TORQUE SENSOR BASED ON VILLARI’S PHENOMENON

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SUMMARY

The paper describes development and construction of the torque sensor based on Villari’s phenomenon (elastomagnetic effect). This paper presents results of the institutional research solved by the Group of Electrical Engineering Theory and Electrical Measurement at the Technical University in Košice. The main task was to create a torque sensor including accessories from homemade materials, experimentally optimize working conditions and to determine metrological properties of the measurement set. The measuring experiment results are evaluated and discussed.

Keywords: *measurement, torque sensor, elastomagnetic effect, measuring apparatus*

1. INDRODUCTION

This paper introduces the basic knowledge about elastomagnetic torque sensor designed for non-contact measurements. The main task of our group was to create a torque sensor including accessories from homemade materials and experimentally optimize working conditions and to determine metrological properties of the measurement set. We looked for low cost, but sufficiently exact solution of torque measurement.

At present, very often used strain gauge torque transducers provide high accurate measurements. Their high cost and using of glue are features that have limited their primary use in production plants with aggressive environment (harmful effect on glue). In addition, strain gauges require high maintenance levels. One of the low cost methods assumes using of elastomagnetic method in torque measurements. The main advantages of elastomagnetic sensors are: high sensitivity (depending on sensor core material), sufficient output voltage and output power, very high reliability, mechanical toughness and ability of multiple torque overloading (in comparison with strain gauges). The shortcomings of elastomagnetic sensors are: higher power consumption, ambiguity of transfer characteristic and sensor errors, e.g. hysteresis (property of sensor core material).

2. DESIGN OF SENSOR AND MEASURING APPARATUS

The elastomagnetic effect is the influence of the elastic stress on magnetization. The effect consists of a change in the magnetizing curve under a mechanical stress action. While external forces act on the sensor's core, the magnetic permeability and electric impedance change. The sensor works like a transformer with a variable coefficient of transformation. Under the action of external forces the output voltage changes.

The sensor consists of one excitation ferromagnetic core (*P*), two sensing cores (*S*) and ferromagnetic tube (*R*), see Fig. 1. The excitation coil consists of excitation core and primary winding. The excitation core is arranged on a ring around the tube. Primary winding is connected by serial way i.e. magnetic pole extensions have a polarity alternation. The distant brass screws (*K*) are centrally located among pole extensions. It makes possible to roll up the sensing cores in comparison with exciting core to 45º. The secondary windings on every sensing core are composed of eight separate sections. The sections are connected among couple pole extensions in series and so created four coils are connected circumferentially and by serial way too. In the center, between exciting and sensing pole extensions, the ferromagnetic steel tube (STN 11 523.0 with diameters D_1 = 43 mm, D_2 = 40 mm) is located. The steel tube is on the both edges circumferentially pre-drilled by eight conic hollows. Using sixteen screws slotted together with hollows, the ferromagnetic steel tube is bolted to the torque-generating device. Therefore, the steel tubes are easily exchangeable.

2.1 Sensor functioning principle

The elastomagnetic sensor function principle for torque measurement is represented in Fig. 2, where the cylindrical case of pole extensions is unrolled in plane (excitation core – middle, and sensing cores – out side). Fig. 2.a illustrates half magnetic field of unloaded steel tube. Magnetic field is symmetric around excitation core (its pole extensions) and so magnetic potential difference between sensing cores A and B is zero. No magnetic flux goes through sensing winding and so electric voltage on sensing winding is zero too.

The magnetic field in steel tube at loading by torque starts to differ from previous shape and bend approximately to the shape in Fig. 2.b. Therefore, magnetic potential difference appears between sensing winding poles A and B. Through sensing cores (its pole extensions) alternating magnetic flux penetrates and actuates alternating electric voltage in sensing winding. The poles marked A become as “north” and B as “south”. Indicated mechanical stress intensity +σ (tensile load) and -σ (pressure load) is actually rolled out torque effecting on steel tube.

