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ANGLE TRANSDUCER WITH FREQUENCY OUTPUT BASED ON MAGNETOSTRICTIVE AMORPHOUS WIRES

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Abstract - Amorphous wires are relatively new materials exhibiting outstanding features that make them very suitable to be employed in sensors construction. In iron-rich magnetostrictive amorphous wires (MAW) several interesting effects occur, among which Matteucci effect is of particular relevance. This effect consists in generation of sharp pulses between the ends of a straight MAW when it is concomitantly subject to an axial alternative magnetic field and to a torsion strain. The pulses amplitude depends, among other factors, on the torsion angle. In the paper, the construction of such a sensor is presented, along with a method of signal conditioning designed to converting the peak amplitude of the sensor output pulses into frequency information. The conditioning section uses a loop that controls the magnetic field intensity through the current feeding a coil, considering as control parameter the pulses amplitude. The transducer performances were assessed in comparison with a circular encoder taken as reference. The experimental tests revealed good performances to the transducer, despite its low cost. An analysis of several external influence factors upon the transducer operation and characteristics is performed.

Keywords: amorphous wire, angle transducer

1. INTRODUCTION

Angle transducers are widely used in a wide range of technical applications, from precise positioning tools in mechanical mobile systems to leading angle control in avionics. A large palette of constructive variants is now commercially available. Excepting optical encoders and incremental transducers that provide direct digital output, all the others present analogue quantities as output whose level depends proportionally on the input angle. If digital platforms are employed for information processing, analogue to digital conversion must be performed subsequent to analogue signal conditioning circuitry of the transducer. Of course, optical transducers are best suited for such applications, but their high cost forces the user to think more seriously to efficiency.

Taking advantage from some outstanding features that the new amorphous materials in wire form exhibit, we have conceived a low cost angle transducer, which provides a rectangular signal as output whose frequency is proportional to the input angle.

From the large palette of such materials now available, we have chosen for our experiments iron-rich magnetostrictive amorphous wires (MAW) having $Fe_{77.5}Si_{7.5}B_{15}$ as composition, provided by Unitika Ltd. Japan. Many authors [1], [2], [3] recommend it as very attractive for the construction of sensors designed to measure quantities like stress, torsion, magnetic field, current or displacement.

The effect on which our transducer operates is Matteucci effect. This is originally a phenomenon where ac sharp voltage pulses appear at the ends of a torsioned MAW magnetized with an ac field applied parallel to its axis. Actually, this is an alternative to the Large Barkhausen Effect (LBE) that characterizes the behaviour of magnetostrictive amorphous wires in general [4]. The schematic arrangement for observing this phenomenon is shown in Fig.1, whilst in Fig. 2 the shape of such waveform for a certain configuration of the field intensity and frequency, degree of torsion, wire length and axial tensile stress is presented.

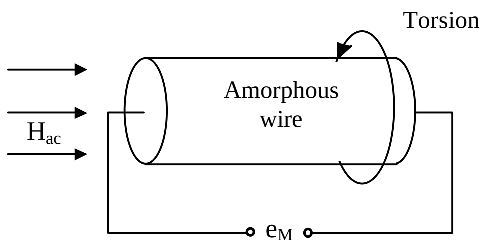

Fig. 1. Arrangement for observing the Matteucci effect

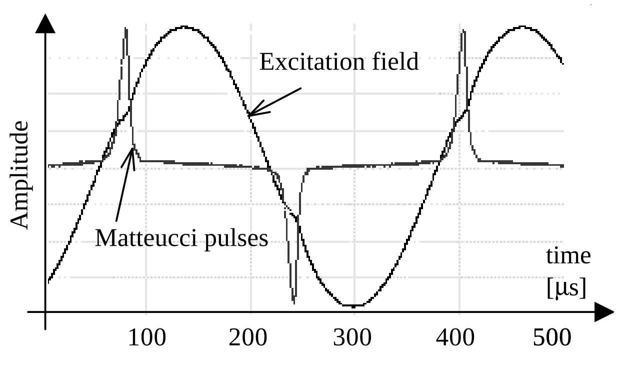

Fig. 2. The shape of Matteucci pulses for H_{ac}= 45 Oe, f = 3 kHz

The pulses amplitude basically depends on how fast the magnetic field intensity surpasses a threshold denoted as "switching field" (H*), but also on the wire torsion degree as well. H* has extremely low values making this feature very convenient to building low consuming devices. For example, the wire involved in our experiments has H* comprised between 9,6 mA/m and 1,4 mA/m.

