The Gear Tooth Flank Temperature Measurements System

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Abstract — **This paper deals with a design of equipment for the temperature measurements near the gear tooth flank. The paper describes choosing of temperature sensors and a method of data transport from the rotating shaft. The calibration of sensors is described too. Instructions for use are introduced in the text. The equipment for temperature measurements was tested on a little stand which was specially designed. The goal of this paper is the design and testing of equipment for temperature measurements near a gear tooth flank.**

Keywords — Measurement, temperature, gear, tooth flank.

I. Introduction

Many different types of transportation vehicles are manufactured and performed in the world. The vast majority of this vehicles use mechanical gears for transformation of the engine power. Gears and gearboxes are very much monitored parts of vehicles [1]. Every year a great emphasis is put on the research of gear topics. Good performance of the gearbox depends on many used parts. The main required parameters of gearboxes are low noise (e.g. [2]) and high efficiency (e.g. [3, 4]). The fuel consumption of a vehicle depends on efficiency of the gearbox too. Efficiency of the gearbox is very important parameter because dissipated energy is mostly transformed to heat. The following changes of temperature affect physical parameters of the gearbox parts. The gearbox can be destroyed during an extreme heat load.

The main place of mechanical energy dissipation is the contact area between two surfaces where are the tribological processes ongoing. The contact places are in the bearing and shaft sealing for example. But the main place of friction processes is the contact between tooth flanks. Many theoretical and practical information about friction between tooth flanks are in available literature (e.g. theoretical friction parameters as load and velocity in [5], practical information about temperature in [6]).

The result from the information above is that the temperature measuring near a tooth flank is very useful for understanding of processes related with the gearbox operation. For the temperature measurements it is necessary to have a special equipment. This short article describes the design of a special equipment for the temperature measurements near a tooth flank of the gear in a real gearbox.

II. Equipment for Temperature Measurements

The next part of this article describes parts of equipment for the temperature measurements near a tooth flank. The parts with optimal technical parameters were chosen from a wide range of commercial products.

A. Temperature Sensors

The temperature sensor is the main part of equipment for the temperature measurement. Many types of sensors are used in technical praxis at present. Main used sensor types are resistance based sensors and voltage producing sensors – thermocouples. Thermocouples are well-known for their small mounting space. The thermocouple signal processing is relatively difficult. The resistive sensors are more suitable for our application.

Metal resistance sensors and semiconductor sensors are two basic types of resistive sensors. The temperature resistance characteristic of the metal resistive temperature sensor is linear. The linear characteristic of resistance is better than a nonlinear one, later processing of the data is easier. The metal resistance sensors are bigger than the semiconductor sensors. The semiconductor temperature sensors are possible to subdivide as NTC and PTC thermistors. The resistance characteristic of the thermistors is not linear but is possible to solve it by a calibration. The electric resistance of the PTC thermistor increases with temperature. The resistance of the NTC thermistor decreases with temperature. The modern types of thermistors are well-known for their small dimensions, short response time and high accuracy.

Finally we chose a miniature NTC sensor for our application. The type of the chosen sensor is 2K7MCD1 by Telemeter Electronic GmbH (Fig. 1).

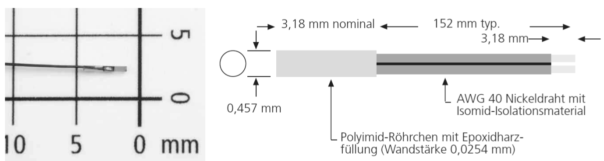

Fig. 1. Thermistor NTC 2K7MCD1.

The 2K7MCD1 is one of the smallest temperature sensors. The reaction time of this sensor is 200 ms only during use in a liquid medium. The characteristic resistance of 2K7MCD1 is 2 kΩ in 25 °C/77 °F. The possible error of the measurement in 25 °C/77 °F is ± 0,2 °C. The temperature sensor is good protected by a polyamide tube cover and inner filling of the epoxy resin. Connection of the sensor is realized by the sheathed cable. The connection cable and sensor are supplied by the producer as a set.

B. System for Data Transportation

The main system of this equipment is an electronic circuit for the temperature measuring and data transport. The temperatures are measured on a rotating shaft and wireless transport to the stationary part is necessary. The first signal and data treatment is performed on the rotating shaft already. The block diagram of the measuring system is in Fig. 2.

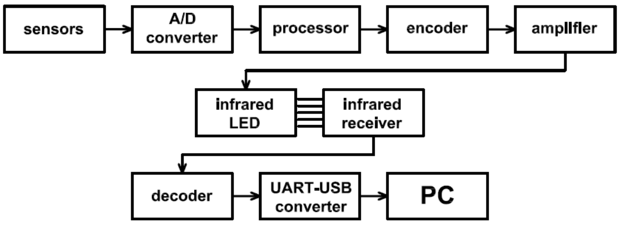

Fig. 2. The block diagram of the measuring system.

