Hysteresis Compensation in a Magnetostrictive Linear Position Sensor

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Abstract

A new linear position sensor (Micrus) has been developed, based on the transmission of ultrasonic signals in a waveguide. Waves are generated at the cursor position by the magnetostrictive effect, and their times of flight to the ends of the waveguide are used to estimate the position of the mobile element. The choice of the generating/transmitting metal for this kind of sensor is discussed. We have found that the magnetic hysteresis inherent to the magnetostrictive phenomenon translates into measurement hysteresis, affecting the performance of the sensor. An explanation of the link between both effects is given, and a compensation technique based in focusing the ultrasonic generation is offered. This compensation technique is tested using an electromagnetic finite element method program and then empirically in the Micrus sensor, with satisfactory results.

1. Introduction: the Micrus sensor

We have developed a linear position sensor, named Micrus [1], which is based in the measurement of the time of flight of ultrasonic signals propagating in a waveguide. When an intense magnetic field is applied at the cursor position (see figure 1), the magnetostrictive effect [2] couples a fraction of the electromagnetic energy into a mechanical deformation which originates two ultrasonic waves that propagate towards the ends of the waveguide, where they are picked by piezoelectric transducers. By using narrowband excitation signals with an appropriate central frequency, the effects of dispersion [3] can be neglected, and we can assume that the received signals are identical except for a time delay:

$$v_2(t) = v_1(t - D_{12}).$$

If we estimate the time delay $\widehat{D}_{12}$ (check reference [4] for a review of available methods), the displacement z of the cursor from the left side of the waveguide is

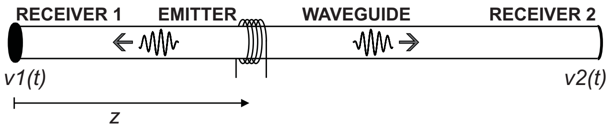

Figure 1: Working principle of the Micrus sensor.

linearly related to the delay:

$$\widehat{z} = \frac{1}{2}(L - c \cdot \widehat{D}_{12}),$$

where L is the total length of the waveguide and c is the propagation speed of the ultrasonic signals.

In the next section we will discuss the choice of metal for the tube that serves as a generating and transmitting element of the ultrasonic waves in the Micrus sensor. The algorithms that estimate the time delay perform better when the signal to noise ratio (SNR) is high, according to the Cramér-Rao criterion [4]. To achieve the precision in the position measurement required in the machine-tool application environment, we employ the magnetostrictive effect instead of the comparatively weaker Lorentz force for the generation of the ultrasonic signals in the waveguide. Unfortunately, this mechanism has the shortcoming of being affected by non linearities and hysteresis.

In section 3 we will deal with the connection between magnetostrictive and position measurement hysteresis, and offer an explanation for the appearance of that phenomenon.

In section 4 we introduce a technique that serves to compensate the existence of hysteresis. After being investigated first with finite element method simulations, an improved emitter transducer is built and empirically demonstrated in the Micrus sensor. Finally, some conclusions are stated at the end of the paper.

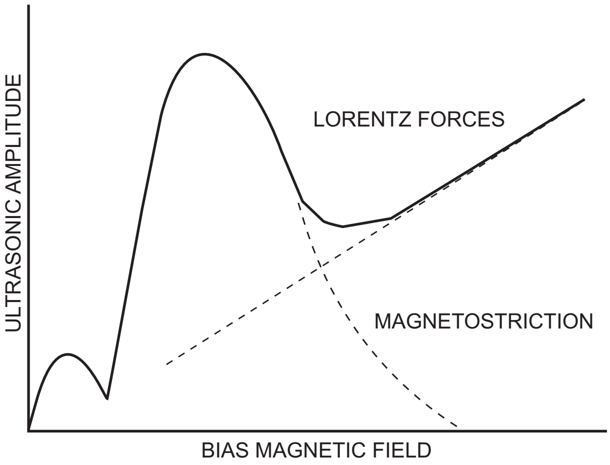

Figure 2: Dependence of the amplitude of the ultrasonic waves generated electromagnetically in a ferromagnetic metal with the bias magnetic field [5]. While the Lorentz force term shows a linear increase, the magnetostrictive term reaches a peak and then saturates.

2. Material for the transmitting element

In the design of a linear position measurement sensor, electromagnetic excitation methods are very attractive due to their contactless nature. In this section we will explain the choice of metal that will serve both as the generating and propagating element for the ultrasonic waves.

