SIMPLE MAGNETOMECHANICAL TORQUE SENSOR – DESIGN, CONSTRUCTION AND TESTING

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Abstract

The aim of this paper is to present a design of the simple magnetomechanical torque sensor composed of the steel shaft, the pair of ball bearings, the magnetising coil and the search coil. Also, it presents the results of initial testing of the assembled sensor. Testing has been made with different diameters of the shaft loaded with cyclic variations of static torque. The results obtained have been presented and discussed in the paper.

Keywords: torque sensor, magnetomechanical effect, design, construction, testing.

INTRODUCTION

The origins of the magnetomechanical effect, related to the variation of magnetisation of a magnetic material with the applied mechanical stress, are well presented in the literature [1-3]. Previous research on the magnetomechanical effect under torsional stress has shown that it can be measured using a simple measurement setup with the magnetising coil and the search coil [4]. However, that research has been done on large scales, where the dimensions of the components were much larger than those in practical applications.

This paper presents a design, construction and testing of a simple torque sensor which works on the principle of magnetomechanical effect. Such sensor has a compact size. It consists of one steel shaft, a pair of ball bearings and two coils, the magnetising coil and the search coil. An alternating voltage of the constant amplitude has been supplied to the magnetising coil in order to produce an axial magnetic field in the shaft. The shaft has been exposed to the torsional stress and the variation of voltage induced in the search coil has been measured. Such measurements have been done with different amplitudes and frequencies of the supply voltage. Also, several shafts with different diameters have been used in the testing of the sensor. Initial tests have been performed under variable static torque produced by a steel lever arm. Further tests have been made on specialised testing station that contains induction motor, electromagnetic brake and flexible couplings.

The paper gives all details on the sensor parts and its construction. Also, it presents the results of sensor testing, as well as their detailed discussion.

TORQUE SENSOR

Designed torque sensor consists of mechanical and electrical parts.

Mechanical parts are:

1. steel shaft,
2. pair of ball bearings and
3. plastic housing.

Electrical parts are:

1. magnetising coil and
2. search coil.

All parts are separately presented in Fig. 1. Some part of the sensor is specific, such as the steel shaft, since it is replaceable. Therefore, shafts with different diameter, as it has been presented in Fig. 2, have been used for construction of the sensor. Four shafts have been made from one long C45 carbon steel shaft of 17 mm diameter [5]. Each shaft has reduced diameter in the central part. Reduced diameters are 4 mm, 6 mm, 8 mm and 10 mm. The length of that central part of the shaft is the same with the length of the coils and amounts 50 mm. A total length of each shaft is 145 mm. Steel shaft needs to be placed inside the coils and fixed in place with Seeger ring and ball bearing on each side. Mounted together, these parts need to be placed inside the 3d printed plastic housing, as it has been presented in Fig. 3. \

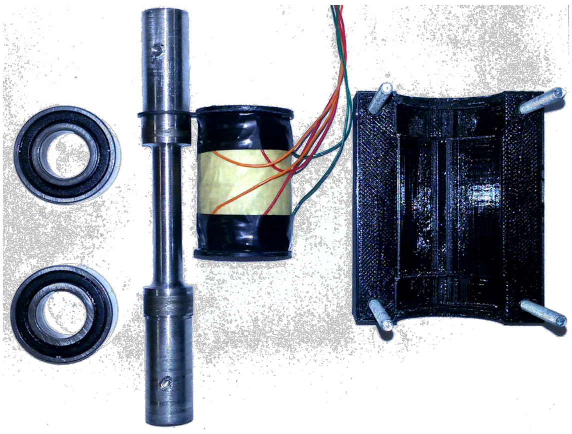

Fig. 1. *Parts of torque sensor.*

Fig. 2. *Steel shaft with different diameter.*

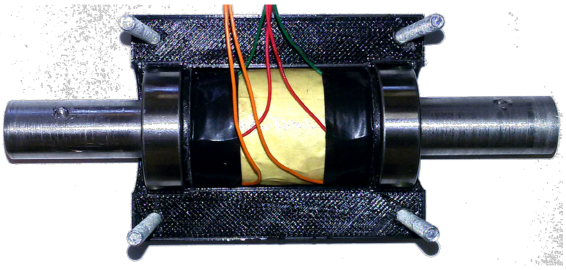

Fig. 3. *Position of sensor parts inside housing (cover removed).*

Finally, a top cover of the housing need to be put in place and fixed with four screws. Assembled sensor (top view and side view) is shown in Fig. 4. Dimensions of the housing are 80×62×42 mm.