2. TRANSDUCER DESCRIPTION

The following parts compose the transducer: the sensing element and the corresponding signal conditioning circuitry.

2.1. Sensor

The sensor conception is presented in Fig. 3.

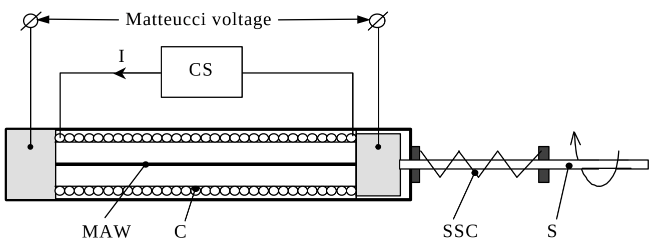

Fig. 3. Schematic representation of the sensor

The alternative current flowing through the coil C, generated by a stabilized current source CS, creates the magnetic field H_{ac} axially oriented with respect to the magnetostrictive amorphous wire, MAW. The MAW is axially stressed by the spring for stress control, SSC, which has the role of creating a certain axial tensile stress into the wire. The torsion degree of the MAW is controlled by the angle displacement of the sensor shaft, S, which is the input quantity to be measured. The magnitude of the angle was gauged by means of an angular encoder (not shown in the figure) with the resolution of 0.1 minutes and 0.2% accuracy. Characteristics, performances, sources of errors and some possibilities of application of this device are widely described in [5].

2.2. Signal conditioning circuitry

As stated above, the input quantity of the transducer is the torsional degree of the MAW, measured by the rotational angle of the sensor shaft with respect to a fixed reference. The sensor output is represented by the Matteucci pulses amplitude, which can be measured by using an analogue peak detector.

We have extended the functionality of the transducer by adding an electronic adapter in order to obtain digital information as output, particularly the frequency of a squarewave signal.

The block diagram of the signal conditioning part of the transducer is presented in Fig.4. In principle, this circuit is a loop that controls the current flowing through the coil by means of the voltage controlled oscillator VCO and the power amplifier PA. The VCO supplies a squarewave signal whose frequency is proportional to the peak-to-peak value of Matteucci pulses delivered by the sensor (U_{ppM}). The VCO input is fed by the signal obtained from the peak detector PD, amplified with the amplifier A.

From the variable resistor R1, the span of the voltage driving the VCO, which is actually the angle range of the transducer, can be set. From the variable resistor R2 one can establish the free oscillating frequency of VCO corresponding to the above domain.

The transfer function of the system can be expressed as a function between the output frequency *f*, and all the factors that influence the overall characteristic:

$$f = k_{osc} U_1 = k_{osc} A U_{ppM} = k_{osc} A \Phi(\alpha, A_p H, f) \quad (1)$$

where

$$\Phi(\alpha, A_p H, f) = \sum_{i=0}^{4} \sum_{j=0}^{2} \sum_{k=0}^{2} (A_p H)^k f^j \alpha^i \quad (2)$$

is a polynomial function. In the above expression, k_{osc} is the VCO gain, A is the amplifier gain, H is the magnetic field intensity, A_p is the power amplifier gain and α is the input shaft angle.

This is an implicit relation between the angle α and the frequency *f*, expressed in general as a non-linear dependence.

3. PERFORMANCES AND ERRORS

In this section we shall discuss the transducer characteristics and performances along with the influence of several parameters that must be taken into consideration when assessing its performances.

Table 1 displays the comparative values for linearity error, accuracy and sensitivity in different conditions related