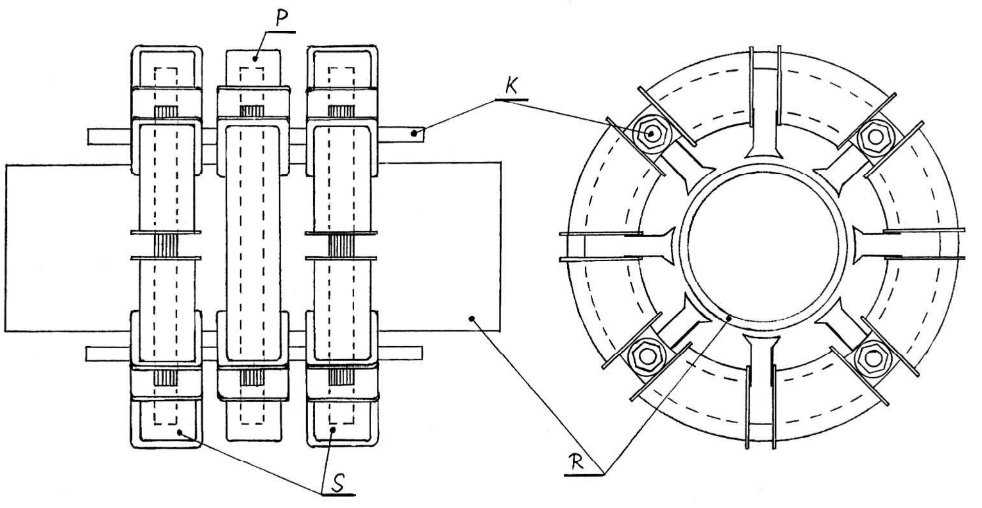
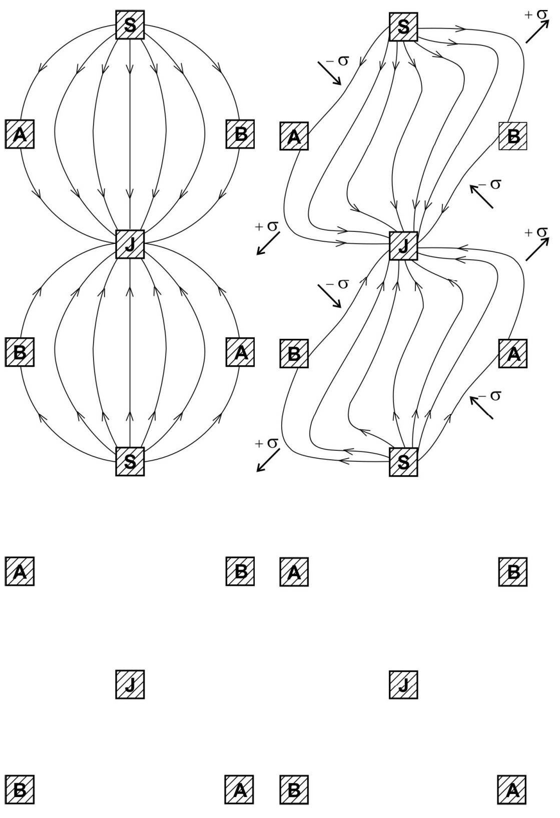


Fig. 1 Construction of torque sensor



a) **b)**

Fig. 2 Magnetic field of a) unloaded, b) loaded steel tube of torque sensor

2.2 Torque device

The device for torque testing works on the principle of the first kind lever, whose scheme is illustrated in Fig. 3. Water is an input quantity and it is removed from the N_1 vessel on the shorter lever arm, to the N_2 vessel on the longer lever arm. Torque from the lever on the deformable steel tube is transferred by double arm lever. The force transfer among vessels, arms and steel tube is realized through hardened steel cutting edges and synthetic corundum bedding (or more simply hardened steel bedding) [3]. The maximum reachable torque value of device is 279.6 Nm. For the transferred torque the following equation is given:

$$\begin{aligned} M_k &= (F_1+\Delta V.\rho.g).a - (F_2-\Delta V.\rho.g).b = \\ &= F_1.a - F_2.b + \Delta V.\rho.g.(a+b) \end{aligned} \tag{1}$$

Where ΔV is water volume difference in comparison with the balanced state lever (in vessel N_1 water level has risen and in vessel N_2 water level concurrently has fallen); F_1, F_2 are forces adequate to water weight in balanced state vessels; a, b are lengths of relevant lever arms where they are effective; ρ is specific mass; g is gravitation. Substituting actual lever dimensions and parameters a = 1296 mm, b = 604 mm, ρ = 1 kg.dm^{-3}, g = 9,81 m.s^{-2}, we got relation:

