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Measurement of Gearbox Efficiency by Strain Gauges: Direct Application

LOPOT F.[1,a], DUB M.[1,b], HAVLÍČEK M.[1,c], ŠTOČEK O.[1,d], VESELÝ T.[2,e], KUČERA L.[2,f]

[1]Department designing and machine elements, Faculty of mechanical engineering, Czech Technical University in Prague, Technická 4, 160 00 Prague 6, Czech Republic

[2]Department of Information and Communication Technologies in Medicine, Faculty of Biomedical Engineering, Czech Technical University in Prague, nám. Sítná 3105, 272 01 Kladno 2, Czech Republic

[a]frantisek.lopot@fs.cvut.cz, [b]martin.dub@fs.cvut.cz, [c]martin.havlicek@fs.cvut.cz, [d]ondrej.stocek@fs.cvut.cz, [e]tomas.vesely@fbmi.cvut.cz, [f]lukas.kucera@fbmi.cvut.cz

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Abstract.
Experimental determination of gearboxes efficiency provides important information. The use of specialized torque-sensors is, however, often complicated. Thus, we engage in experimental determination of the efficiency by direct strain gauges application. To achieve meaningful results, the calibration quality and strain gauges location are crucial. There is also an effort to increase the overall apparatus sensitivity by placing strain gauges in notches vicinity. To make the apparatus as light as possible, the amplifiers were replaced by 24 bits AD-converter. Places for the strain gauges installation are selected using FEM analysis. This analysis is used as a "virtual" calibration of the apparatus at the same time. Currently tested gearbox for city rail-vehicle was mounted in the measuring stand in full compliance with its real installation. Strain gauges were installed directly at the input shaft and at the output both, on the shaft and on Hirt teething on coupling hub. The presented method demonstrates reliable interpretation of results from measurements with conventional foil wire strain gauges far beyond their commonly declared sensitivity at the level of about 2 MPa. Furthermore, it brings a proposal how to define realistic uncertainities of the measured data considering calculated directly from raw data set without any filtering or other processing to eliminate the noise or in contrary highlight the points of interest.

Introduction

Experimental determination of gearboxes efficiency provides important information. Use of special torque sensors is, however, often complicated mainly due to spatial reasons. Moreover, their installation will affect the araangement of the whole set. Thus, we engage in experimental determination of the efficiency by direct application of strain gauges on the shafts of the measured gearboxes or on the hubs of the shaft couplings used. Also, the measuring apparatus is usually placed directly on measured rotating shafts. To achieve meaningful results, the quality of calibration and location of strain gauges are crucial [2, 3, 4, 6, 7, 9, 10]. There is also an effort to increase the overall apparatus sensitivity by convenient placing of strain gauges in notches vicinity. The use of notches for strain gauges is quite common, especially in the field of sensors [4, 5, 6].

A fundamental prerequisite for the use of a notch is clear linear relationship between mechanical stress and deformation. Because the stress is concentrated in the notches, the proportionality limit (yield point) can be exceeded locally. This condition is limiting for their use for strain gauge measurements, although it cannot be an obstacle for the operation of the component. Therefore, it is very important to subject the notch area to a thorough analysis.
The second fundamental output of this analysis is the determination of the area in which the searched local maximum of mechanical stress is located. Its position depends not only on the shape of the notch, but also on its size, geometry of the surroundings, surface roughness and many other factors. The influence of these factors varies depending on parameters of the material, production technologies, etc. [5, 11]. For this reason, it is appropriate to accompany the computational analysis with an experiment. The experience of our team so far indicates that the geometry of the notch and its surroundings has an overwhelming influence on steel shafts produced by turning and grinding.

Methods

Our measurement of efficiency by direct application of strain gauges is a complex process of series of successive steps. These steps can vary in specific design according to the situation. In any case, however, these steps are perfomred according to the following specifications:

- analysis of drawing documentation
- FEM analysis
- Preparation of installation foils
- Installation of strain gauges and apparatus
- Measurement
- Data processing using virtual calibration through processed FEM analysis
- Interpretation of results

The analysis of the drawing documentation represents an input step. In frame of it, places for installation of strain gauges and apparatus are selected. Secondly, the drawing documentation is used for preparation of installation foils. Usually, and in this case also, we use to work with standard foil strain gauges, LY series from HBM.

FEM analysis is a key step. First, it is used to select locations for installation of the strain gauges. A criterion for the final selection is the highest achieved stress value at a location, which must be available and large enough to install the strain gauge. As a rule, subjects of an evaluation are stress values in the network nodes. The smallest possible strain gauges are used for the measurement and it is thus not necessary to determine the average stress value over their length usually. In other words, the error we introduce into the result in this way is well below the limit of measurability. However, depending on the software used, it is possible to use various beam-type elements for strain gauge simulation. The above mentioned measurement error can thus be nearly completely eliminated. In order to be sure of the correctness of analysis results, the FEM calculation is repeated several times with various degrees of local refinement of the network and various settings of other marginal conditions. As the subject of monitoring, there are values in selected places of the calculated geometry. These values are compared with each other for various versions of the calculation. The result of the FEM analysis is considered correct when an invariable result is achieved. It is practically impossible to achieve a completely unchanging result. Obviously, results obtained by the FEM calculation after stabilization fluctuate around actual value (Fig. 1). It is therefore necessary to work with differences that are understood to be negligible.

