TORQUE SENSOR MODELED BY NEURAL NETWORK

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SUMMARY

This paper describes principle and design of elastomagnetic torque sensor and with it related neural network model. Multilayer feed-forward neural network was used. The parameters of this neural network were changed in wide range. The most suitable solution is presented. Other neural network solutions have not been presented in this paper. The basic measuring apparatus was set and output characteristics at various input supply current were analyzed. The substitute circuit model of the sensor was determinated from measured data set. The substitute functions for output characteristics were stated by linear regression. The statistical model was compared with neural network model and errors were computed.

Keywords: *measurement, torque sensor, elastomagnetic effect, error reduction, neural network*

1. INDRODUCTION

Torque measurements are important and usefulness in manufacturing environment, but at the same time, monitoring and measuring of torque must be accurately and economically. Although strain gauge torque transducers provide high accuracy, their high cost and bulkiness are features that have limited their use primarily to research and development laboratories and in quality assurance testing in order to verify standards. In addition, such transducers require high maintenance levels, making them unsuitable for mass integration into manufacturing systems. Low cost methods have been tried to control torque in the manufacturing environment, including non-direct systems, which for example, monitor changes in electrical power consumption. But such methods typically provide poor resolution and are not accurate enough to be useful.

This solution assumes a using of elastomagnetic method of torque measuring. Elastomagnetic torque sensor may be use in growing application – monitoring electric motor or machine tool efficiency. Elastomagnetic torque sensors can be integrated directly into machines to monitor efficiency in real time. Further potential applications for these sensors are enhanced when they are coupled with position or speed encoders, or rotation counters.

This paper introduces the basic knowledge about elastomagnetic torque sensor designed for non-contact measurements. The theoretical considerations are verified by experimental results.

2. PRINCIPLE OF TORQUE SENSOR

The principle of elastomagnetic sensor is based on existence of elastomagnetic (Villari) effect. It appears in ferromagnetic material as follows - if external force affects ferromagnetic material, it is deformed. In consequence of this deformation, the relative distances of the atoms in crystal structure are changed. The magnetic properties are represented by permeability and it will be changed in accordance with acting force. Dependency of permeability change $\Delta\mu$ from mechanical tension σ describes the next relation obtained from thermodynamic equilibrium in ferromagnetic material in alternating harmonic magnetic field:

$$\Delta\mu = \frac{2\lambda_{ms}\mu^2}{B_{sef}^2} \cdot \sigma \tag{1}$$

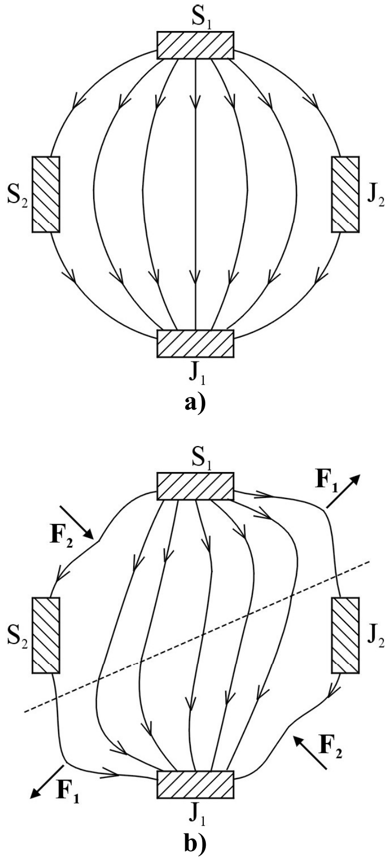
Where λ_{ms} is a mean value of magnetostrictive coefficient in saturation, μ is value of permeability when mechanical tension is equal to zero, B_{sef} is effective magnetic induction in saturation in harmonic magnetic field.