2.1. Theoretical background

Basically, two different effects can be used for the magnetic generation of mechanical waves in metals: magnetostriction and Lorentz forces [5]. The magnetostrictive effect is caused by the rotation and/or deformation of the magnetic domains and happens only in ferromagnetic metals. The Lorentz forces act on the parasitic currents induced in the metal by a dynamic field, and are present in all metals, ferromagnetic or not. In the case that both phenomena occur at the same time, the prevailing effect depends mainly on the bias magnetic field [5, 6], in a way which is illustrated quantitatively by figure 2. The magnetostrictive contribution starts at a high efficiency, but then reaches a peak and decreases as the material saturates magnetically; the Lorentz force term increases linearly with the bias field.

To reach the linear region in figure 2, rather large biasing magnets should be used, but this is disadvantageous because of the increase of the mass of the moving head, limiting the displacement speed of the cursor. Therefore, it is preferred to use the nonlinear magnetostrictive effect, which, although more efficient at low bias magnetic fields, it is prone to the appearance of hysteresis, as we will see in section 3.

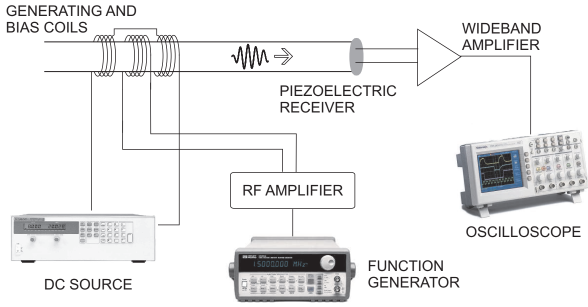

Figure 3: Experimental setup for the characterization of the electromagnetic generation of ultrasound in metal tubes.

2.2. Experimental results

Several metals were considered as possible choices for the transmitting element. To find their respective ultrasonic generation efficiencies, the experiment shown in figure 3 was carried out. A short description of the setup follows. The emitter transducer is formed by a generating coil, with length of 8 mm, diameter of 18 mm, consisting of 16 turns of copper wire of thickness 0.95 mm, and an external coil to provide the bias field (length of 54 mm, diameter 18 mm, formed by 400 turns of copper wire of thickness 0.5 mm). The magnetic efficiency of both coils was measured with a Hall effect sensor (Honeywell SS19) and it was found that the ratios magnetic induction/current were $H_1/I_1 = 780\ \mathrm{m}^{-1}$ for the generating coil and $H_0/I_0 = 2960\ \mathrm{m}^{-1}$ for the bias coil.

The transmitting elements were tubes with nominal dimensions: outer diameter 8 mm, inner diameter 6 mm and length 1000 mm, of the following metals: aluminum, brass, copper, iron, AISI 304 austenitic steel and SAF 2304 duplex steel.

The excitation signal consists of a sine train modulated by a Hanning window [7], which is created in a computer and transmitted via the GPIB bus to an arbitrary function generator (Agilent 33120A). The central frequency of the signal is 50 kHz, chosen to minimize the dispersive effects in the waveguide, and to obtain a high efficiency in the generation and reception processes. A power amplifier (ENI 240L) is used to excite the generating coil. The ultrasonic waves are picked up at the ends of the tube by bimorph piezoelectric transducers (Murata MA40B8R), amplified by a wideband amplifier (Panametrics 5660C) and then displayed in an oscilloscope. A high current DC source (Agilent 65510A) connected to the bias coil is employed to change the bias magnetic field in a controlled way.

A comparison of the amplitude of the generated ul-

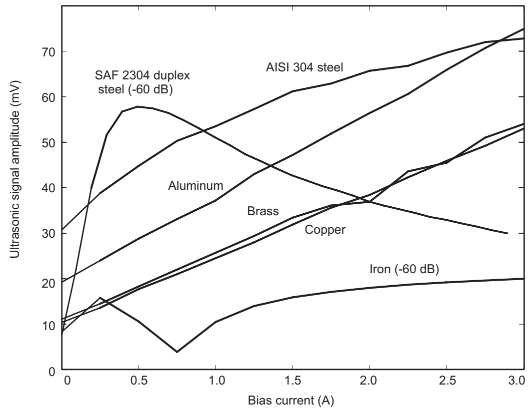

Figure 4: Amplitude of the ultrasonic signal generated in magnetic and non-magnetic metals for different bias fields. The iron and duplex steel data have been downscaled by a factor 1000.

trasonic signal as a function of the bias current for the metals enumerated above is shown in figure 4. As expected, the amplitude in the non magnetic metals (aluminum, brass and copper) varies linearly with the bias field (Lorentz force generation), while the austenitic AISI 304 steel has moderate nonlinear behavior, and iron and duplex steel SAF 2304 are highly nonlinear (prevalent magnetostrictive generation).

