and repeatability of the sensor response. Regarding the problem of the sensor linearity, one has to tailor the $\lambda(H)$ function to obtain a linear response of the voltage output with respect to the applied field. From the experiments, it has been seen that a linear region of the sensor response can be determined for amorphous wires after annealing. Considering the noise elimination problem, which affects significantly the sensor uncertainty, one approach is the use of low pass filtering. Research work is under way to develop such a signal conditioning system.

Reproducibility of the sensor is mainly affected by the so-called MDL non-uniformity response, defined as the fluctuation of amplitude of readings along the length of the line. Although such fluctuation is large for the case of ribbons, it can be eliminated in amorphous fibers even in the as-cast form, while heat and magnetic annealing greatly improves their sensitivity and magneto-elastic uniformity. Additionally, such sensor reproducibility is also assisted by the non-hysteretic behavior of the $\lambda(H)$ function of the annealed amorphous wires, allowing negligible sensor hysteresis.

The proposed sensor can also detect magnetic field, by measuring the dependence of the voltage pulse trains on the ambient field along the MDL axis. It has also been observed that pulsed voltage output can be sufficiently detected and processed for distances, between acoustic stress point of origin and receiving coil even greater than 100 cm.

Experimental results also show that the minimum distance between two consequent MDLs, can be 5 cm, without magnetic interference for two-dimensional arrays for magnetically mapped plane surfaces, laboratory tables, production lines dependent on terrestrial field etc.

An alternative set-up was also developed according to which, a pulsed current generator was used to transmit current to a metallic tube, made of a low resistivity metal, used as pulsed current conductor, preferably made of copper. Conductive spikes, housed in the metallic tube ends, are used to transmit pulsed current through the metallic tube connectors, to allow uniform distribution of the pulsed current density on the surface of the conducting tube. The magnetostrictive material, in the form of ribbon or wire, was wound around the conducting tube forming a single layer solenoid, paying attention in obtaining no stress along the length of it, forming a coily magnetostrictive delay line. Two receiving coils were set at the two ends of this coily MDL and their output was driven to the above described electronic circuitry. The two far end pulses were propagating as elastic waves and are detected by the receiving coils as two discrete pulsed voltage outputs, V_{o1} and V_{o2} respectively. These voltages had a delay between them proportional to the wound length of the MDL. Provided that the magnetoelastic uniformity along the length of the MDL is broken for any reason, the above described symmetry is also broken, resulting in a propagating elastic wave, which is detected as pulsed voltage between the two far end pulses V_{o1} and V_{o2} respectively. There are two ways to break this magnetoelastic uniformity. One is the modification of the ambient field and the other is force or pressure on the MDL, both applied in a local region of the MDL. Modification of biasing field results in non-uniform and therefore non-zero local microstrains, while force on the ribbon or wire results in acoustic reflection. Both signals can propagate and be detected as magnetoelastic pulsed voltage outputs. In our application, we used the modification of the biasing field because it does not affect the life time of the MDL due to mechanical load on it. The ways of breaking this magnetoelastic uniformity using local ambient field change,

are biasing field at a given region or permanent magnet displacement, both being close to the MDL. The permanent magnet displacement can be used for position sensors by means of using either a moving magnet along the length of the conducting tube or a moving magnet orthogonal to it. In both cases the sensors are cordless. In the case of a moving magnet along the length of the conducting tube, the sensor output is the delay time of the pulsed voltage corresponding to the region where the permanent magnet brakes the symmetry of the MDL, while the input is the position of the permanent magnet on top of the conducting tube. Therefore, the sensitivity of the arrangement is improved by a ratio equal to the diameter of the coil MDL cross section or the diameter of the pulsed current conductor over the pitch of the coily MDL set-up. Since the above mentioned diameter and pitch are of the order of 50 mm and 0.5 mm respectively, the sensitivity is improved by up to 1 μm . Furthermore, having broken the magnetoelastic symmetry of the delay line by local change of ambient field, the new MDL arrangement can be used for measuring stress and torque applied along the length of the pulsed current conductor, due to the modification of the magnetomechanical coupling factor.

We have performed experiments using this MDL arrangement, determining the dependence of V_o on magnetic field, displacement of a permanent magnet along the length of the pulsed current conductor and orthogonally to it, as well as stress and torsion applied on the set-up. In the experiments we used a copper conducting tube having 30 cm length, 0.8 mm thick and 15 mm diameter.

5. CONCLUSIONS AND FUTURE WORK

We have developed a position sensor able to perform measurement of the displacement of a moving magnet along its axis. The sensitivity and the uncertainty of the sensor are 1 μm and 10 μm respectively when a stress-current annealed amorphous fiber is used. Further work is underway to improve the sensor response and to realize a market oriented distribution sensor system.

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