A Novel Torsion Sensor

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Introduction

Torque and twisting angle sensors are broadly used in industry. The mostly used technique is based on strain gauges that measure the elastic deformation of a shaft to which they are attached at the outside. Due to the elastic limits of the strain gauge element the torsion angle is restricted to very small values. A different type of torque sensors is based on the stress-induced anisotropy of a magnetic shaft or a magnetic layer plated on a nonmagnetic shaft, referred to as magnetoelastic torque sensors. There the stress-dependent permeability or a magnetic flux emanating upon deformation is detected by means of adjacent coils or other types of magnetic field sensors. Due to this principle the torque on spinning shafts can be measured conveniently whereas the strain gauge based sensors additionally require power transmission to the spinning sensor to operate the sensor electronics. The magnetoelastic sensors are sensitive to external magnetic fields and might require magnetic shielding. For a recent review on the sensor principles see P. Ripka /1/. Here we present a novel and principally rather simple type of torque sensor that is based on the combination of magneto elastic effects with spin electronic effects *in a single piece.* Accordingly, it does not require external coils or magnetic field detectors. Due to its low power consumption and high output signal the sensor arrangement can easily be incorporated into a spinning shaft.

Sensor arrangement

The sensor arrangement comprises a single strip of an amorphous, Cobalt/Iron-based ultra-soft magnetic alloy (Fig. 1). The prototype dimensions are 20mmx1mmx20µm. The strip is electrically divided into two sections by means of two contact pairs A,B and C,D. This provides a so-called “non-local-four point” measurement setup. In principle this is the arrangement as discussed by L. Berger 30 years ago /2/ for a planar situation. At a suitable combination of twist angle and an external longitudinal magnetic field, voltage pulses (V_{out}) appear at the contacts CD when current pulses (I_{in}) are injected in the section AB.

Interpretation of the sensor operation

L. Berger predicted (not considering torsion) that voltage pulses occur at the contacts CD when magnetic domain walls are moving across the contact C, either driven by a current /2/ or by fast rising pulses /3/. It was the starting point of our sensor development to detect these voltages and to observe the predicted domain wall movements. In the beginning it turned out that in a planar setup just “spurious” voltage pulses were observed. However, when the sensor carrying printed circuit board (PCB) was incidentally twisted, voltage pulses of up to 50 mV p-p appeared at the contacts CD. The (earth) magnetic field

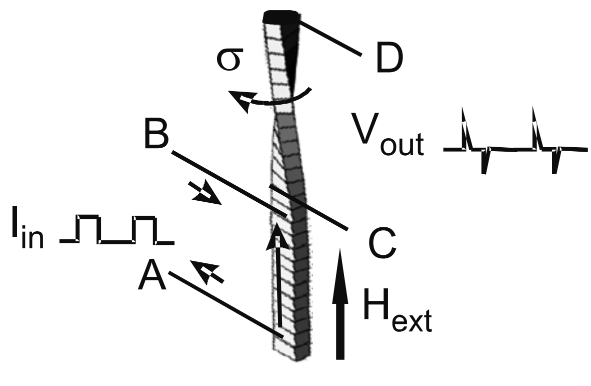

Fig. 1: The principle of the novel torsion sensor. Current pulses (I_{in}) are injected into one half of a soft magnetic strip. Under torsion (σ), voltage pulses (V_{out}) appear between contacts C and D in registry with the transients of the current pulses.

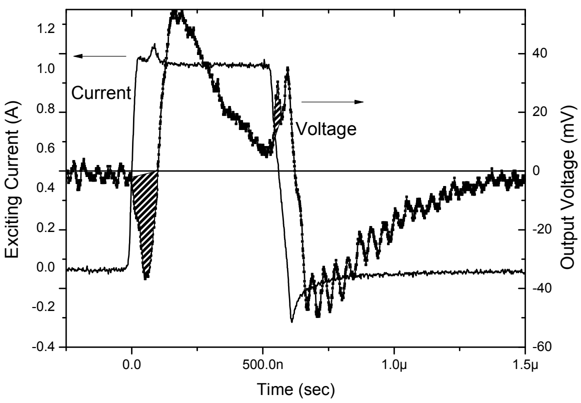

Fig. 2: The signal pulse (V_{out}) in relation to the driving current pulse. The shaded areas indicate the inductive contribution. For a clearer single-pulse signal the pulse current had been increased by a factor of about ten from its usual operating value.