$$M_k = 18{,}64\,\Delta V \quad [\text{Nm; dm}^3] \tag{2}$$

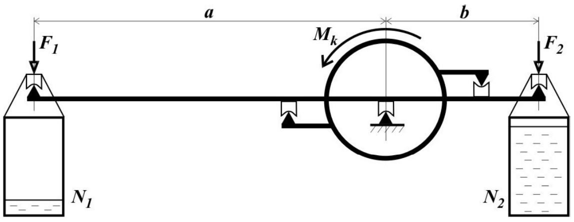


Fig. 3 Torque device

2.3 Measuring apparatus connection

Generator (G) supplies amplifier (▷) and this one supplies sensor winding (N_1) and resistor $R_1 = 1\Omega$, where the voltage drop is measured by voltmeter (DV$_1$). Because of a non-harmonic distortion of the output voltage from the secondary sensor winding, the capacitor (C) is used. The usage of the capacitor enables to compensate high order harmonics of the voltage. It is measured by voltmeter (DV$_2$). The measured data are recorded by personal computer (PC). The frequency of the supply current is measured by frequency counter (Counter).

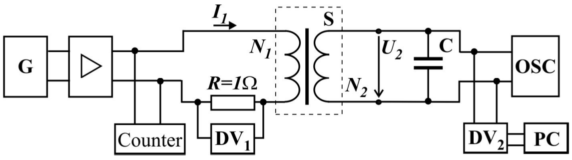


Fig. 4 Measuring apparatus connection

3. EVALUATION OF MEASURED OUTPUT CHARACTERISTICS

The set of measurements with the measuring apparatus (Fig. 4) was done in order to get optimal input parameters. These parameters should be working parameters of torque sensor in order to achieve the most linear transfer characteristic. The problem is to determine optimal frequency f of supply current, and the current I_1. The criteria of determination of optimal input parameters are possibly the smallest nonlinearity and hysteresis errors. Nonlinearity (3) is a deviation of the output of a device from a straight line where the straight line may be defined by using end points, terminal points, or best fit [1].

$$\delta_{nl} = \left(\frac{U_2 - U_{lin}}{U_{2\max} - U_{2\min}} \right)_{\max} \cdot 100\% \tag{3}$$

Where U_2 is an averaged characteristic (from measured characteristics, U_{2max} and U_{2min} are maximal and minimal value), $U_{lin} = K_0 + K_1 \cdot M$ is a specific characteristic (the straight line) calculated by the least square method; this case is called independent nonlinearity. Hysteresis error causes that sensor output values U_2 are different for identical input values M (according to increasing or decreasing input quantity M, $U_2\uparrow$ or $U_2\downarrow$ is obtained):

$$\delta_{hys} = \left(\frac{U_2\uparrow - U_2\downarrow}{U_{2\max} - U_{2\min}} \right)_{\max} \cdot 100\% \tag{4}$$

Torque moment M is the input quantity and output voltage of sensing circuit U_2 is the output quantity. Intensity of magnetic field is the parameter of output characteristics. The intensity of magnetic field is changed by primary electric current I_1.

3.1 Determination of optimal frequency *f*

Evaluation of frequency influence on torque sensor was made at several input currents ($I_1 = 0.2, 0.3, 0.4$ A). Fig. 5 shows dependency of hysteresis error from frequency f for supply current $I_1 = 0.3$ A. Similar dependencies are observed for $I_1 = 0.2$ A and $I_1 = 0.4$ A. The optimal frequency appears around $f = 450$ Hz. The hysteresis increases for high frequencies. The smallest hysteresis errors δ_{hys} are obtained for the individual supply currents at frequencies:

$I_1 = 0{,}20$ A, $f = 450$ Hz	$\delta_{hys} = 4{,}65\%$
$I_1 = 0{,}30$ A, $f = 430$ Hz	$\delta_{hys} = 4{,}03\%$
$I_1 = 0{,}40$ A, $f = 460$ Hz	$\delta_{hys} = 2{,}79\%$.

If influence of technical frequency has to be eliminated, optimal frequency cannot be entire multiple of 50 Hz. So it was stated to $f = 453$ Hz.