The rotating part (Fig. 3) of the equipment contents two printed circuit boards with mounted electrical parts. The sensor signal evaluation and a battery are on a bigger board. The sensor signal evaluation is the first operation in fact. For the measurements of the voltage drop on the NTC sensors an A/D converter is used. There are four A/D converters type ADS1248. The ADS1248 is the 7-channel, 24-bits A/D converter with an internal amplifier and two adjustable electric current sources. The three-wire configuration for connection of the temperature sensors is used. Sixteen channels are possible to use, but only one half is connected in this application. The temperature measurements are realized in eight points of the gear.

The rotating part of the equipment for the temperature measuring contains a second smaller printed circuit board which is connected with the bigger board. The connection is realized by four three-pin connectors. The connectors are used for communication between the A/D converters and other parts installed on the smaller board. The smaller board contains processor (microcontroller) which is necessary for communication with the A/D converters. The microcontroller is the ATTiny2313 8-bit microcontroller with 2K bytes in the system programmable flash. The microcontroller is necessary for operation of the A/D converter and next sending of information to an encoder. The communication between the microcontroller and A/D converters is realized as a SPI with auxiliary signals (START, CS...).

The data from the microcontroller are sent to the encoder by the UART. The encoder transforms data to the right format for the successful sending to the static parts of the equipment. For transforming of the data the TIR1000 encoder is used. The signal transformed by the encoder is amplified by the transistor. The last step is the sending of the amplified signal out by the infrared diode. The infrared diode is the TSMF1020. The TSMF1020 is a high speed infrared light emitting diode with double hetero technology (DH), molded in a clear SMD package with dome lens. This step causes that the data from the rotating part are sent to the static part by a wireless method. All rotating parts of the equipment are in Fig. 3.

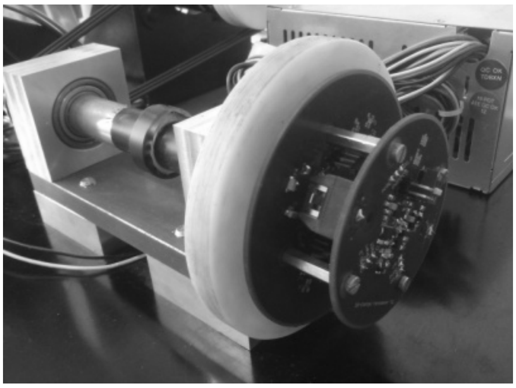

Fig. 3. System for data transport – rotating parts.

The stator part is primarily designed for receiving and treatment of the IR signal from the rotor part. The infrared receiver is the first place where the IR signal from the rotor is delivered. The TFDU4101 infrared receiver module is used here. The MCP2120 microchip for decoding of the signal from the IR receiver on the stator is used. The IR signal is decoded back to the UART.

The output data from the decoder are in the UART format and their transformation for the USB is useful. The USB format of the data is more comfortable for the next computer connection. The USART/USB FT232RL converter for conversion of the signal is used. The output data from the converter are in the USB format and reading of them by the computer connection is easy and comfortable. The stationary part of equipment is in Fig. 4.

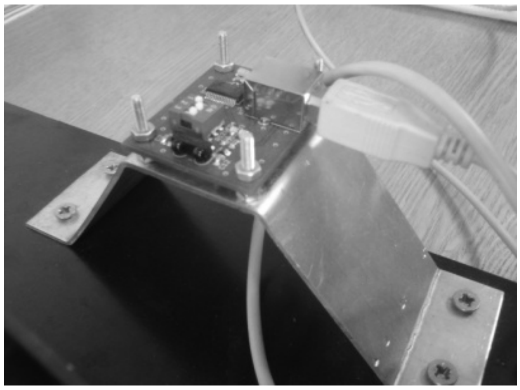

Fig. 4. System for data transport - stationary parts.

C. Calibration

Calibration of the equipment is very important for accuracy of measuring. Every temperature sensor is a little bit different and elimination of this difference is necessary. The whole equipment was assembled for the calibration as in Fig. 5.

Fig. 5. Calibration - assembly of measuring system during calibration.

The calibration furnace Jofra ATC-650B was used. The ATC-650B (Advanced Temperature Calibrator) is dry-block calibrator with dual-heating of the calibration chamber. The maximum possible temperature of the heated chamber is 650 °C (1202 ˚F). Accuracy of the furnace temperature sensor is + 0.11 °C (+ 0.20 °F) with temperature stability + 0.02 °C (+ 0.036 °F). The equipment for temperature measurements was mounted above the calibrator in a common functional position. The stator part and the rotor part during the calibration are in Fig.6. The eight connected temperature sensors were put into the copper isothermal chamber of the calibration furnace, in Fig. 6 too. The calibration cycle was automatically controlled by the furnace control unit.