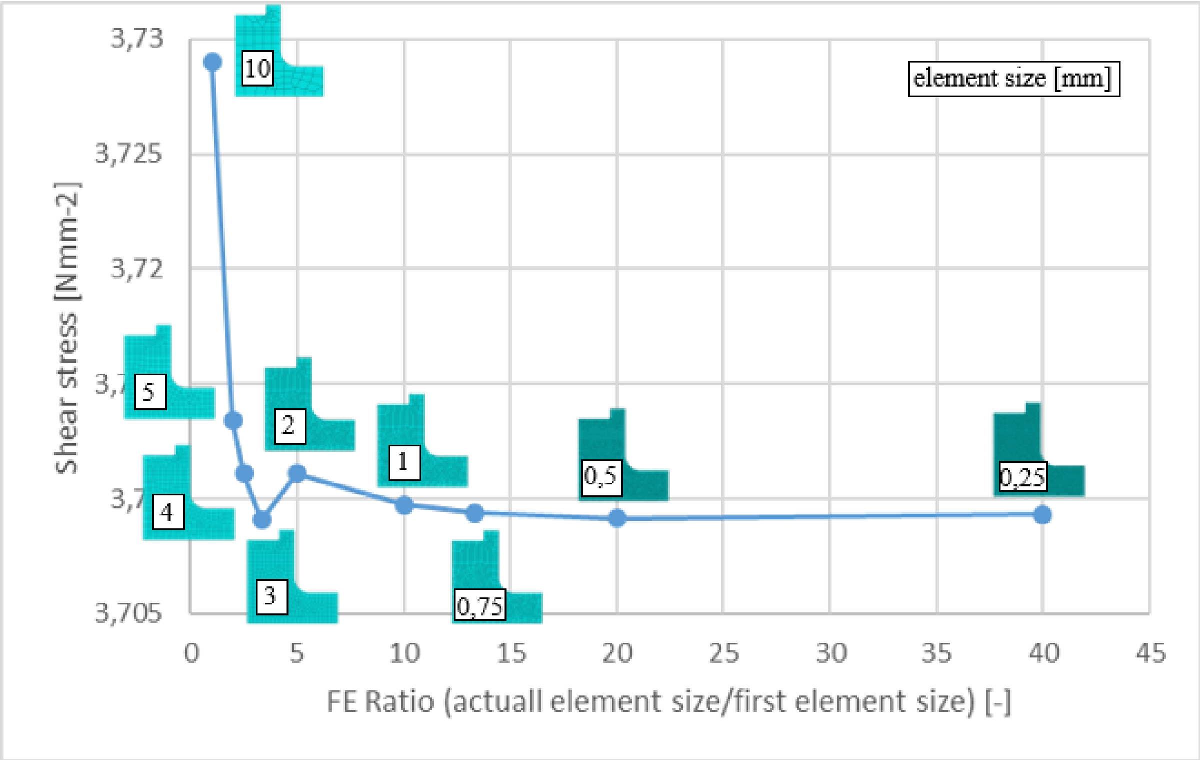

Fig. 1: Result of FEM analysis in strain gauge site related to element size

To calculate the stress value which will be comparable with acquired signal from strain gauge, we calculated presented values as average from results included in site of the strain gauge bordered by its active length [11]. This is the reason why in presented graph at FE ratio 5 (2 mm element size) is discontinuity which is caused by the partition of the area under the strain gauge active length. The number of elements at the edge of the model representing the strain gauge is 2 till the element size of 3 mm. Then, there is the jump in the number of elements from 2 to 4. The following curve then continues in the expected trend. With regards to the accuracy of the detection of actual values by practical measurements, we set this limit at a difference of 1% in our study. Once it is clear where the strain gauges are to be glued, we return to the drawing documentation to determine the specific geometry in specified places as a starting point for the next phase of work. Second, FEM analysis is also used for "virtual" calibration of the apparatus [4] during the processing of the measured data.

Preparation of the installation foils and jigs for the apparatus assembly is a routine step based on projection of measured geometry into the design of assembly jigs for the apparatus and on the use of developed shapes of appropriate geometry for printing of self-adhesive foils. On these foils, the strain gauges are placed before installation. In this way, we are able to position the strain gauges very accurately. The error caused by this way is then immeasurable for us.