Although linear generation would certainly be desirable in our application, the corresponding low ultrasonic signal amplitudes (about 60 dB below magnetostriction) renders this method unusable.

The use of a duplex stainless steel in the Micrus sensor has several advantages, because it combines well known structural properties with a generating efficiency which is as high as those of pure ferromagnetic metals.

3. Position measurement hysteresis

When using the setup described in the previous section, it was found that the Micrus sensor showed high hysteresis in the estimation of the position, in the sense that different values of the measurand were obtained when a reference point was approached from the left or right sides [8]. The amplitude of the hysteresis loop was 500 μm for the SAF2304 duplex stainless steel tube and twice as large for iron. This level of hysteresis would make impossible to reach the sub-milimeter precision demanded in machine-tools sensors, and must be corrected.

3.1. Theoretical explanation

The relationship between the magnetostrictive and position measurement hystereses is explained with the help of figure 5. The upper part shows the Micrus emitter transducer schematically. By the magnetostrictive effect, the dynamic magnetic field created by the coil causes local deformations of the lattice which originate an ultrasonic wave. A set of four permanent magnets are placed in the emission region, providing a constant bias magnetic field H_0 to reduce the non-linearity effects. Thus the complete magnetic field in the tube can be written as $H(z,t) = H_0(z) + H_1(z)e^{j\omega t}$, with $H_1 \ll H_0$.

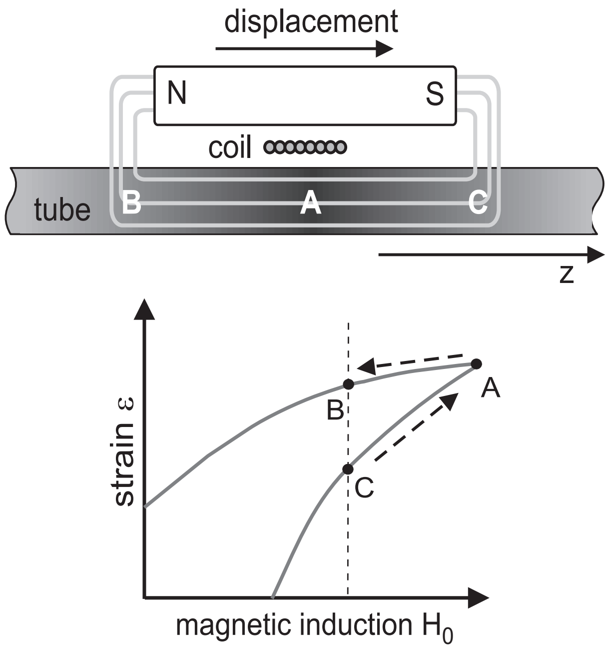

Figure 5: Physical link between the magnetostrictive and position measurement hystereses.

The magnetic generation of ultrasound takes place mainly in region A directly under the exciting solenoid, with minor contributions from lateral regions B and C. The static magnetic intensity H_0, provided by the biasing magnet, has roughly the same value in points B and C. But, as the cursor is moving to the right, the material is not in the same magnetic state in points B and C, because the field is growing in point C while it is decreasing in point B (see the lower part of figure 5). The strain ϵ caused in the material by the magnetostrictive effect is physically linked to its magnetization [2], and, as the amplitude of the generated ultrasonic wave depends mainly on the slope $d\epsilon/dH$, it can be seen that an asymmetry exists between the signals originating from the left and right sides of the cursor. The situation would be exactly opposite if the cursor was moving from right to left, which explains the hysteretic behavior observed experimentally in the Micrus sensor.

3.2. Correction of hysteretic effects

One immediate way to reduce the effect of hysteresis would be to ensure that points B and C in figure 5 are in the same magnetic state. This could be achieved by using larger biasing magnets or long enough bias solenoids. The first alternative would increase the weight of the cursor element, and the second the power consumed by the machine. Any of them suppose a limitation of the utility of the Micrus sensor.

A different way of minimizing the hysteresis is to focus the magnetic field so that the ultrasonic generation taking place in B and C is negligible compared to that of A. To achieve this, we have placed two copper rings next to the generation coil. In response to the magnetic field created by the excitation coil, eddy currents are induced in the rings, which by Lenz's law tend to cancel out the magnetic field and limit the magnetostrictive generation region. A similar technique has been applied in Non Destructive Testing with eddy currents [9]. Note that the width of the generation region can be effectively regulated by the separation of the copper rings.