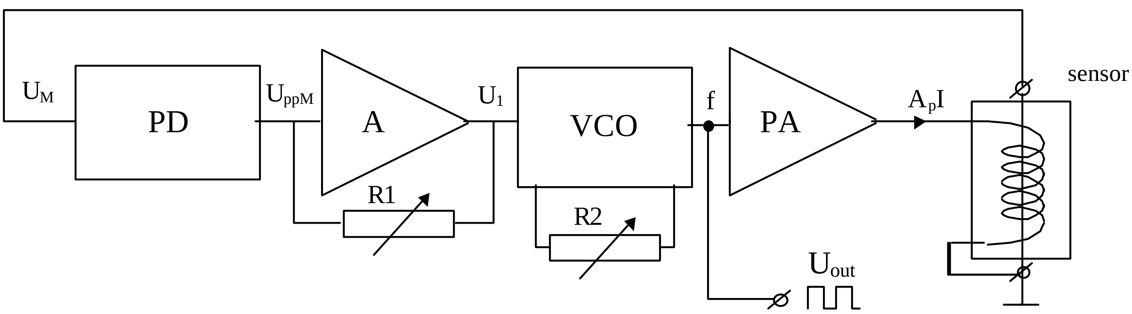

Fig.4. Block diagram of the signal conditioning circuit

Table 1. Comparative performances for different values of *f* and H_{ac}

Oscillating frequency [Hz]	Field intensity [A/m]	Range	Linearity error ε_l [% of FS]	Average sensitivity [Hz/°]
10^3	0,3	220°	11,7	10
		120°	2,38	
	0,6	220°	6,15	18
		120°	1,25	
10^4	0,3	220°	7	25
		120°	1,9	
	0,6	220°	3,2	36
		120°	0,85	

to VCO free oscillating frequency and field intensity, parameters that can be fixed from R1 and R2 resistors.

As can be noticed from the table, the higher the field intensity is, the better sensitivity and linearity become. Better results might be also obtained when the VCO free oscillating frequency increases, taking advantage of the square shape of the signal delivered by the VCO, which is approximately the same shape of the current through the coil. This is a direct consequence of the speed at which the field passes across the critical value, H*, thus creating narrow and sharp Matteucci pulses proportional to the flux speed in the vicinity of this value. However, the low pass filtering effect of the coil becomes important as the frequency increases, having as consequence smoothing rectangular waveform edges. This is why the expected gain in sensitivity and linearity caused by the square shape is not fully achieved, since the edge slopes are significantly reduced due to this filtering effect.

Fig. 5 and 6 show the dependence of the transducer output signal frequency, *f*, on the torsion angle of the shaft, α, for the two VCO free oscillating frequencies indicated in the table.

The transducer metrological parameters such linearity, accuracy, input range and sensitivity are influenced more or less by the following factors: excitation field intensity, frequency and shape, axial tensile stress, wire diameter and length, thermal treatments and temperature. The role played by each factor in the transducer functionality is further discussed.

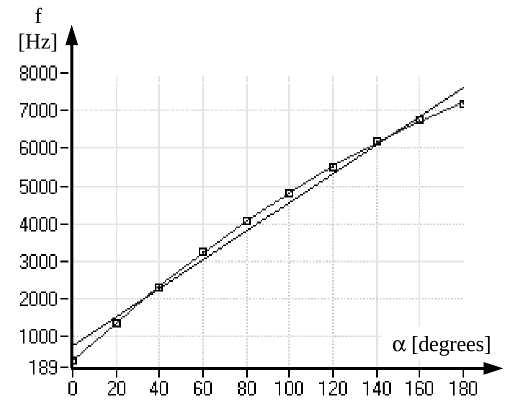

Fig.5. Characteristic *f* vs. α for f_0=1 kHz and H_{ac}=0,3 A/m

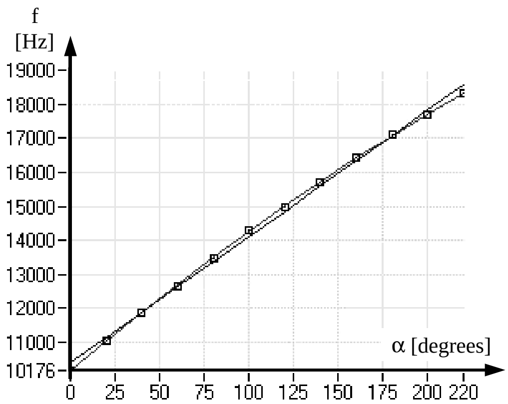

Fig.6. Characteristic *f* vs. α for f_0=10 kHz and H_{ac}=0,3 A/m

3.1.Field intensity, shape and frequency

As stated above, the extremely low value of H* at which Large Barkhausen Effect and Matteucci Effect occur, allows the using of low values for the axial field intensity provided that H* is exceeded as fast as possible. In essence, the Matteucci pulses amplitude directly depends on the magnetic flux change speed inside the wire core, despite this change theoretically occurs “by jump”. In the case of sinusoidal field, the slope around the zero crossing is proportional with the field amplitude, thus explaining the sensitivity increase with this parameter. If the field has a squarewave shape, this slope should be theoretically infinity. However, the low-pass filtering effect of the coil attenuates the slope. This effect depends on the field frequency, being more significant at frequencies above 10 kHz.