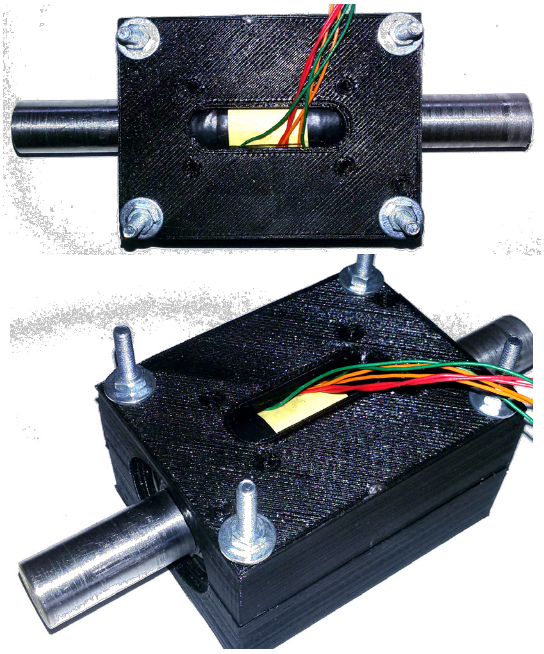

Fig. 4. *Assembled torque sensor.*

The magnetising coil and the search coil have three layers with 2000 turns in each layer. The magnetising coil has been wounded first and the search coil is wound above the magnetising coil.

RESULTS OF TESTING

In order to examine sensor response at no-load condition, initial tests have been started without applied torque and under stable sinusoidal supply voltage of 5 V (RMS value) at the frequency 50 Hz. This voltage produces the electric current *i* in the magnetising coil larger than 20 mA (RMS value), as it has been presented in Fig. 5. The induced voltage *u* in this case is higher than 2 V (RMS value). Such level of the induced voltage is adequate for accurate measurement.

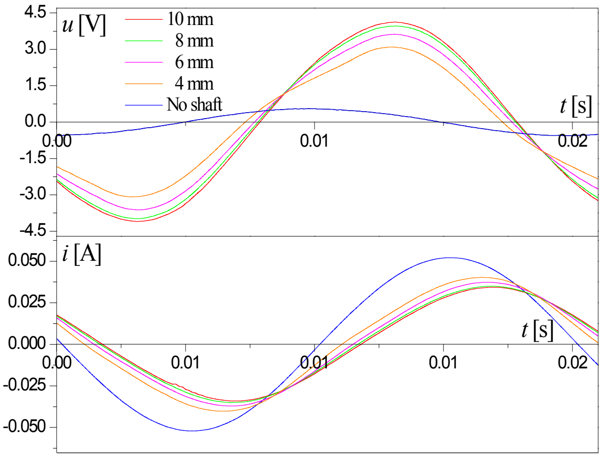

Fig. 5. *Magnetising current and induced voltage – without shaft and with different shafts.*