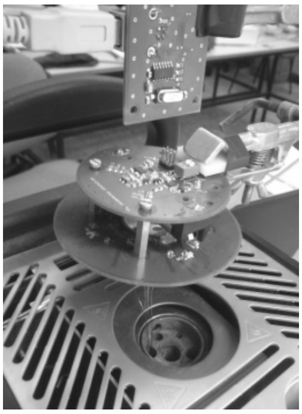

Fig. 6. Calibration - sensors of temperature in the isothermal chamber.

The calibrating cycle was in eleven values of the temperature from 25 °C (77 °F) up to 125 ° C (257 °F) therefore one step was 10 °C (18 °F). The data "representing" a temperature were stored in the computer. The stored data was assigned to the temperatures during post-processing. The problematic of the data recording is described in the next part of the paper.

D. Software for Data Processing and Calibration

Creating of the computer program for the data processing was necessary. The LabVIEW software was used for reading and evaluating of the data at first. The data reading and display was possible. This operation ran in real time, but some problems with the data loading came along. We decided for another type of the data reading. The easy program in the Delphi software was created and data reading was realized. The format of the output data is as a text file. It is not possible to show the output data in real time, but the number of errors is almost zero.

The output data are in a text file as written. The LabVIEW software is possible to use as a smart tool for post-processing. The data are put into the program created in the LabVIEW and the data processing is possible. The final graphs of temperatures are created by the program.

A special algorithm was used for the calibration of temperature sensors. The data stored during calibration cycle (already described) was processed by the own created LabVIEW program and the constants of the thermistors were calculated.

The used thermistors are nonlinear NTC temperature sensors. The NTC sensor resistance characteristics are approximately described by the equation

$$R = A \cdot e^{\left(\frac{B}{T}\right)}. \qquad (1)$$

The constant "A [Ω]" depends on material and shape of the thermistor body. The constant "e" is base of the natural logarithm. The constant "B [K]" reflects temperature-resistance characteristics of the thermistor material. The parameter "T [K]" is absolute temperature. Equation (1) can be modified to

$$R_t = R_{25} \cdot e^{B \cdot \left(\frac{1}{T} - \frac{1}{T_{25}}\right)}. \qquad (2)$$

The parameter "R_{25}" is resistance at 25 ˚C (77 ˚F). The constant "B" corresponds with equation

$$B = \frac{2{,}3026(\log R_1 - \log R_2)}{\frac{1}{T_1} - \frac{1}{T2}}. \qquad (3)$$

The resistances "R_1, R_2" are adequate to the temperatures "T_1, T_2". The resistances "R_1, R_2" are measured for the temperatures "T_1,T_2". For the right temperature measurements it is very important to know the thermistor constant "B". The constants of thermistors are specified in the datasheet. The temperature sensors are produced with the manufacturing tolerances, for a better measurement accuracy it is better to calculate "B" for every temperature sensor.

The resistance of the 2K7MCD1 NTC sensor is 2 kΩ at 25 °C (77 °F), this is the main point for the calculation. Equation (2) was modified:

$$R_i = R_{25} \cdot e^{\left(\frac{B_x}{t_i + 273} - \frac{B_x}{298}\right)} \qquad \begin{array}{l} R_{25} = 2[k\Omega] = const. \\ B_x \in \langle B_{\min}, B_{\max} \rangle \\ t_i \in \langle 25;125 \rangle \end{array} \qquad (4)$$

The parameter "B" can be put into equation (4), "B" is chosen from the interval around the "B" value specified by the manufacturer. The parameter "t_i [°C]" is the value of ideal temperature steps during calibration.

The measured calibration data can be linearized using the linear regression method. To the "R_i" computed parameter the value of "u_i" measured parameter was assigned. The parameter "u_i" is "number" sent from the rotating part of the equipment for temperature measurements to the static part, it is not real value of any physical quantity but it is a number corresponding with the real temperature value. The table of "R_i"-"u_i" values is suitable as data for creation of linearized equations. The final equation is a common equation for the linear function with parameters k_x, q_x for the corresponding parameter B_x. In our case it is possible to write the linear equation representing resistance characteristic of the thermistor by this way:

$$u_i = \frac{k_x}{2000} \cdot R_i + q_x \quad . \qquad (5)$$

Equation (5) is possible to transform:

$$R_i = (u_i - q_x) \cdot \frac{2000}{k_x} \quad . \qquad (6)$$

Finally it is possible to compare equations (4) and (6). From this final equation (7) we can compute "t_i" depending on B_x, k_x, q_x.

