Simple Measurement of Magnetomechanical Effect of Cylindrical Steel Shaft under Static Torsional Stress

Vojislav Vujičić, Miloš Božić, Branko Koprivica and Alenka Milovanović

***Abstract*—The aim of this paper is to present a detailed description of one simple experimental setup for measurement of the magnetomechanical effect of the cylindrical shaft made of commercial steel. This setup contains mechanical parts that allow generation of static torsional stress to the shaft. It also contains a large solenoid that produces an alternating magnetic field for axial magnetisation of the shaft, which is placed in the centre of this solenoid. Another smaller solenoid is also placed inside the large solenoid and around the shaft to detect changes of the magnetic flux in the shaft under applied torque. The paper also presents initial measurement results obtained with this experimental setup, as well as proper discussion of these results.**

***Index Terms*—Magnetomechanical effect, torsion, steel shaft, solenoid, LabVIEW.**

I. Introduction

THE magnetomechanical effect is related to the variation of magnetisation of a magnetic material with the applied mechanical stress [1]. This effect is well known for a long time [2] and it is still interesting to researchers in testing of behaviour of novel magnetic materials and because of its wide practical applications [3-7]. Magnetic material can be stressed in different ways, such as compressive or tensile stress under mechanical force and bending or torsion stress under mechanical torque. The influences of these stresses on magnetisation of the material are different, as it has been already discussed in the literature [2].

This paper presents simple laboratory setup for measurement of the magnetomechanical effect of the cylindrical steel shaft under static torsional stress. An initial idea was to test commercial steel shaft in an axial magnetic field and under static torque to detect the eventual appearance of magnetomechanical effect in the material. The intention was to test the material that is often used in production of rotating shaft and parts exposed to the torque. Also, such material is interesting for testing since its magnetic characteristics are unknown. Another idea was to perform non-contact measurement by detecting the change of magnetic flux density (induced voltage) in the shaft with excitation coil, without magnetic thin film deposition on the tested shaft.

A simple laboratory setup, that contains mechanical and electrical parts, has been constructed for the purpose of testing. During the tests, steel shaft under test has been magnetised with an alternating magnetic field of constant amplitude and it has been exposed to torsional stress of different magnitudes. Testing is starting from non-stressed state and with the increasing of the torque and then with decreasing of the torque to the non-stressed state in order to examine the presence of hysteresis effect. During the tests, values of applied torque and induced voltage have been recorded. Tests have been repeated with different amplitudes of the magnetic field in order to examine the influence of such variation on measurement results.

Results of variation of normalised induced voltage with the applied torsional stress have been presented in the paper. Also, the influence of the magnetic field strength (excitation current) on the variation of the induced voltage has been presented. A proper discussion of all results has been given.

II. Laboratory setup and test procedure

A drawing of cross-section, electrical scheme of connections photo of laboratory setup for measurement of the magnetomechanical effect in steel shaft under torsional stress are presented in Fig. 1. It contains mechanical and electrical parts and measurement equipment.

Mechanical parts are:

1. tested shaft mounted on the steel rack with bearings for support (400 mm long and 10 mm in diameter),
2. steel lever arm for torque generation and
3. set of weights.

Electrical parts are:

1. variable voltage power supply (50 Hz),
2. large solenoid for generation of magnetic field (360 mm long and 65 mm in diameter),
3. smaller solenoid for measurement of magnetic flux variations (300 mm long and 20 mm in diameter) and
4. 1 Ω, 10 W, resistor for measurement of electrical current of large solenoid.

Measurement equipment consists of a data acquisition card NI 6036e connected to a personal computer with LabVIEW software. This card has the following characteristics: 16

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analog input channels of 200 kS/s maximal sample rate and 16 bits of resolution, with programmatically adjustable voltage range from ±0.05 V to ±10 V.