In Fig. 1, an electromagnet (with north pole S_1 and south pole J_1) is applied to isotropic ferromagnetic material. It produces symmetrical magnetic field (Fig. 1a). If force F_1 or F_2 is acting to ferromagnetic material (plate form or cylinder jacket form) with positive value of magnetostrictive coefficient then magnetic field is deformed (Fig. 1b). If forces F_1 and F_2 are acting to ferromagnetic material together, a deformation action is increased. It represents situation of acting torque. A sensing magnetic circuit is consists of S_2 and J_2. In consequence to deformation, places around S_2 and J_2 have different magnetic potential. So, at the end of the sensing winding is detected induction voltage – sensor output signal [1].

3. EXPERIMENTAL PART

3.1 Measuring apparatus

The proposed torque sensor consists of deformation part – tube, exciting magnetic circuit and sensing magnetic circuit. Measurements have been carried out with tube fixed at one end (see Fig. 2). Torque from 0 up to 185 Nm has been applied via a torsion arm.



a)

b)

Fig. 1 Magnetic field of torque sensor

Deformation part of sensor is iron tube with inner diameter d = 44.8 mm and outer diameter D = 47.2 mm. Length of tube is 120 mm. The maximal shear stress τ_{max} of tube is much lower like shear stress corresponding to shear capacity τ_s.

$$\tau_{\max} = \frac{M_{\max}}{W} = 1{,}89 MPa \tag{2}$$

Where M_{max} is maximal measure torque and W is torsion section modulus of tube:

$$W = \frac{\pi \cdot D^3}{16} \cdot \left(1 - \frac{d^4}{D^4}\right) = 9{,}745 \cdot 10^{-5} m^3 \tag{3}$$

The maximal twisting angle of tube is defined:

$$\varphi = \frac{M_{\max} \cdot l}{G \cdot J} = 2{,}98 \cdot 10^{-2} rad \tag{4}$$

It corresponds with torsion arm slewing; a point at the end of the arm is moved down about 3 cm. G is modulus of elasticity in shear (for iron G = 81000 MPa), l is lenght of tube (120 mm) and J is modulus of toughness in torsion:

$$J = \frac{\pi}{32} \cdot \left(D^4 - d^4\right) = 9{,}179 \cdot 10^{-8} m^4 \tag{5}$$

So this tube has good mechanical properties and it is available for torque measurement.

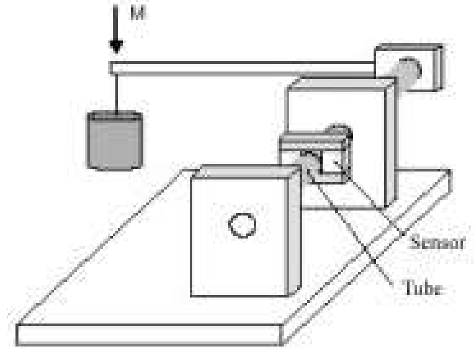


Fig. 2 Table-bed for measurements

The exciting magnetic circuit is composed of coil with 300 turns (Cu wire, diameter 0.5mm) and magnetic core. The sensing magnetic circuit is composed of coil with 170 turns (Cu wire, diameter 0.2mm) and magnetic core. The measuring apparatus was set in order to achieve the metrology characteristics. It consists of supply power (G), amplifier (▷), digital wattmeter (W), digital voltmeter (V), variable resistors (R_1 and R_2) and elastomagnetic torque sensor (S) – in Fig. 3.

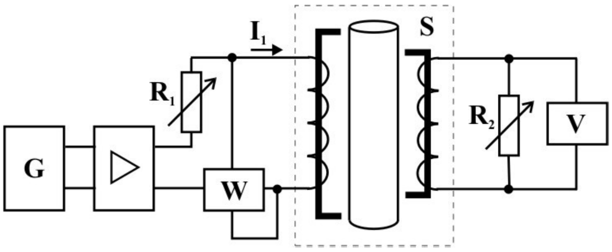


Fig. 3 Measuring apparatus

3.2 Measured values

The input quantity was torque moment M and output quantity was effective induction voltage of sensing circuit U_2. The parameter of output characteristics was intensity of magnetic field. Intensity of magnetic field was changed by primary electric current I_1. The active input power P_1, reactive input power Q_1 and input voltage U_1 were measured, too.