4. Demonstration of the compensation technique

4.1. Finite Element Method Simulation

The performance of the compensation technique is first investigated with an electromagnetic finite element method program [10]. The geometry of the problem is shown in figure 6 (the vertical axis is the axis of cylindrical symmetry). The dimensions of the tube used as a transmitting element in the Micrus sensor have already been given in section 2. In the case of ultrasonic frequencies, it is known that the electromagnetic (EM) wave will not penetrate completely in the metal, but is restricted to a small layer in the outer surface, whose thickness is given by the skin penetration depth $\delta = (2/\omega\mu_{ri}\mu_0\sigma)^{1/2}$ [11]. As long as δ is small compared with the thickness of the tube, this element can be modeled electromagnetically by an impedance boundary condition [12], thus simplifying the numerical solution of the problem.

The metal considered for the tube is a type of duplex steel (Sandvik SAF2304), the same used in Micrus, and for which we assume the following data: relative incremental permeability $\mu_{ri} = 50$ and conductivity $\sigma = 10.4 \times 10^6$ S/m. At a frequency of operation of $f = 50$ kHz, the skin depth is 0.1 mm, a tenth of the thickness of the tube. The exciting coil is placed 4 mm away from the tube's outer surface, and consists of 10 turns of 1 mm thick copper wire, carrying a current of 1 A. The focusing elements are two copper rings, with length 10 mm and thickness 1 mm, situated between the steel tube and the generating coil, and with a mutual separation that is varied between 5 and 20 mm.

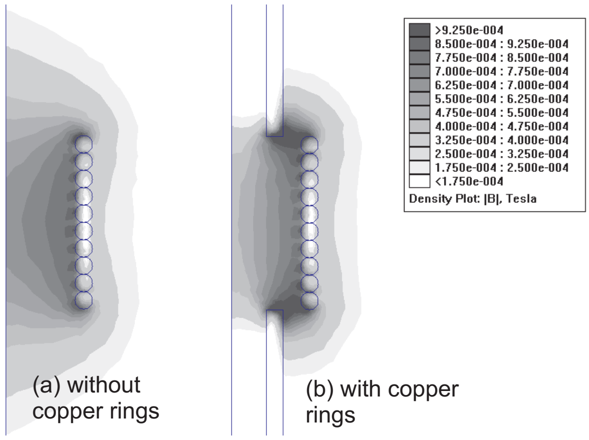

Figure 6: Finite element method simulation of the distribution of the dynamic magnetic field, with and without the copper rings. The plot shows the field density $|\mathbf{B}|$ as shades of grey.

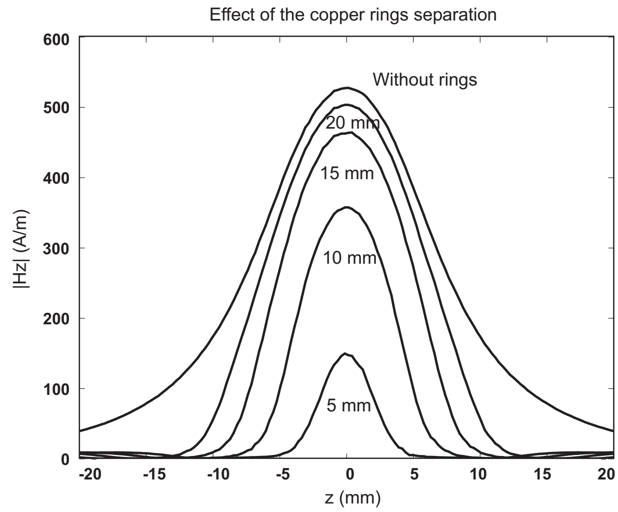

Figure 7: Effect of the separation of the copper rings in the distribution of the axial magnetic field at the outer surface of the steel tube.

In figure 6 we show the spatial distribution of the magnetic field as simulated by the finite element method program. The copper rings effectively suppress most of the magnetic field in the portion of the tube below them.

The focalization of the magnetostrictive emission can be controlled changing the separation of the rings, as illustrated in figure 7, but notice that it is achieved at expense of a decrease of the peak of the magnetic field. When using this data to adjust the separation of the rings, a third factor must be considered: the efficiency of the excitation of ultrasonic waves in the steel tube depends also on the ratio ultrasonic wavelength/width of the generation region [13, 14].