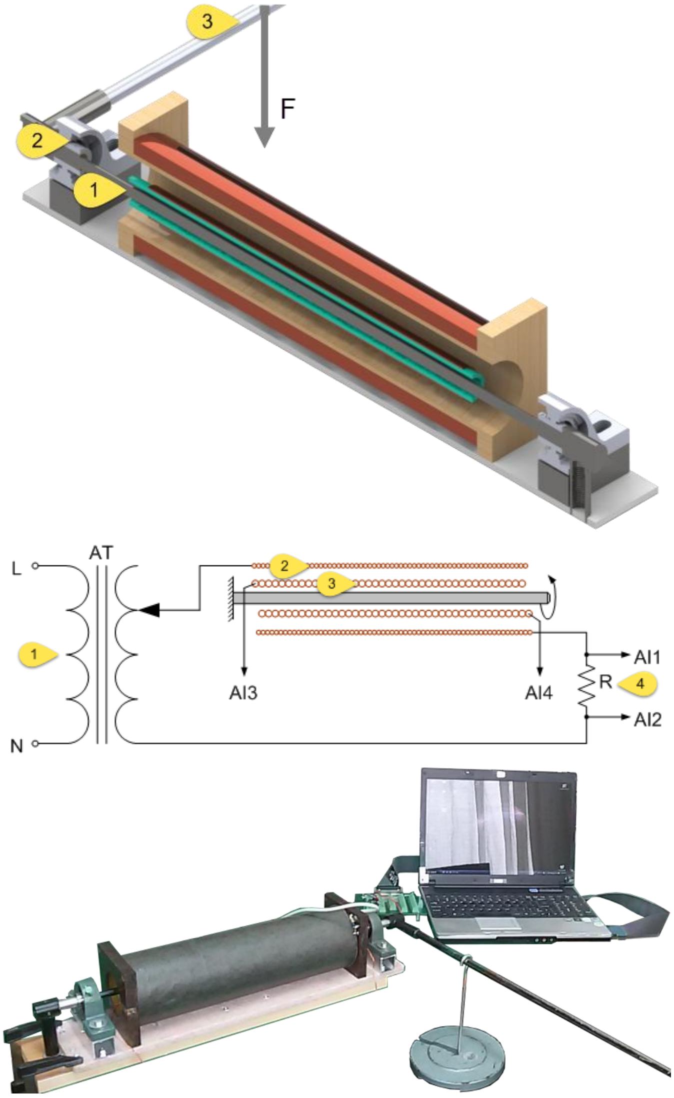

Fig. 1. Drawing of axial cross-section, electrical scheme of connections and photo of laboratory setup.

Measurements have been performed according to the following procedure:

1. initially, the shaft has been demagnetised and no torque has been applied,
2. the electric current of large solenoid has been increased to the desired level and the shaft has been magnetised, no torque has been applied,
3. the shaft has been magnetised and torque has been applied in the increasing direction to the certain maximum and then torque has been decreased to the non-stressed state; during this step values of the torque and RMS value of the induced voltage have been recorded; this step has been repeated three times.

This procedure has been repeated for different values of the electric current of large solenoid. The average value of three measurements of induced voltage, for a particular value of the electric current, has been calculated.

III. Measurement Results and Discussion

Measurement results obtained according to the procedure described in the previous section have been obtained for four different values of electric current of large solenoid: 0.02 A, 0.04 A, 0.06 A and 0.08 A. Previously has been performed measurement of the magnetic field intensity of that solenoid for 0.3 A of electric current, without steel shaft inserted, and approximate intensity of the magnetic field was 4400 A/m. Therefore, for electric currents used in the measurements with steel shaft, the magnetic field intensity generated by the large solenoid varies from 300 A/m to 1200 A/m. This magnetic field will cause significant magnetic flux density in the shaft. Since the frequency of the magnetisation field is 50 Hz and the shaft has high conductivity, induced eddy currents in the shaft are significant. Accordingly, magnetic flux density will be much larger closer to the surface of the shaft than in its central part. However, this effect has not been considered in the analysis of the results presented in this paper. Moreover, since the magnetic properties of the tested steel shaft are unknown, the analysis of magnetic field and flux density, or magnetic hysteresis, of the shaft has not been performed. For that reason, only variations of the induced voltage (its RMS value) in the smaller solenoid with a variation of the applied torque has been presented and analysed in this paper.

