MAGNETOSTRICTIVE BILAYER SENSOR FOR MICRO TORQUE MEASUREMENTS

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ABSTRACT

The paper reports the practical application of novel, highly bending sensitive bilayer sensors, of about 100 µm in thickness, which consist of a magnetostrictive layer and a non-magnetic counter layer. Bending yields stress in the magnetostrictive layer, the sensitivity being adjustable by the composition of the counter layer. Extremely high sensitivities proved to yield effective applications for the detection of ultra-low values of torque M (order of 10^{-6} Nm) as being typical for micro-motors. Torque measurements were performed utilizing the cable brake principle. By means of a thin thread wound around the motor shaft, increasing load - and thus decreasing rotational speed n - was attained by continuous displacement of the left end of the thread. The thread was fixed at two calibrated bilayer sensors which detected the thread forces F_1 and F_2. The torque was calculated as $M = (F_1 - F_2) \cdot (R_d + r)$, with R_d the radius of the shaft and r the radius of the thread. By measuring the speed by means of a laser tachometer the dependence of torque on rotational speed was evaluated. The compact and low cost bilayers proved to act as ultra-low-force sensors with highest sensitivity, enabling rapid and effective torque tests of micro-motors.

1 INTRODUCTION

The need of miniaturized motors for Micro-Electro-Mechanical Systems (MEMS) applications has rapidly increased within the last decades. Apart from cameras and watches, micro-motors are also used in many wireless communication products with mass data storage requirements. Medical devices, systems for minimal-invasive surgery (MIS), gyroscopes, micro-scanners and micro-robotics are potential applications as well. On the other hand, users have demanded compact energy supplies for small, portable electronics such as computers, cell phones, GPS receivers, etc. driven by high-speed micro-turbogenerators.

When these micro-motors are designed, special methods for miniaturisation are used, e.g. the similarity-method or the usage of several simulation and modelling softwares[1]. Yet, by using such an approach, the mechanical behaviour of the motors is calculated based on the macroscopic domain and on experience with motors which have already been produced and tested. Therefore, testing of the micro-motors will show whether their actual behaviour corresponds to the calculated characteristics.

The two main parameters to be measured are rotational speed and torque. The output torque of these devices is estimated to be in the range of 10^{-6} Nm. Therefore the development of innovative and highly sensitive measurement systems is essential. Moreover, most of the times the sensing of torque on rotating shafts cannot be performed directly. One of the principles used to indirectly measure the torque of a motor is by a suitable braking equipment. By varying the braking moment the rotational speed-over-torque- characteristic can be calculated. In general, the torque measurement in the micro domain though, is a challenging task due to space limitations or very low range of forces to be measured.

In this paper the development of such a highly sensitive torque measurement system, using novel, magnetostrictive bilayer force sensors[2-3] will be presented.

2 EXPERIMENTAL ARRANGEMENT

A highly sensitive torque measurement system for mini and micro motors utilizing the cable brake principle[4] was designed, developed and tested. Specifically, the cable brake is a closed force system, consisting of a cable (or thead) and a cable disc mounted on the motor shaft as shown in Fig. 1. The force along the thread is determined using two novel, magnetostrictive micro-force sensors fixed at the two ends of the thread.

The thread is chosen according to its diameter, slip and thermal expansion. In the presented case the most suitable thread is as thin and smooth as possible aiming to improve the slide friction between the thread and the disc. Taking the above into consideration optimum results were obtained using a silk thread. The thread is wound around the aluminium disc which has a chamfer to guide the thread in a single loop.

When the disc rotates and the thread stretches, the thread causes friction, brakes the disc and therefore brakes the motor shaft. Two different forces are measured at the two ends of the thread (see Fig. 1). The force difference is applied to the disc due to friction between thread and disc. This friction force acts upon the disc's circumference, creating a friction torque with respect to the middle point of the disc. Thus, if the forces F_1 and F_2 act on the thread the rotational speed of the shaft is reduced. This force difference is measured using two novel, highly sensitive magnetic bilayer force sensors, as it will be described below. The torque is then calculated by:

$$M = (F_1 - F_2)\cdot(R_d + r) \quad , \qquad (1)$$

where R_d is the radius of the disc and r the radius of the thread.

It is worth mentioning that by changing the radius of the disc the force ranges can be inflenced whereby torque measurements can be expected to be more accurate with smaller disc radius.