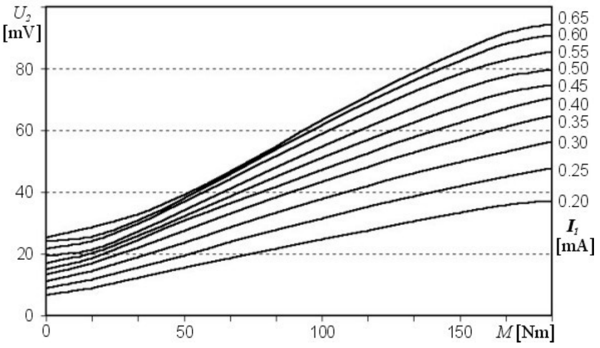


Fig. 4 Output torque sensor characteristics

In accordance with IEC 61 298-2 standard [2], the output sensor characteristics were obtained by using the apparatus (Fig. 4). In order to achieve the most linear output sensor characteristic, errors of measured processes were computed. From this point of view, the most linear characteristic of torque sensor was characteristic with these working parameters – effective supply current 0.25 A, frequency of supply current f = 523 Hz and temperature 23°C. Effective span of sensor output was approximately 40mV. This characteristic was considered to be a transfer characteristic. There are two problems - finding the ideal transfer characteristic according to the best conversion of output sensor voltage to measured torque and reduction of sensor errors (mainly non-linearity). The linear line was computed from gained sets of measurements by the least square method. It was the ideal transfer characteristic for this case and its expression was $y_{lin} = 0.2177 \cdot M + 8.8254$.

IEC 60 770 standard [3] defines the error of transfer characteristic as a difference between measured quantity and corresponding ideal output value. Generally, percentage error is expressed according to a span of ideal output and it is defined:

$$e = \left(\frac{y_{measured} - y_{ideal}}{y_{\max} - y_{\min}} \right) \cdot 100\% \tag{6}$$

The positive error means that the measured value of sensor output is bigger than the ideal output value.

Non-linearity (7) is defined like the maximum of difference between the average characteristic y_{mean} (from measured characteristics) and specific characteristic (the linear line). The linear line $y_{lin} = K_0 + K_1 \cdot x$ is calculated by the least square method. This case is called independent non-linearity.

$$\delta_{lin} = \left(\frac{y_{mean} - y_{lin}}{y_{\max} - y_{\min}} \right)_{\max} \cdot 100\% \tag{7}$$

Non-repeatability is defined like tightness of equality of consecutive measurements. The consecutive measurements of output signal are made at same input signal and same working conditions.

3.3 Substitute sensor circuit model

The substitute circuit model of the senor was determinated from measured data of input values for all torque-measured range. In accordance with constant power supply values, mutual feedback between primary and secondary magnetic circuit is negligible. So the substitute sensor circuit model of exciting part is sufficient. The values of substitute circuit elements were computed at frequency 523 Hz and outer values of torque (M = 0, $M = M_{max}$). Computed values of substitute resistance R_{Fe} (which represents ferromagnetic losses) were mutually different. The maximal difference was 2%. The maximal difference among computed values of substitute inductance L was 3%. These differences can be caused by power supply instability and measurement errors. Substitute model connection of the torque sensor is shown in Fig. 5.

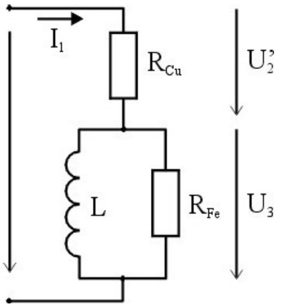


Fig. 5 Substitute model connection of the sensor

Computed values of substitute parameters are: substitute resistance of active exciting coil resistance R_{Cu} = (2.041 ± 0.001) Ω, R_{Fe} = (331 ± 3) Ω, L = (33.0 ± 0.5) mH. The power ratio of sensor at nominal torque are: P_1 = 2.08 W, P_2 = 0.752 μW. The useful output voltage ΔU_2 is defined like difference between output sensor voltage at nominal torque (ΔU_{max}) and output sensor voltage at zero torque (ΔU_0). The useful output voltage is ΔU_2 = 38.8 mV for I_1 = 0.25 A case.