As it has been presented in Fig. 5, time waveform of the induced voltage and the magnetising current, at 5 V/50 Hz supply voltage, depend on the diameter of the steel shaft. Thus, for the Ø4 shaft the current is the highest, while the induced voltage for this shaft is the lowest. However, it is important to notice that the waveform of the Ø4 shaft induced voltage and current are not sinusoidal. Therefore, this shaft is magnetised more than other shafts and the nonlinear magnetic behaviour of the steel is more expressed in this case. This can be better observed on the $\int u\mathrm{d}t=f(i)$ loops (equivalent to $B=f(H)$ loops) presented in Fig. 6. Such loop for the Ø4 shaft is deformed from elliptical shape, as well as the Ø6 shaft loop, while loops for the Ø8 and Ø10 shafts are very close to the ellipse. Since all shafts have been made of one material, this means that shafts with smaller diameter have been magnetised more than shafts with larger diameter. Calculation of the magnetic flux density in the shaft is not a simple task because of the ferromagnetic nature of the steel and because of the presence of eddy currents. Even so, according to the waveforms given in Fig. 5 and loops given in Fig. 6 it is better to use shafts with larger diameter, such as Ø8 and Ø10 shafts, in order to avoid the undesired nonlinearity effect.

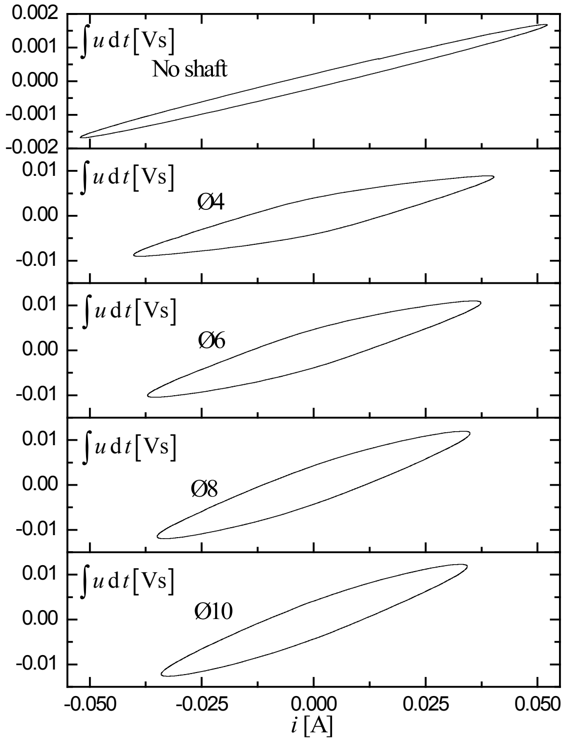

Fig. 6. *Hysteresis loop – without shaft and with different shafts.*

A variation of the frequency of supply voltage has been also considered during testing of the sensor. Under the same amplitude of supply voltage, the decrease of the frequency increases the magnetisation current and nonlinearity effect, while the increase of the frequency decreases the current and the nonlinearity, but increase linearly the induced voltage. However, the sensitivity of the sensor has remained the same, regardless the variation of the frequency. Therefore, it has been decided to keep initial settings (5 V/50 Hz).

The second phase of testing considered sensor response under applied torque. Two rounds of testing under static torque have been performed, one under the torque produces with the lever arm and weights and the other under the torque produced by the induction motor coupled to the electromagnetic brake.

In the first case, one side of the sensor steel shaft has been fixed to the solid support. The lever arm has been mounted on the other side of the shaft. The test has been started without weights on the lever arm and continued by adding one by one of four 1 kg weights on the lever arm at the position distanced by 30 cm from the shaft longitudinal axis. Also, weights have been removed one by one in order to obtain the unloading of the shaft. This procedure has been repeated four times in a row for each steel shaft. Plastic deformation has been observed with the Ø4 shaft and it has been removed out from further tests. The results obtained for other three shafts are presented in Fig. 7.

These results show variation of the induced voltage with the mass of weights during four cycles of loading and unloading of the sensor shaft. Also, an average loading and unloading path has been presented in the zoomed inset. The result obtained for Ø6 shaft show the increase of the voltage with the increase of the load mass from 0 kg to 1 kg and the decrease of the voltage with the increase of the load mass from 1 kg to 4 kg. Other two results obtained for Ø8 and Ø10 shafts show a continuous decrease of the voltage with the increase of the mass. Analogue behaviour has been observed during the decreasing of the load mass. Accordingly, the response of the sensor with the Ø6 shaft has been interpreted as inadequate and this shaft has not been used in further tests. The response of the sensor with Ø8 and Ø10 shafts is adequate. The presence of hysteresis has been observed in the results during all tests. This is the mechanical hysteresis, typical for the used steel.