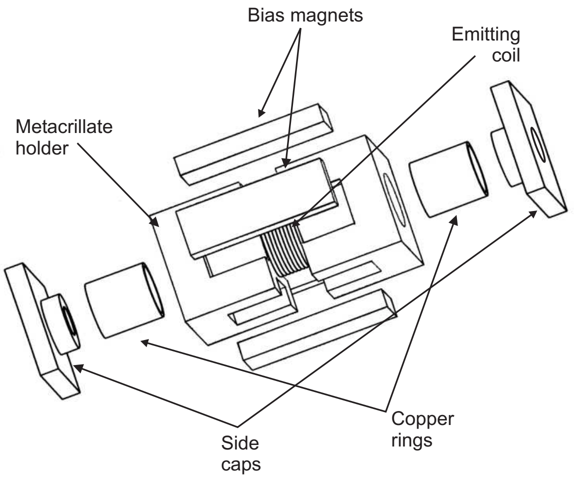

Figure 8: Ultrasonic emitter of the Micrus position sensor, implementing the compensating scheme to reduce the hysteresis.

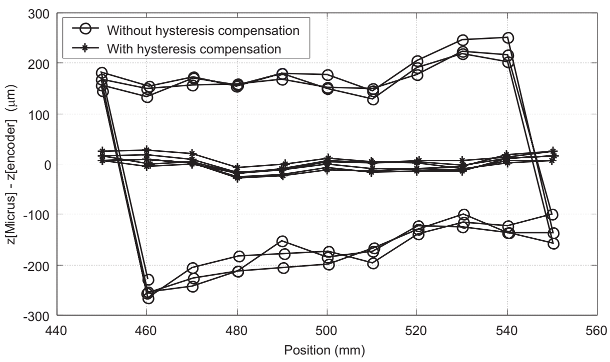

Figure 9: Correction of hysteresis in the measurement of position in the Micrus sensor.

4.2. Experimental Check with the Micrus sensor

An emitter transducer with the compensation scheme just described was designed for the Micrus position sensor and is shown in figure 8. The separation between the focusing copper rings was taken to be 18 mm [1], as a compromise between low hysteresis and good transduction efficiency.

For an experimental demonstration of the hysteresis reduction, the sensor was operated in three complete cycles, with a span of 100 mm around the middle point of the sensor range ($z = 500$ mm). The position is estimated by the Micrus system and also read from a commercial optical encoder, with an accuracy of 5 μm. We consider the error $\widehat{z}$[Micrus] $-$ $\widehat{z}$[encoder], after a linear fit between both measurements of position is carried out.

In figure 9 it is shown that without any compensation, the error curve is dominated by a large hysteresis loop, with a width of 500 μm (curve of open circles). The corrected curve using the copper rings, is shown in figure 9 (with asterisks), and in its own scale in figure 10, from which it can be acknowledged that the amplitude of the error is now 50 μm, and that there is no apparent correlation between the sense in which the curve is traversed and the error in the position. At this point, the main source of error is not due to hysteretic behavior but rather to the slow thermal drift of the sensor in the different cycles of operation, which has several effects in the performance of ultrasonic systems [15]. Some method of active compensation for the temperature changes must be developed before the system can meet the requirements of operation in a machine-tool environment.

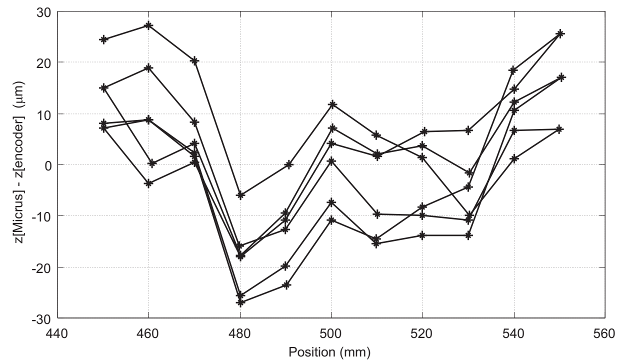

Figure 10: Error curve after the hysteresis of the Micrus sensor has been corrected.

5. Conclusions

The operation of a new linear position sensor (Micrus), which is based on the propagation of ultrasonic signals along a waveguide, has been described. Several aspects of the generation of ultrasonic waves by electromagnetic fields are discussed, especially the choice of transmitting metal. A phenomenon which couples the magnetostrictive hysteresis to position measurement hysteresis is described and identified. We propose a passive focusing method based on partial cancellation of the magnetic field by the eddy currents induced in copper rings placed concentrically with the emitter coil. After testing the technique by a finite element method simulation, it was implemented in the Micrus sensor, with satisfactory results (a reduction of the error due to hysteresis by a factor 10).

Acknowledgments

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