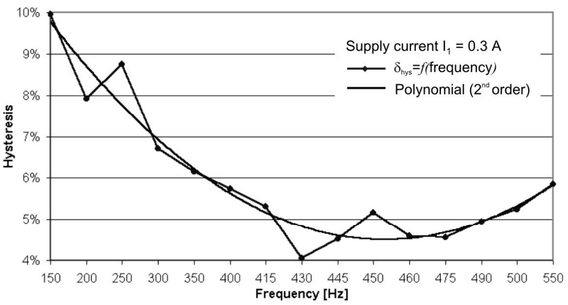


Fig. 5 Frequency influence on torque sensor

3.2 Determination of optimal supply current I_1

Determination of the optimal supply current I_1 was experimentally established in two ways – without previous loading of torque sensor and with previous loading. In accordance with IEC 61 298-2 standard [2], the output sensor characteristics were obtained by using the apparatus (Fig. 4) at temperature 23°C and frequency of supply current $f = 453$ Hz. The output sensor characteristics are shown in Fig. 6. Only characteristics of torque sensor, which was loaded before measuring, are presented. This way of measuring is more similar to real sensor working conditions.

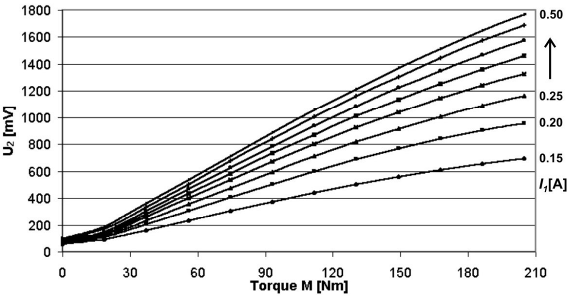


Fig. 6 Output characteristics of torque sensor

In order to determine the most linear output sensor characteristic, nonlinearity and hysteresis errors are computed. Considering criteria of the optimal input parameters determination (mentioned above), the characteristic with effective supply current 0.50 A is the most linear characteristic of torque sensor. The smallest hysteresis δ_{hys} = 1.25% and very small nonlinearity δ_{nl} = 3.00% represent this characteristic, see Fig. 7.

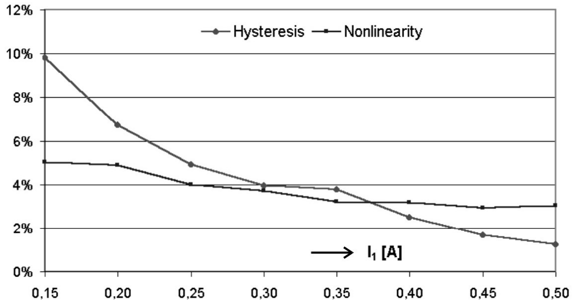


Fig. 7 Nonlinearity and hysteresis processes of torque sensor

4. CONCLUSION

Elastomagnetic torque sensor may be used in various growing applications – monitoring of motors, engines or monitoring of machine tool efficiency. Elastomagnetic torque sensors can be integrated directly into machines to monitor efficiency in real time. Further enhancement of potential applications for the elastomagnetic sensors are coupled with position or speed encoders, or rotation counters.

In the paper, a new low-cost torque sensor is described. The torque is measured contactless without special treatments of the tube, using the elastomagnetic effect. For optimal input parameters of torque sensor (supply current I_1 = 0.5 A, frequency f = 453 Hz), the output parameters are as follows:

- nominal torque: 200 Nm
- max. operational torque: 150 % of nominal torque
- full scale output: 95 – 1700 mV
- the effective span of sensor output: 1600mV
- zero drift: 95-98 mV
- hysteresis: 1.25 %
- nonlinearity: 3 %

The linear line is computed from gained sets of measurements by the least square method. It is the ideal transfer characteristic for this case and its expression is $U_{lin} = 158.67 \cdot M + 86.09$ [mV].

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REFERENCES

[1] IEC 61298-2, Process measurement and control devices - General methods and procedures for evaluating performance - Part 2: Tests under reference conditions, 1995-07.

[2] IEC 60770, Transmitters for use in industrial-process control systems - Part 1: Methods for performance evaluation, 1999-02. Part 2: Methods for inspection and routine testing. Part 2: Methods for inspection and routine testing, 2003-01.

[3] MOJŽIŠ, M. et al. Torque sensor (Snímač krútiaceho momentu – in Slovak). In: *Acta Electrotechnica et Informatica*. vol. 2, no. 2 2002, p. 51-55.

BIOGRAPHY

Miroslav Mojžiš (doc, Ing, CSc) was born in 1942. He graduated in 1963 from Faculty of Electrical Engineering at the University Transport and Communications, Žilina. He received his CSc. (PhD.) degree in Measurement technology from Slovak Technical University, Bratislava in 1981. He is head of the Department of Theoretical Electrotechnics and Electrical Measurement, TU FEI in Košice. The main topic of his present research activities is measuring of forces via elastomagnetic sensors.

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