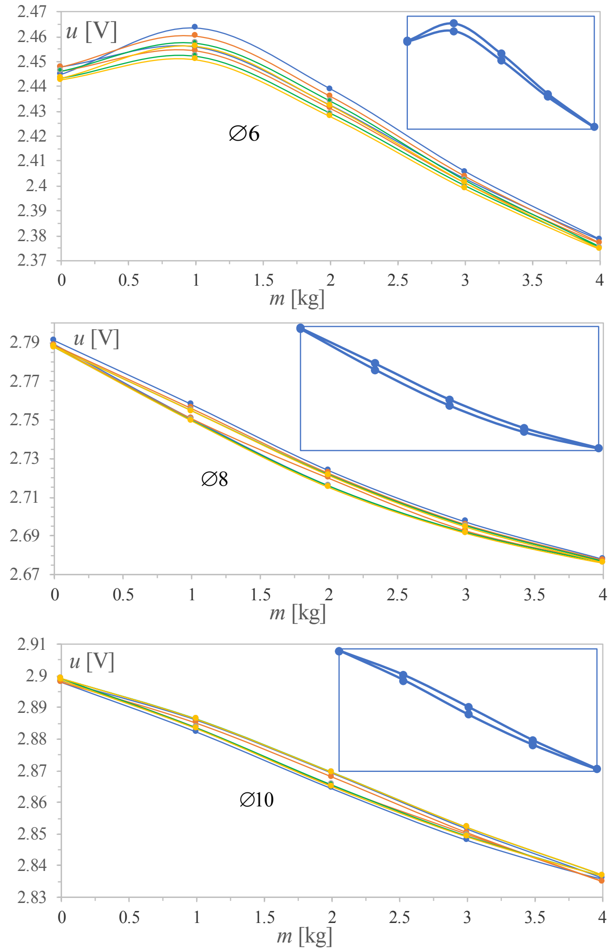

Fig. 7. *Variation of induced voltage with mass of weights (blue line – first cycle, orange line – second cycle, green line – third cycle, yellow line – fourth cycle).*

Sensor tests at the test station with induction motor (IM) and electromagnetic brake (EB) have been performed only with Ø8 and Ø10 shafts. The sensor is mounted together with the IM and EB as it has been presented in Fig. 8.

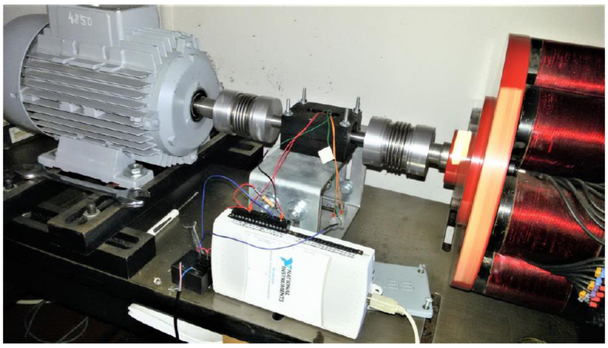

Fig. 8. *Sensor mounted on the test station.*

The IM has been supplied with rated phase-to-phase voltage (380 V) and run without the load to reach rated speed. Then, the electric current of the EB has been set to 0.3 A to produce low torque. After a short period of time a steady state has been reached and the recording of the induced voltage of the sensor has been started. The electric current of the EB has been increased in equal steps of 0.1 A up to 0.8 A and then decreased back to 0.3 A and the induced voltage has been recorded during this procedure. The result of such test for Ø8 and Ø10 shafts has been presented in Fig. 9. The upper graphs in Fig. 9 show that the induced voltage changes gradually with the change of the applied torque (the EB current). The lower graphs in Fig. 9 have been constructed of the data from the upper graphs. An average value of the measured voltage has been calculated for each current value (each step-stair in the upper graphs). Each value presents one point in the lower graphs. These lower graphs show the presence of the hysteresis, which is in accordance with graphs presented in Fig. 7. There is no significant difference between the hysteresis loops presented in Fig. 9.