Static torsional stress (torque) has been produced by weights placed on the lever arm which is perpendicular to the tested shaft. The maximum value of the applied torque was approximately 16 Nm. Tested shaft can stand much larger torque than 16 Nm, but with larger torque twisting of the shaft is significant. The intention was to keep this twisting within minimal level and for that reason applied torques were at relatively low level.

Measured induced voltage amounted from about 0.15 V to about 1.1 V, depending on the excitation current. However, in order to have comparable results, in each set of results voltages have been normalised to its maximal value in the set. Variations of these normalised induced voltage with torque, obtained for four different values of electric current in large solenoid, have been presented in Figs. 2-5.

Presented results confirm the presence of the magnetomechanical effect in the tested steel shaft. Measured induced voltage (magnetic flux density in the material) decreases with increase of torque. Therefore, magnetic permeability of steel shaft decrease with increase of torque. Results also show the presence of hysteresis effect in the shaft. It seems that the hysteresis effect is more expressed at lower magnetisation currents, but this influence need to be investigated more. Therefore, the more general conclusion on this influence cannot be given in this paper. Some irregularities in the shape can be observed in loops given in Figs. 2-5. They are a consequence of errors made during measurements. Namely, any small oscillation of lever arm with weights results in significant variation of the induced voltage. This has been intentionally left as it is to show the sensitivity of experimental setup on such unwanted oscillations.

Value of induced voltage of maximal torque has been 2 % to 4 % smaller than the voltage induced in non-stressed state for all magnetisation currents. It can be interpreted in this way: lower variation is obtained with higher magnetisation current and higher variation is obtained with lower magnetisation current. This may be related to the value of magnetic permeability of the material at different magnetisation levels. It is well known that the magnetic permeability of ferromagnetic material increases fast at lower magnetisation level, reaching a maximum, and after that maximum it rapidly decreases and in saturation it is close to the permeability of vacuum.

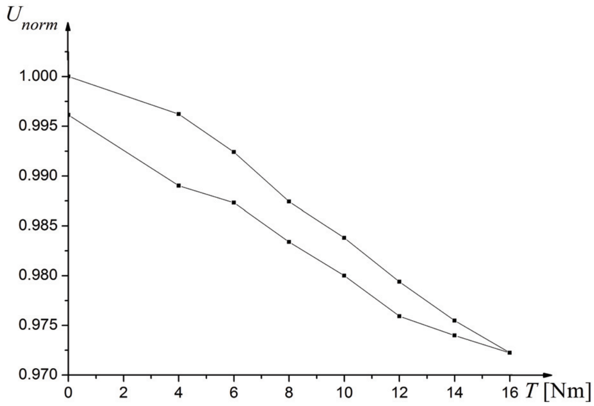

Fig. 2. Variations of normalised induced voltage with torque – 0.02 A.

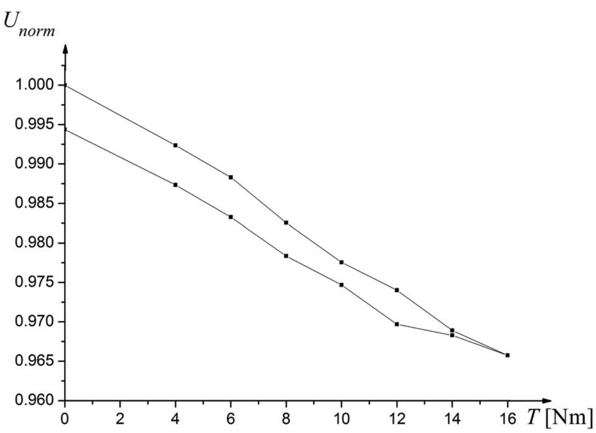

Fig. 3. Variations of normalised induced voltage with torque – 0.04 A.