$$(u_i - q_x) \cdot \frac{2000}{k_x} = R_{25} \cdot e^{\left(\frac{B_x}{t_i + 273} - \frac{B_x}{298}\right)} \quad . \qquad (7)$$

At the end it is necessary to define which combination of the parameters B_x, k_x, q_x for the computing of the real temperature is the best. For this decision it is optimal to have parameter "Δt_x", equation (8). The parameter "t_{kali}" is ideal value of the one from the temperature steps during the calibration.

$$t_{kali} - t_{i(B_x, k_x, q_x)} = \Delta t_i \qquad (8)$$

The application of the least square method (Δt_i^2) is suitable for defining the best combination of the above specified constants; the best of all "B" parameters is possible to choose. The best parameter "B" for the every sensor is possible to put into the program for post-processing of the measured data.

E. Stand for Equipment Testing

For the testing of equipment for temperature measurements near of a tooth flank a small stand was designed and manufactured. The testing stand is a very easy equipment which is necessary for testing of the temperature measuring system not yet in his real operation condition but "in the office" only. This little stand is in Fig. 7.

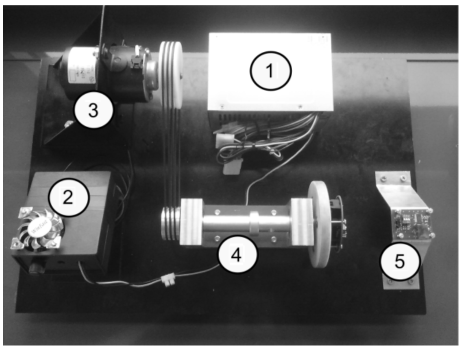

Fig. 7. Stand for equipment testing.

The power supply is number 1 in Fig. 7. The power supply gives 12 V for operation of a little electric motor. The electric motor is number 3 in Fig. 7. The rotation speed of the motor is possible to change by a regulator. The regulator is number 2 in Fig. 7. The rotation of the electric motor is transformed by a belt drive on the rotating shaft which is number 4 in Fig. 7. This shaft rotates with a similar frequency as in a real gearbox. The rotation frequency of the shaft is about 5200 rpm. The rotating parts of the tested equipment for temperature measurements are applied on the shaft. The sensors are fixed in the middle of the rotating shaft.

The static parts (stator) of the measuring equipment are installed on a small holder, number 5 in Fig. 7. The IR receiver is contained in the stator of the equipment. The IR receiver has to be mounted before the infrared LED in a right distance and in the axis of the IR LED (shaft) rotation.

III. Conclusion

This short article deals with the design, manufacturing and testing of the equipment for temperature measurements near of a tooth flank of the gear in a real gearbox. The article brings short information about used technologies, software and sensors. The calibration is shortly described here. The relative articles are [7, 8]. The problematic of this type of temperature measurements is very large and next outcomes will be presented.

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References

[1] V. Moravec, Z. Dejl, M. Němček, Z. Folta, and J. Havlík, *Čelní ozubená kola v převodovkách automobilů*. VŠB-TU Ostrava, 2009. ISBN: 978-80-7225-304-3.

[2] A. Dočekal, *Design Optimization of Gearbox considering reduction of noise emission*. Ph.D. thesis, VUT Brno, 2003.

[3] T. T. Petry-Johnson, A. Kahraman, N. E. Anderson, and D. R. Chase, "Experimental investigation of spur gear efficiency," in *Proceedings of the ASME 2007 International Design Engineering Technical Conferences & Computers and Information in Engineering*, Conference IDETC/CIE 2007 September 4-7, 2007, Las Vegas, Nevada, USA DETC2007-35045.

[4] B.-R. Höhn, K. Michaelis, and M. Hinterstoißer, "Optimization of gearbox efficiency", *GOMABN*, 48(4), pp. 441-480, ISSN 0350-350X.

[5] V. Moravec, *Konstrukce strojů a zařízení II – čelní ozubená kola*. ISBN-80-7225-051-5, 2001.

[6] S. B. Rao and D. R. McPherson, "Gear tooth temperature measurements," *Gear Solutions*, August 2009.

[7] M. Mazač, "Stand for Measuring Temperatures of the Main Gears of Automobile Differential," *54th International Conference of Machine Design Departments*, 10th-12th September 2013, Hejnice, Czech Republic, ISBN 978-80-7372-986-8.

[8] M. Mazač, P. Herajn, and M. Svoboda, "The Equipment for Temperature Measurements near a Gear Tooth Flank," *55th International Conference of Machine Design Departments (ICMD2014)*, Beroun, September 9.-12.2014, ISBN 978-80-01-05542-7.