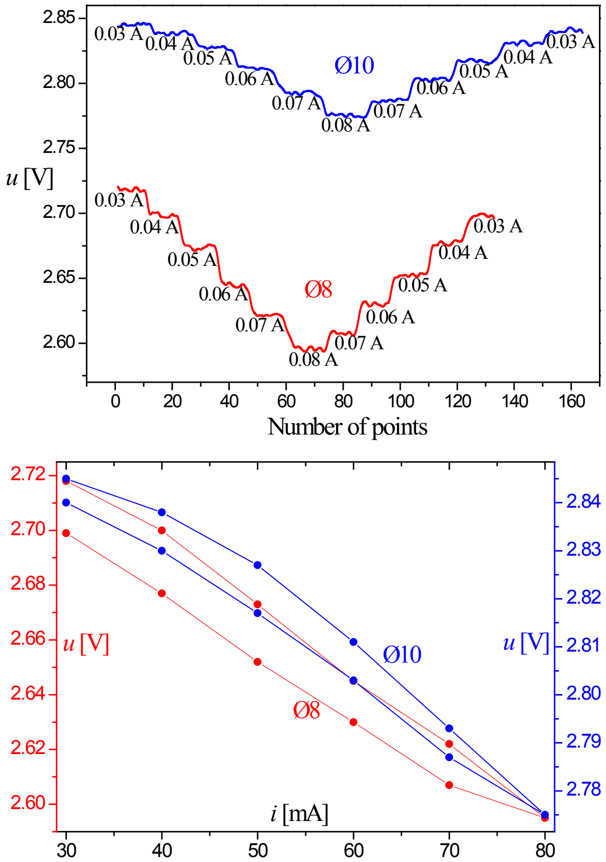

Fig. 9. *Response of the torque sensor during the test with IM and EB.*

In general, there is just one difference between the response of sensor obtained with the Ø8 shaft and the response of sensor obtained with the Ø10 shaft. The difference is in the sensitivity of the sensor. In the particular case, the variation of the output voltage when the Ø8 shaft has been used amounted about 0.12 mV and the variation of the output voltage when the Ø10 shaft has been used amounted about 0.07 mV.

DISCUSSION

There are advantages and disadvantages of the proposed design and construction of the torque sensor.

The advantages are:

- a small number of parts of a very simple design which can be easily made,
- easy assembling and disassembling,
- easy installation with the rest of the test equipment, such as induction motor and electromagnetic brake,
- the supply voltage has low level and the frequency of electric network and
- simplicity and low cost of the sensor.

The disadvantages are:

- presence of the mechanical hysteresis,
- no information on the direction of the applied torque and
- relatively small changes of the output voltage even for significant torque applied.

Further research would be devoted to the solving of these disadvantages and to the calibration of the sensor with another torque sensor with known characteristic.

The proposed magnetomechanical sensor can be also used for investigation of the magnetic characteristics of steel shafts. The material can be characterized in DC and AC magnetic fields of different amplitudes, shapes and frequencies, with and without applied torque.

It can be also used in the educational purposes within the courses of electrical and mechanical engineering, mechatronics and physics.

CONCLUSION

This paper presents the realization of a simple and low cost magnetomechanical torque sensor which has been built of simple mechanical and electrical parts. The basic parts of the sensor are the steel shaft, the magnetising coil and the search coil. The shaft has been magnetised and mechanically stressed at the same time. Shafts with different diameters have been tested. The variation of the induced voltage in the search coil with the applied torque has been observed. After cyclic variations of torque from no-load state to maximum load state the mechanical hysteresis appears.

A detailed presentation of all results obtained, as well as a proper discussion, has been given in the paper.

Further research would be devoted to the calibration of the sensor with another torque sensor with known characteristic. Also, ways of elimination or minimization of the hysteresis effect will be examined in the future.

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