dependence then was quickly seen. The torsion-dependent signal here is considered to be related to spin electronic effects, as concluded from an analysis of the signal spectrum, as will be discussed later. The torsion dependence of the voltage pulses stems from the interplay between a time-dependent helical magnetic induction within the AB section caused by the longitudinal external magnetic field in combination with the circumferential Oerstedt field of the current pulses with a torsion-dependent helical anisotropy induced in the section CD when it is twisted /4/. We suggest that the relation between both helicities determines the amplitude of the voltage pulses which accordingly reflects the amount of torsion. The helical induction in the section AB is present only during the transients of the current pulses. When the pulse is on the magnetization is circumferential whereas when it is off it is longitudinal. This explains why the signal (V_{out}) decays to zero during the steady states of the current pulse.

Fig. 2 shows the output voltage of the sensor in relation to the exciting current pulse. To reduce ringing the rise and fall times of the pulses have been flattened to about 20ns. The hatched areas are interpreted as inductive peaks due to stray fields interacting directly with the leads since they seem not to be affected by torsion. They partially overlap with the main part of the signal pulse which is considered to be related to the spin excitations. The decay time of these pulses that follow the hatched areas in Fig. 2 is comparatively long (200 ns and more). These parts of the voltage pulses are considered to be due to the decay of spin excitations occurring during the flanks of the current pulse. It is not clear yet whether the ringing seen in Fig. 2 is of trivial electronic origin due to impedance mismatch or if it is of magnetic origin, i.e. due to spin precessions.

Sensor characteristics

The signal pulses (V_{out}) depend in their amplitude, sign and shape on the combination of the sign of the current pulses (I_{in}), the direction of the longitudinal external magnetic field (H) and the torsion angle (σ) (cf. Fig. 1) in a characteristic manner. The signal phases exhibit a chessboard pattern (see Fig. 3) in the H, σ plane for fixed sign of the current pulses. Fig. 4 shows the measured signal V_{out} in part of the H,σ plane. Due to rectification, the sign information has been lost. By directly observing the voltage pulses the data are in agreement with the phase pattern of Fig. 3. With the external magnetic field in the range of 0.2-0.5 Oe the sensor signal increases monotonically with twist angle up to (-)90° and decreases for larger angles (not shown in the figure). This “hill” seen in Fig. 4 for a specific combination of H and σ is a

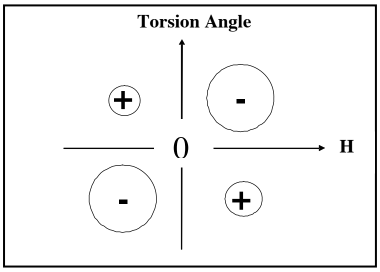

Fig. 3: The relative signal phases for unipolar current pulses of specific sign. The circles are sketches of the signal peaks above the (H, torsion-angle) plane, their diameter is indicative of the signal intensity.

