Determination of Transmission Mechanical Efficiency by Strain Gauges Measurement

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Abstract: This paper is focused on determination of the transmission mechanical efficiency during the test and as well as usual operation. Efficiency is one of the main indicators of the transmission quality. In general, that is determined either by analytical calculations with conditions or by value from the electric converter or torque sensor.

Keywords: Efficiency; Transmission; Measurement; Strain Gauge.

1 Introduction

The mechanical efficiency is usually monitored during transmission laboratory testing. For this purpose values from the torque sensor or electrical quantity of the electric motor from the converter are used most often. However, values from electric converter are influenced by mistake, because parameters are included in the electric motor efficiency and it is not only finding transmission mechanical efficiency. Also using torque sensor is not suitable for the universal measurement because in most cases torque sensors are used during laboratory testing. Potential customer wants this transmission efficiency in usual machine operation. There is not space to modify assembly of the complete device which is usually necessary in the process of torque sensors installation. For this purpose the new method was created. This method is created on the basis of measurement with strain gauges on input and output shafts.

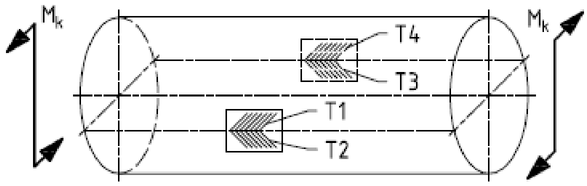

Fig. 1: Shaft under torsion with X rosettes strain gauge [6].

2 Measurement

2.1 Sensor

The sensor consists of several strain gauges. Special X rosettes strain gauges are used for measurements on a shaft under torsion (Fig. 1). Connection is carried out to the full Wheatstone bridge circuit (Fig. 2). The full bridge circuit configuration is the most sensitive bridge and the best in compensation signal from additional normal and bending loading.

Experiment design comes from loading values during measurement. The first step is calculation of maximum stress (deformation) of the measured shaft. For the shaft under torsion this equation is used (M_k is torque, τ is shear stress, ε is strain, G is shear modulus and W_k is torsional section modulus)

$$M_k = W_k \cdot \tau = W_k \cdot G \cdot 2 \cdot \varepsilon \tag{1}$$

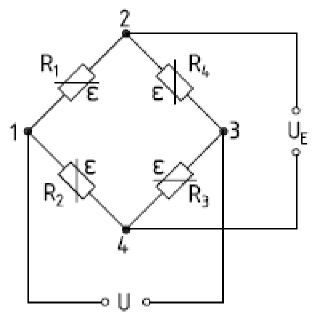

Fig. 2: Shaft under torsion with X rosettes strain gauge.

For full bridge circuit this equation is used (U_E is bridge excitation voltage, U is bridge output voltage, R_i is resistance, ΔR_i is resistance change)

$$U = \frac{U_E}{4}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right) \tag{2}$$

For X rosettes strain gauge in full bridge circuit is used (k is $k-factor$ of the strain gauge)

$$\frac{\Delta R}{R} = k \cdot \varepsilon \tag{3}$$

After that, this gives:

$$\varepsilon = \frac{1}{4}\frac{4}{k}\frac{U}{U_E} \tag{4}$$

And for the torque

$$U = \frac{U_E \cdot M_k \cdot k}{W_k \cdot G \cdot 2} \tag{5}$$

For example maximum torque is $3000Nm$, $U_E = 2.5V$, shaft diameter is $100mm$, $k = 1.4$, $G = 81000MPa$, for this parameters output voltage is $0.33mV$. These are real parameters for common loading. Measuring signal output voltage is very low and for this measurement the result will be with low sensitivity.