On the other hand, by increasing the frequency, a better linearity is obtained for the same range due to the same reason of fast flux change across H*. In Fig. 7, the dependence of peak-to-peak values of Matteucci pulses against the field frequency for the two shapes, sinusoidal and squarewave, are presented. As can be observed from this figure, the squarewave shape is very efficient in the domain of low frequencies, usually up to 10 kHz, when the Matteucci pulses amplitude can be 3 to 4 times greater than that obtained when the field is sinusoidal, in the same conditions.

3.2.Axial tensile stress

In the model presented in Fig. 1, the elastic force created

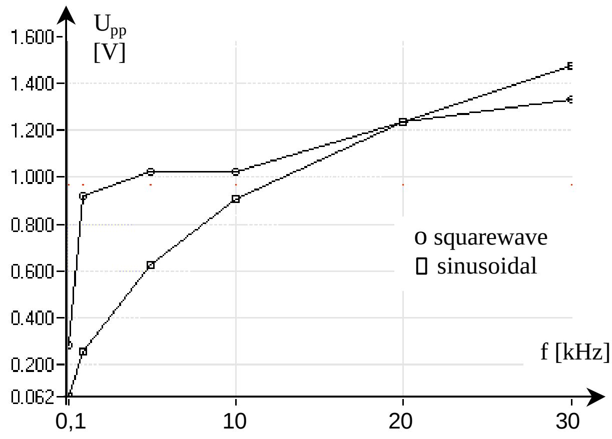

Fig.7. The dependence of peak to peak value of Matteucci pulses vs. the field frequency for sinusoidal and squarewave waveforms

by the spring SSC is applied to the wire as an axial tensile stress, which has the following consequences upon the magnetic behaviour of the wire:

- a helicoidally displacement of the magnetization vector inside the wire core;
- variation of H* with the axial stress, as a consequence of increasing the magneto-elastic energy accumulated in the magnetic domains walls.

In our experiments, the maximum axial tensile stress was 3 N. By reducing this value towards zero, an increase of the average sensitivity over 1,5 times was observed, along with a growth of linearity error, more significant in the domain of low field intensity. Experiments have been performed also to study the device behaviour as a force sensor. Even if this study is not the subject of the present paper, as sake of information, we can affirm that for á=180° and H_{ac}=0,5 A/m, our device behaves as an excellent force transducer whose characteristic f=a(F) (where *f* is the output frequency and *F* is the applied axial tensile stress) exhibits a linearity of 0,8% of FS and an average sensitivity of 6 Hz/mN, for the range of 0 to 0,8 N.

3.3.Wire diameter and length

In order to study the influence of wire diameter upon the sensor characteristics, we have employed 3 samples of $Fe_{77.5}Si_{7.5}B_{15}$ MAW with diameters of 125 ìm, 95 ìm and 70 ìm respectively. The diameter reducing was accomplished by etching method, using a diluted solution (10%) of HNO_3 and HCl in equal proportions. Three lengths of wire were also taken into consideration: 30 mm, 55 mm and 75 mm. The conclusions drawn from this experiment were the following: i) diminishing the wire diameter leads to enlarging the pulses width, concomitantly with an amplitude reduction caused by an incomplete LBE, and ii) as soon as the wire length decrease under a critical value (for this wire, 55 mm), the pulses become more "smoothed", being closer to a sinusoidal form, but with considerably decreased amplitude. By contrary, when the wire length is above the critical value, its influence is no more significant. Hence, for obtaining optimum results from this point of view, the best suited wire length is about 60-70 mm at the as-cast diameter of 125 ìm. It must be noticed that not all the wire must be inside the magnetic field, since the LBE propagates along the wire.

3.4.Temperature

The increased temperature mostly affects the internal stress distribution into the wire core, this leading to diminishing the LBE and hence the contribution of Matteucci effect. The temperature coefficient is about $7\cdot 10^{-3}$ %/°C, but this depends on the wire composition.

4.CONCLUSIONS

The transducer described in the paper was mainly designed to measure rotational angles based on the Matteucci effect occurring in magnetostrictive amorphous wires. It provides a squarewave signal as output, whose frequency depends on the rotational angle of the transducer shaft. The influences of several external parameters that affect the transducer operation were analysed, and the possibility of using the proposed transducer for measuring other quantities than the angle was discussed.

Finally, we found the optimal free oscillating frequency as large as 10 kHz, which corresponds to an angle span of 180° with linearity less than 1% and a sensitivity of 37 Hz/°.

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