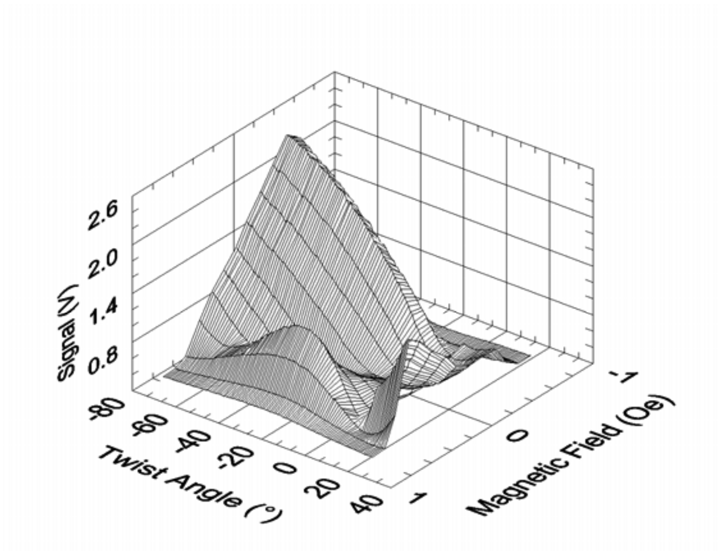

Fig. 4: Dependence of the sensor signal on the twist angle and an external magnetic field. The CD section of the sensor is mounted on a flexible substrate of 30 mm length whereas the AB section is rigid.

very clear manifestation of the magneto mechanical (magnetoelastic) effect. The magnetic field and the mechanical deformation (torsion) influences are seen to be of equal importance. Despite the large angular range covered in Fig. 4 torsions of less than 0.1° can be detected. Sensor materials can be tailored for special demands on the torsion and magnetic field sensitivities.

An important question is about hysteresis. Fig. 5 shows that under proper conditions hysteresis is virtually absent.

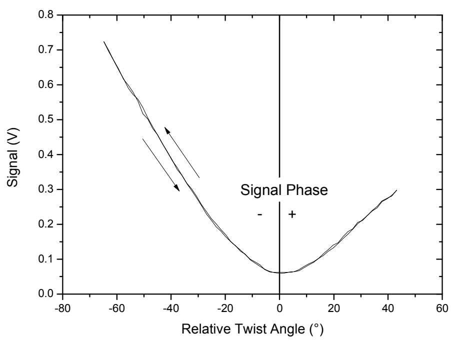

Fig. 5: Dependence of the sensor signal at fixed external magnetic field on the twist angle for clockwise and counter clockwise rotation.

Very small torques can be measured due to the small torsion modulus of the strip. With a device like that shown in Fig. 7 torques of 0.5µNm or even less should be measureable. The lower limit has not yet been determined.

Eliminating the magnetic field dependence

A proper biasing field for obtaining the optimal torsion sensitivity is needed (cf. Fig. 4). The biasing field can be provided by a magnetized wire attached to the sensor at a position that yields large torsion sensitivity. Despite the need for magnetic biasing, the external magnetic field influence has to be reduced or eliminated. As a valuable side effect of employing a biasing magnetized wire the ambient field influence is already considerably reduced so that the device is useable for applications that are tolerant on precision demands (like in steering wheels in game stations). For precise measurements however the magnetic field dependence has to be eliminated. This has been done by shielding the sensor strip by a Mumetal foil. Fig. 6 shows the characteristics of a sensor shielded in such a way. Comparing with the unshielded (and unbiased) case shown Fig. 4 the success of this approach is obvious. The biasing field

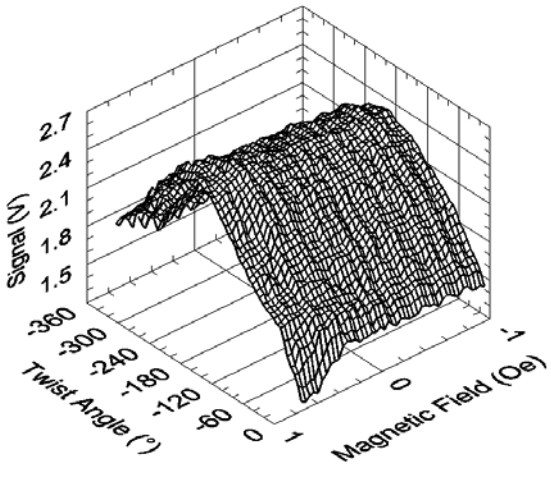

Fig. 6: Dependence of the magnetically shielded sensor signal on the twist angle and an external magnetic field. The shield is a Mumetal tube into which the sensor strip is inserted. The sensor was magnetically biased for optimal torsion sensitivity by a magnetized wire. The ripples are due to electronic noise.

can also be generated by a coil wrapped around the sensor. This approach would have the advantage that the operating point can be adjusted dynamically. Also, by modulating the biasing field with a tone frequency, signal detection can be made very efficient, by e.g. a Lockin amplifier. Another approach for eliminating the magnetic field dependence is to use electronic field compensation instead of shielding. The sensor principle offers a convenient method: A second receiver section C'D' fed by the same driving section as the CD section (see below) is made not twistable and its signal is used as an indicator for the magnetic field. By using a controller circuit the field can be continuously adjusted to its optimum value.