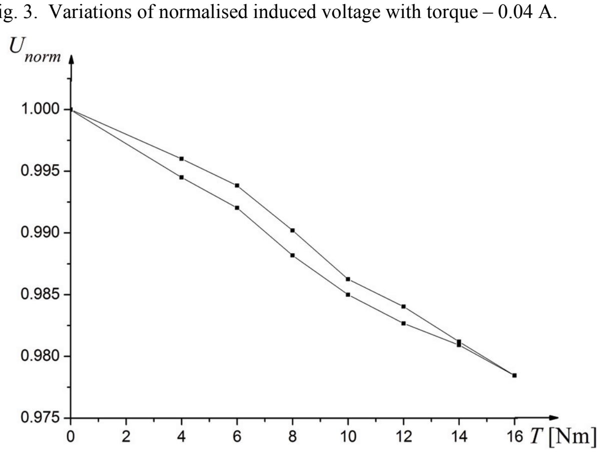

Fig. 4. Variations of normalised induced voltage with torque – 0.06 A.

In order to examine this influence, a comparison of normalised values of induced voltage at different magnetisation currents is presented in Fig, 6. Also, comparison of minimums of normalised induced voltage at different magnetisation currents is given in Table I.

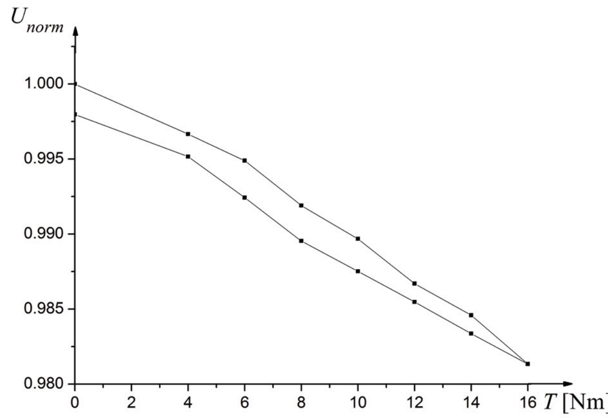

Fig. 5. Variations of normalised induced voltage with torque – 0.08 A.

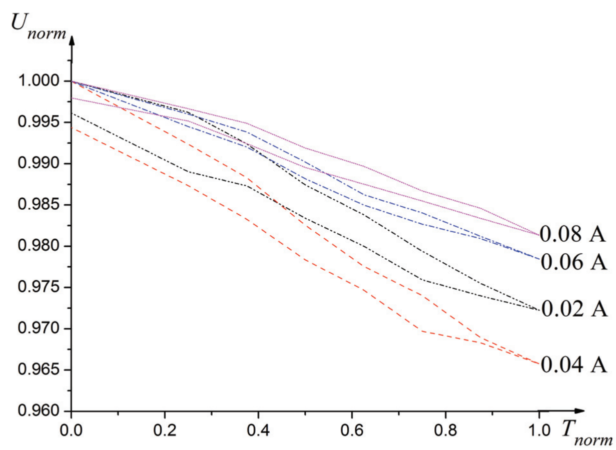

Fig. 6. Variations of normalised induced voltages with normalised torque.