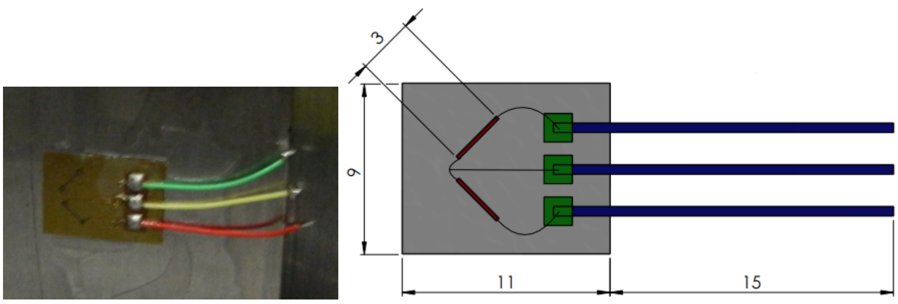

Fig. 3: Semiconductor strain gauge for torque measurement

There is one more option, to use more sensitivity strain gauge. Semiconductor strain gauges are used for this purpose (Fig. 3). In general, these gauges have 60x higher strain sensitivity. Equation for semiconductor strain gauge is different from common strain gauges. There are two gauge factors C_A and C_B. Basic equation is

$$\frac{\Delta R_i}{R_i} = 1 + C_{iA}\varepsilon_i + C_{iB}\varepsilon_i^2 \tag{6}$$

and in equation for full bridge circuit this gives (with $\varepsilon = -\varepsilon_1 = -\varepsilon_2 = -\varepsilon_3 = -\varepsilon_4$ from strain gauges installation on shaft)

$$U = \frac{U_E}{4}\left(\varepsilon(C_{1A} + C_{2A} + C_{3A} + C_{4A}) + \varepsilon^2(C_{1B} - C_{2B} + C_{3B} - C_{4B})\right) \tag{7}$$

and

$$U = \varepsilon \cdot V + \varepsilon^2 \cdot W \tag{8}$$

$$U = \left(\frac{M_k}{2 \cdot G \cdot W_k} \right) V + \left(\frac{M_k}{2 \cdot G \cdot W_k} \right)^2 W \tag{9}$$

Gauge factors have approximately values $C_A = 130$ and $C_B = 4000$. With semiconductor strain gauges gives output voltage $31mV$. Measuring signal from semiconductor strain gauges is about 100x higher and also therefore these gauges are better for measurement of efficiency. These develop to semiconductor strain gauges for measuring a shaft under torsion. These strain gauges are custom-made.

2.2 Measuring device

Unconventional measuring devices have to be used for this measurement because there is small space for installation around shafts and also because shafts rotate with high speed and there is not possible to use wire connection. Special autonomous measuring apparatus were created and device has own power source (batteries) and own recording part (memory card). At the same time device enables to transmit on-line signal to computer. Maximum sampling frequency is 2000Hz for 6 measuring channels. Device is resistant to centrifugal force caused by rotation.

2.3 Efficiency measuring

Sensors with strain gauges are installed on an input haft and on an output shaft. Efficiency is determined on the basis of compare input torque with output torque. Equation for this is

$$\eta = \frac{M_{kout}}{M_{kin} \cdot i} \tag{10}$$

where η is a mechanical efficiency and i is a gear ratio.

Measurement of a torque is based on the determination of a deformation caused only by torque without another loading. However shaft loading is combined by bending, torsion and tension/compressing. If full bridge circuit is used then bending and tension/compressing are compensated. This bridge gives on output only deformation from torsion loading. After measuring with this bridge there is no difficulty to calculate a torque from output signal.

Moreover one difficulty can appear. Input and output transmission shafts have several possibilities of geometrical change of their shape. Computation of torque is based on geometrically regular shape and it is circle for a shaft. On the shaft there are grooves for key, diameters changes a many others possibilities. It is a case of stress distribution surroundings of notch. In the beginning FEM computation should be made for to set a place for strain gauge installation, which are not affected by notch (Fig. 4).