The magnetic field dependence of the bare sensor can be employed for magnetic field measurements. The magnetic field sensor might be referred to as a "coil-less fluxgate".

Mechanical arrangement

It is convenient to attach the sensor to a flexible PCB which makes handling very easy. The PCB then can be attached to the elements of which the torque or the torsion angle is to be determined. The sensor might be mounted axially in a tube or bore of a shaft. Attaching it to the periphery of a shaft as it done with strain gauges is also feasible. Fig. 7 shows an axial mounting scheme. There the sensor strip is freely suspended between a fixed and a rotatable mount. The rotatable mount is the end of a shaft suspended by means of double ball bearings to provide ease of rotation and also to avoid bending to which the sensor strip also sensitive.

Large torques can be measured by using an appropriate torsion tube or rod and gluing the sensor terminals to it. In this case the sensor signal serves for measuring the torsion angle between the sensor terminals from which the torque can be derived.

A single driving section (AB) can feed several receiver sections C'D', either in a linear arrangement (C'D'ABCD) or in more sophisticated arrangements. In a double-T configuration, when the current pulses are applied to the middle section of the double-T and the H-field is directed parallel to that section, output signals are observed at any of the four legs, each exhibiting appropriate symmetry relations with respect to its direction with respect to the middle section, the sign of the current pulses, the field H, and the

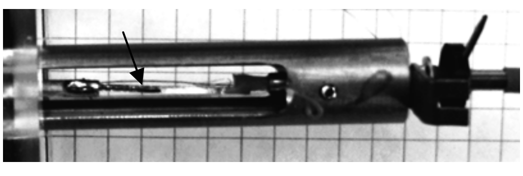

Fig. 7: A sensor strip (marked by the arrow) is fixed at the left side. The right side is suspended on a rotatable shaft, hold by miniature ball bearings. The mesh size shown is 5x5mm.

torsion angle σ. Such multiple receiver sections can be used for compensating not torsion related influences on the sensor signal (e.g. due to bending or changes in temperature or magnetic field).

Electronic set-up

Due to the specific decay time of the sensor signal (see Fig. 2) the optimal operation frequency is in the 1 MHz range. This makes it possible to use since simple AM receiver techniques for amplifying and demodulating the signal. For example, a very simple setup is made up by a quartz oscillator chip for pulse generation (the current output of common devices is sufficient) and a three-pin AM receiver chip like the MK484 to amplify and demodulate the signal. To increase the sensitivity an LC resonance circuit might be used. Since the MK484 is strongly non-linear, instead an RF amplifier together with a true-RMS converter like the LT1968 might be used. Without much effort the sensor can made free-spinning allowing inserting it into spinning shafts.

Conclusions and projections

I have presented the characteristics of a novel and principally quite simple torsion sensor based on magneto elasticity in combination with spin electronic effects in a single sensor strip arrangement. A free spinning device has been setup. Applications of the torsion sensor could be in electronically controlled assembly tools like torque wrenches and screw drivers, in automotive applications for torque detection and vehicle steering, in wind power generators, in household appliances, in toys and in controllers for game stations. I have used the sensor arrangement to steer a go-cart (Ketcar) and to detect the torque applied to a bicycle pedal crank. The magnetic field dependence of the bare sensor arrangement could be used alternatively in very cheap low-field magnetometers that might be used for vehicle detection or in electronic compasses. Miniaturizing the sensor arrangement and using plated materials instead of ribbons should be possible. This all is subject to further investigations.

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