4. NEURAL NETWORKS

4.1 Neural network proposal

The neural network proposal consists of the properly topology selection, specification of number of layers (mainly hidden) and number of neurons, selection of learning algorithm and setting of properly learning parameters. The problem of learning by example can be considered equivalent to a multivariate function approximation problem in many cases [4]. It has been shown that an multilayer neural network, with a single hidden layer, can approximate any given continuous function on any compact subset to any degree of accuracy, providing that a sufficient number of hidden layer neurons is used [5, 6]. However, in practice, the number of hidden layer neurons required may be impractically large. In addition, the training algorithms are "plagued"' by the possible existence of many local minima or flat spots on the error surface.

A multilayer feedforward neural network (FF NN) was selected for conversion of output sensor voltage into measured torque and error correction. This FF NN was trained by Backpropagation learning algorithm.

The measured sensor values were divided into training and test sets. The neural network was created in simulation program SNNSv4.2 (Stuttgart

Neural Network Simulator) [7]. The neural network was learned with different parameter α (learning parameter specifies the step width of the gradient descent) – Fig. 6. If α parameter was less than 0.1, the sum square error (SSE) of training and test set was decreased slowly. The learning algorithm Std_Backpropagation was used with parameters α=0.5 and d_{max}=0 (the maximum difference between a teaching value and an output of an output unit which is tolerated). In Fig. 7 is shown training process of neural network with α=0.5 and number of training cycles was 200000. Increasing of training cycles decreased the SSE error of training set, so the NN respond to known data was better. However, the NN respond to untrained data was worse – over-trained NN, in this case neural network memorized the patterns rather than generalized well.