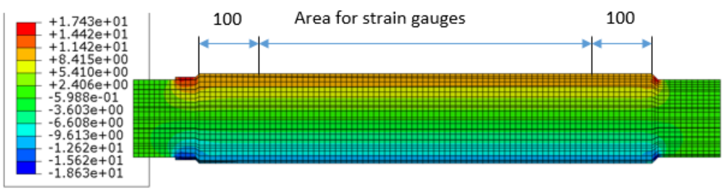

Fig. 4: Determination of area for strain gauges (Shear stress [MPa])

3 Results and Conclusion

As stated above several measurements were made according to this method. Measurements are made in more loading levels. This is very useful measurement tool for compare efficiency with vibration, noise, temperatures individual parts or oil and e.g. with mesh quality which is monitored in teeth transmission [1], [3], [5] or monitoring of gearbox external forces (hinge of tram gearbox) [2], [4]. Presentation of torque measurement is in Fig. 5. Range efficiency value was 84 %.

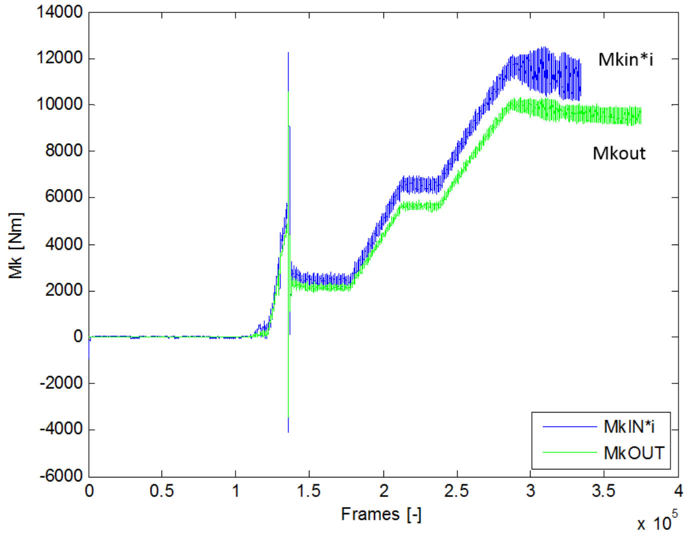

Fig. 5: Time behaviour of torque

The results of these measurements are review of the designed method. The adjust method gives relevant results. Used semiconductor strain gauges have sufficient sensitivity. The designed procedure (measuring method) can be repeated.

Next tasks will be mainly set of measurements that enables to determine the real measurement error.

Acknowledgement

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References

[1] O. Berka, F. Lopot, M. Dub, Experimental Analysis of Gear Loading in Planetary Transmission, in proc.: EAN 2014 - 52nd International Conference on Experimental Stress Analysis (2014), P. Polach, VZU Plzen, Marianske Lazne.

[2] M. Dub, at al., Experimental analysis of stress state and motion of tram gearbox hinge, in proc.: EAN 2014 - 52nd International Conference on Experimental Stress Analysis (2014), P. Polach, VZU Plzen, Marianske Lazne.

[3] O. Berka, at al., Analysis of satellites loading in planetary transmission, in proc.: EAN 2015 - 53nd International Conference on Experimental Stress Analysis (2015), P. Padevet, CTU in Prague, Cesky Krumlov, 16-19.

[4] M. Dub, at al., Backlash and torsional stiffness of a gearbox, in proc.: EAN 2015 - 53nd International Conference on Experimental Stress Analysis (2015), P. Padevet, CTU in Prague, Cesky Krumlov, 74-77.

[5] O. Berka, at al., Mesh quality monitoring in evolventn teeth in gearboxes under operation -signal identification, in proc.: XXI IMEKO World Congress ”Measurement in Research and Industry” (2015), J. Holub, CTU in Prague, Prague, 1582-1586.

[6] K. Hoffmann, An Introduction to Stress Analysis and Transducer Design using Strain Gauges, Pfungstadt, HBM, 1987.