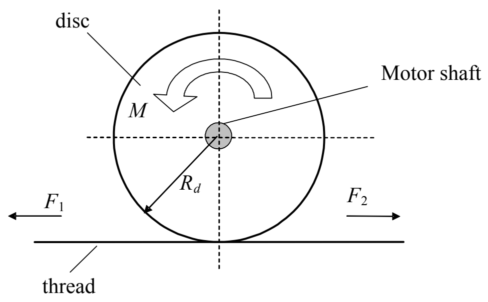

Figure 1: Cable brake principle for torque measurements at a motor shaft.

Figure 2 shows a schematic of the developed torque measurement set-up. It consists of the motor to be tested, the thread wound around the motor shaft (specifically around the disc which is mounted on the shaft), and the two force sensors. One force sensor (Sensor 1) measuring the force F_1 is fixed on a mobile holder. As the holder is displaced, the thread stretches. Therefore due to friction the disc brakes thus braking the motor shaft. That means that the displacement of the holder acts upon the motor shaft as a load. A second force sensor (Sensor 2) measuring the force F_2 is fixed on a non-mobile holder. The results obtained from the experiments are presented on section 4 of this paper.

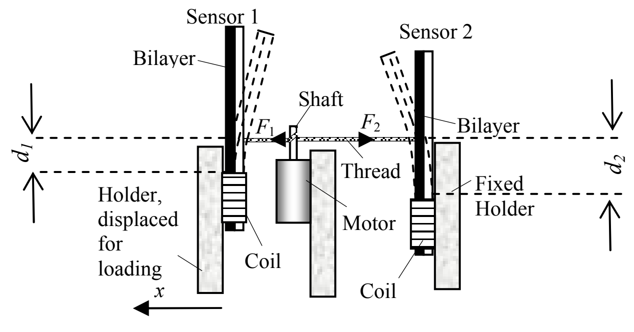

Figure 2: Torque measurement set-up.

3 FORCE SENSORS

As mentioned in section 2, the force measurements are performed using novel magnetostrictive bilayer (BL) sensors[5-6]. The bilayers consist of a magnetostrictive layer (ML) and a non-magnetic counter layer (CL). Bending yields stress in the ML, the sensitivity being adjustable by the composition and the material parameters of the CL i.e. its Youngs modulus and its thickness[7-8]. Bending signals are established on the basis of the stress dependent permeability changes of the ML which are detected by means of an impedance measurement[9] at a coil wound around the BL. This yields a sensor signal which depends on the curvature of the BL. The BL is applied for the force measurements by fixing one of its ends, while the force acts on the free end (Fig. 2). The coil for signal establishment is wound around the fixed BL end.

To detect the permeability changes of the ML, the BL is magnetised by a magnetic field generated by applying a sinusoidal current i of constant amplitude 20 mA and frequency f on the pick-up coil. The magnetic field, characterized by the flux Φ, depends on the MLs μ and the force F, respectively, as well as on i. The induced voltage u of the pick-up coil is given by

$$u = -N \frac{d\Phi(\mu, F, i)}{dt}, \qquad (2)$$

where N is the number of windings. Changing the position of the BLs free end yields a corresponding change of u which was detected. For this reason the electronic circuit depicted schematically in Fig. 3 was developed. Beside the excitation of the coil, the circuit manages the signal processing in three steps. First, it produces the amplitude signal U of u by means of a common amplitude demodulation technique. Second, the compensation of the signal level measured before loading the thread yields the change ΔU of U corresponding to the permeability change. At last it generates the output signal Δs by amplifying ΔU as a measure of F. The excitation frequency f is 20 kHz, where the high sensitivity is guaranteed due to negligible resistive load and low eddy current losses.

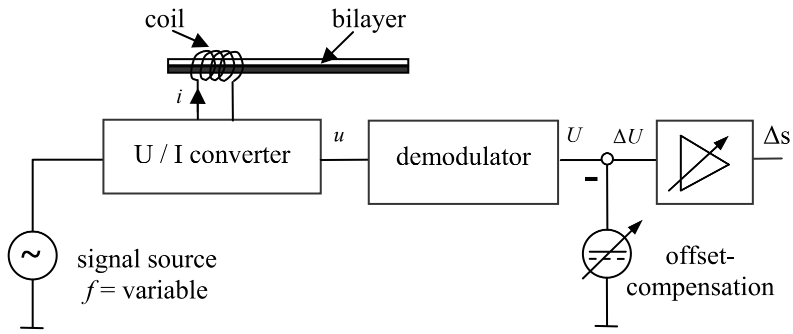

Figure 3: Scheme of the signal establishment electronics.

As shown in Fig. 2, two force sensors have to be applied which will measure different force values as given from Eq. (1). By adjusting d_1 and d_2, the distance between the fixed part of the bilayer and the application point of the force (Fig. 2), it is possible to use two identical bilayer sensors exhibiting different sensitivities for different force ranges.