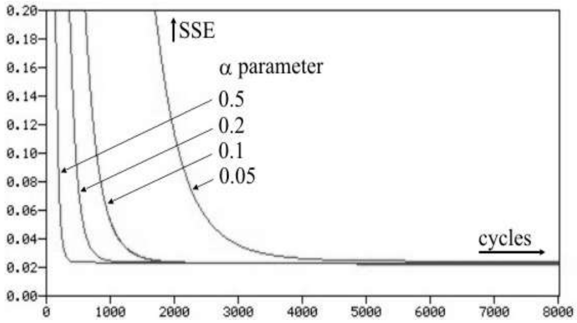


Fig. 6 The learning processes with different α parameter

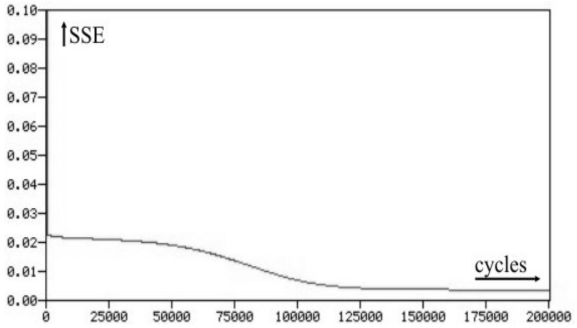


Fig. 7 The learning process with α=0.5

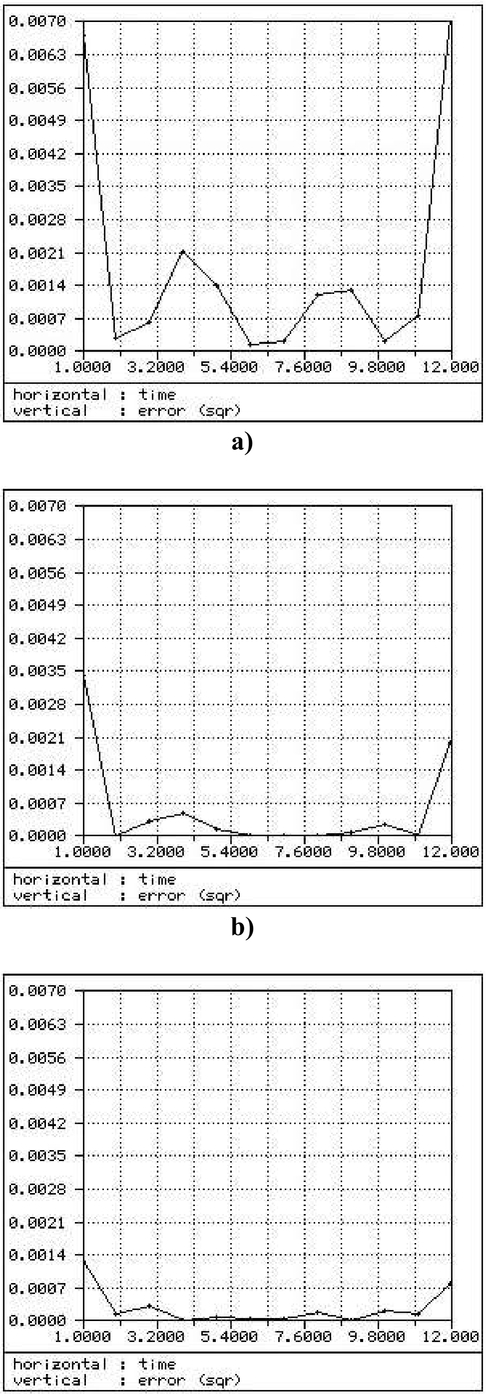
5. RESULTS

The measured data were gained from torque sensor as output sensor voltages. The neural network is directly trained to conversion of output sensor voltage to measured torque, so input (output sensor voltage) and output (measured torque) of NN are data of different type. Neural networks analogous to statistical models work with large amount of data, NN solve problems of approximation functions, prediction problems, linear and non-linear regression and data classification. The advantages of neural networks are learning from examples, input-output data mapping, adaptability to changing conditions of environment and error resistance.

$$sqr = \left(t_i - o_i\right)^2 \tag{8}$$

The *sqr* (8) errors of test sets (t_i are targets of NN and o_i are outputs of NN in validation process) are shown in Fig. 8. These *sqr* error processes vary in number of training cycles (Fig. 8a – 10000 cycles, Fig. 8b – 100000 cycles and Fig. 8c – 200000 cycles).

A comparison of errors according to IEC 60 770 standard is shown in Tab. 1. These errors correspond with measurements of torque without neural network model and measurements with NN model A (10000 training cycles) and with NN model B (200000 training cycles).



a)

b)

c)

Fig. 8 The *sqr* error processes

	Without NN model	**With NN model A**	**With NN model B**
Inaccuracy	<-2.94%; 1.78%>	<-1.14%; 2.79%>	<-1.04%; 1.70%>
Non-linearity	2.84%	2.74%	1.64%
Non-repeatability	0.46%	0.15%	0.14%

Tab. 1 Comparison of errors according to IEC 60 770 standard

As we can see, errors of NN model A are worse than errors of NN model B. The reduction of non-linearity error by neural network model B is approximately a half. It is due to learning process, when targets of training set were data corresponding to measured torque and it was a linear change. Non-repeatability was improved from 0.46% to 0.33% and inaccuracy was improved from range <-2.94%; 1.78%> to <-1.04%; 1.70%>.

6. CONCLUSION

In the paper, a low-cost magnetic torque sensor principle was described. The torque is measured contactless without special treatments of the tube, using the elastomagnetic effect of ferromagnetic materials. Proposed torque sensor provides relative good results with errors described above.

The proposed solution is based on successful using of feedforward neural networks. Advantages of neural networks led to the error reduction of elastomagnetic torque sensor. By using of proposed feedforward neural network (model B), the non-linearity error was reduced from 2.84% to 1.64%.

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BIOGRAPHY

Jozef Vojtko (Ing.) was born in Michalovce, in 1976. He graduated from Department of Electronics and Multimedia Telecommunications, Faculty of Electrical Engineering and Informatics at the Technical University of Košice in 1999. He works as an Assistant Professor at Department of Theoretical Electrotechnics and Electrical Measurement, TU FEI in Košice. His interests are the reduction errors of sensors and neural networks.

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. degree in Measurement technology from Slovak Technical University, Bratislava in 1981. He is head of the Department of Theoretical Electrotechnics and Electrical Measurement. The main topic of his present research activities is measuring of forces via elastomagnetic sensors.