TABLE I
COMPARISON OF MINIMUMS OF NORMALISED INDUCED VOLTAGE AT DIFFERENT MAGNETISATION CURRENTS

Magnetisation current [A]	Minimum of normalised induced voltage [V]
0.02	0.972
0.04	0.966
0.06	0.978
0.08	0.981

According to the results presented in Table I the following can be observed: 1. the normalised voltage minimum is the lowest at 0.04 A, 2. it is lower for 0.02 A than for 0.06 A and 0.08 A, 3. it is highest for 0.08 A. In relation to the magnetic permeability this can be explained as follows: it is high for 0.02 A, but for 0.04 A it is higher and for 0.06 A and 0.08 A it is lower and it has decreasing trend after 0.04 A. Even this variation of the permeability look like one usually observed in ferromagnetic material, it should be investigated more by representing hysteresis loops, magnetisation curve and Stoletov curve of permeability.

IV. CONCLUSION

This paper presents a description of simple measurement setup for investigation of the magnetomechanical effect in cylindrical shaft made of commercial steel. This setup contains mechanical and electrical parts, as well as measurement equipment. Mechanical parts support tested steel shaft and also generate static torsional stress in the shaft. Electrical parts are two solenoids, one large solenoid that produces alternating magnetic field for axial magnetisation of the shaft, and another smaller solenoid that detects magnetic flux in the shaft. Measurement equipment is based on personal computer with LabVIEW software, connected to data acquisition card.

Initial measurement results obtained with this experimental setup, as well as proper discussion of these results, have been presented in the paper. Variations of normalised values of induced voltage with applied torque, obtained at four magnetisation currents, have been given. The results show the presence of the magnetomechanical effect in the tested shaft. Also, these results show the presence of hysteresis, but this has not been further investigated.

Variations of normalised induced voltage with applied torque are small, only several percentages, for any value of magnetisation current. A comparison of these variations for maximal applied torque has been presented and discussed. Values of induced voltage have been related to the magnetic permeability of the tested shaft. It has been observed that it acts as usual for this kind of material - it is increasing fat with the increase of magnetisation field, reaching a maximum, and then decrease with further increase of the field. However, this should be investigated more through the analysis of magnetic hysteresis loops, magnetisation curve and Stoletov permeability curve.

In general, results presented in this paper confirm that described simple experimental setup can be used for measurement of magnetomechanical effect. However, it requires some changes and adjustments in order to achieve better precision and accuracy during measurements. This may be the subject of future research and papers.

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REFERENCES

[1] D. C. Jiles, "Theory of the magnetomechanical effect," *J. Phys. D*, vol. *28,* no. *8,* pp. *1537-1546,* Aug. 1995.

[2] J. A. Ewing, *Magnetic induction in iron and other materials, 3*rd ed. London, UK: "The Electrician" Printing and Publishing Company, 1900.

[3] Y. Chen, B. K. Kriegermeier-Sutton, J. E. Snyder, K. W. Dennis, R. W. McCallum, D. C. Jiles, "Magnetomechanical effects under torsional strain in iron, cobalt and nickel," *J. Magn. Magn. Mater.*, vol. *236,* no. *1-2,* pp. *131-138,* Oct. 2001.

[4] P. Zou, W. Yu, J.A. Bain, "Influence of stress and texture on soft magnetic properties of thin films," *IEEE Trans. Magn.*, vol. *38,* no. *5,* p3. *3501-3520,* Sept. 2002.

[5] A. Sipeky, A. Ivanyi, "Magnetic hysteresis under applied stress," *Physica B.*, vol. *372*, no. *1-2*, pp. *177-180*, Feb. 2006.

[6] O. Perevertov, J. Thielsch, R. Schäfer, "Effect of applied tensile stress on the hysteresis curve and magnetic domain structure of grain-oriented transverse Fe-3% Si steel," *J. Magn. Magn. Mater.*, vol. *385*, no. *18*, pp. *358-367*, July 2015.

[7] W. Xu, N. Duan, S. Wang, Y. Guo, J. Zhu, "A stress-dependent magnetic hysteresis model for soft magnetic composite materials," *IEEE Trans. Appl. Supercon.*, vol. *26,* no. *7,* p. *0611305,* Oct. 2016.