Taking the above into account it is concluded that the force sensors should be calibrated prior to measurements. This would result to a correlation between the sensor signal Δs (a voltage difference detected on an oscilloscope) and the applied sensor force. It was tested and concluded that concerning the measurements reported in this paper, the effect of the position of the sensor (parallel or perpendicular to the direction of the earth's magnetic field) on the sensor signal is negligible. Therefore the calibration is performed using a series of different weights and by multiplying this mass with *g* the force is calculated. The calibration curves for Sensor 1 and Sensor 2 are presented in Figures 4 and 5 respectively.

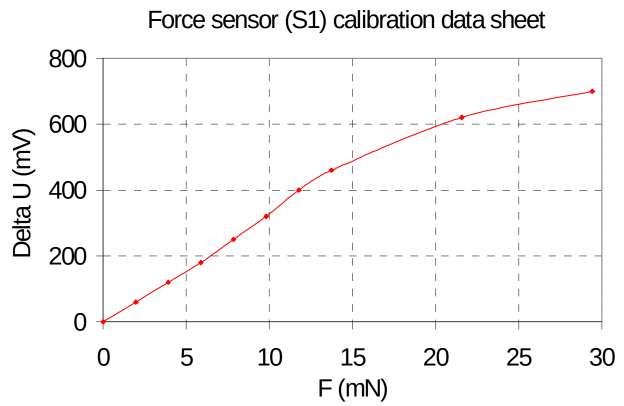

Figure 4: Calibration curve for the force Sensor 1 measuring F_1.

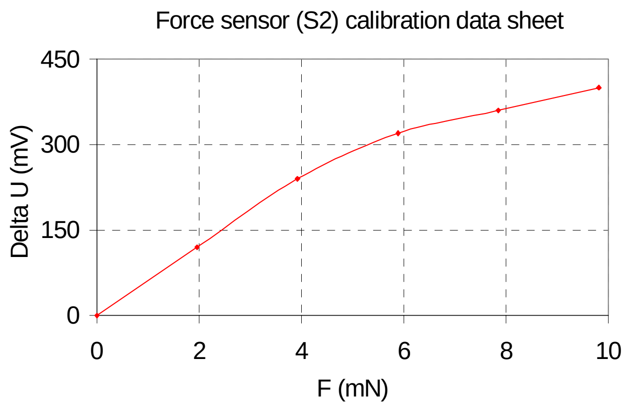

Figure 5: Calibration curve for the force Sensor 2 measuring F_2.

4 RESULTS

In order to investigate the efficiency of the novel, magnetostrictive bilayer sensors for torque applications experiments were performed on a test mini motor. Specifically, a commercially available DC mini motor (shaft 0.7 mm in diameter, 4 mm length) was tested. A thin silk thread (70 μm in diameter) was used as a brake cable and an aluminium disc (2 mm in diameter) was mounted on the motor’s shaft. In general a characteristic curve of a DC motor gives the output torque of the motor corresponding to a specified speed at a nominal voltage. Therefore the rotational speed has to be measured as well. These measurements were performed using a commercially available laser tachometer with the help of a reflective tape attached to the aluminium disc. Fig. 6 presents the acquired results.

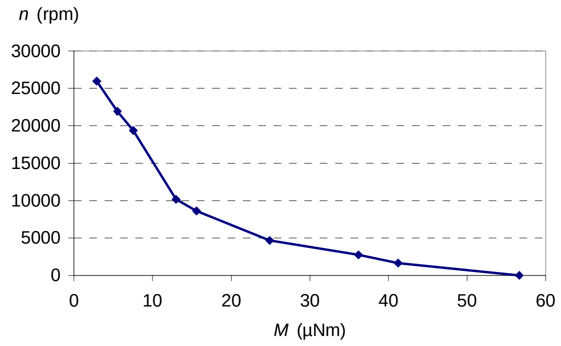

Figure 6: Speed *n* of a micro-motor as a function of torque *M*.

It is observed that torque increases exponentially with decreasing speed. These results demonstrate the compact and inexpensive bilayers prove to act as ultra-low-force sensors with highest sensitivity, enabling effective torque tests of micro-motors.

5 CONCLUSIONS

Novel magnetostrictive bilayer sensors were reported to measure low forces enabling micro torque measurements at mini/micro motors in combination with the cable brake principle. The sensors are able to measure very low forces with high accuracy enabling the developed measurement system to detect torques as low as some µNm. In addition, the system is expected to assure high flexibility with respect to the force and torque ranges as well as to sensitivities by adjusting either the bilayer material, the position of the force application point on the bilayer or the diameter of the shaft by means of a smaller disc.

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