The installation of strain gauges and apparatus already takes place at the installation site of the measured transmission set. During this phase, we follow common recommendations for the installation of strain gauges - thorough surface preparation for gluing, strain gauge gluing and wiring processes, etc. With regards to the need of the determination of the current torque on specified shafts using measurement, we work almost exclusively with strain gauges intended for torsion sensing [9]. These are installed into a full bridge due to temperature compensation. Usually, the apparatus is supplemented by other strain gauges for sensing of bending in two perpendicular planes. Alternating bending is usually an undesirable phenomenon in transmission sets. The function of these strain gauges is thus usually rather checking one. Nevertheless, the information is available. For its application in the calculation of required efficiency, it is not possible to describe a simple universal solution. It is always strongly dependent on each specific task. In general, it can only be stated that in cases where bending is present, there is an outflow of transmitted energy. This outflow is reflected in a decrease of the efficiency of the unit. At the end of this phase of the work, the installed measuring system is tested and the software bridge balancing, or tara zeroing only, is performed [8]. To make the apparatus as light as possible, the amplifiers are not used. Instead, a system developed by our team only works with a 24 bits AD converter. Using a battery with 1500 mAh capacity, we can measure continuously for up to 18 hours. Practically, this phase is performed twice - once for the input shaft and once for the output shaft. In both places, we worked with standard foil strain gauges from, the LY type.

Both subsystems communicate with each other within the overall measuring system via a selected protocol (x-bee, wifi, etc.). They also communicate with the control computer using the same protocol. Data can be read online while being stored on the storage media of both subsystems. We do not normally use online data reading due to high energy demands of this operation. Instead, we send data to the control computer with a significantly lower frequency (around 10 Hz). We display these data online on the monitor to check the operation of both subsystems and the whole complete system. Very often, subsystems are wrapped in a protective foil in the final phase of their installation (Fig. 2).

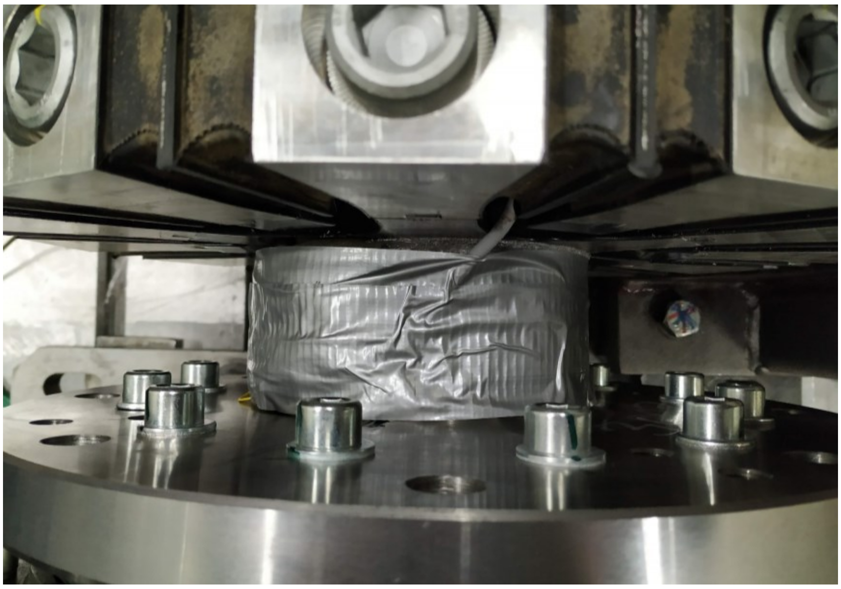

Fig. 2: Installed subsystem wrapped in a protective foil
(see also the shaft coupling with rubber blocks)

Data processing using virtual calibration through processed FEM analysis is performed after measurement finishing. Obtained data are not filtered or otherwise reduced. For the purpose of determining the efficiency of measured set, data processing is focused on reliable determination of mean values of measured waveforms. The question then is how to express the uncertainty of assessed value. We used standard deviation obtained from data set for mentioned average curve. The searched for efficiency is then determined according to the common definition. The gear ratio is considered as constant, because its fluctuations due to the unevenness of the teeth engagement are negligible for involute gearing. Thus, it has practically no effect on the result. An important aspect of data processing is correct signal zeroing. This can be complicated, because the gluing of the strain gauges takes place on the installed equipment during the agreed downtime. Usually, it takes place without any practical possibility of eliminating any residual stresses that remain in the shafts after the machine has been shut down. Noteworthy, the presence of these residual stress is specifically reflected in the measured signal by a step change of recorded values after starting the unit and its approach to prescribed test mode.

Interpretation of results is the final phase of the work. In frame of it, obtained results are arranged into comprehensible outputs, most often into so-called efficiency maps.

Efficiency maps clearly show a connection between efficiency and important parameters that directly or indirectly define it. In case of transmissions, it is primarily the speed and the transmitted torque that define the degree of load on the transmission under investigation. These are therefore 3D graphs, where the parameter is most often the operating temperature in the case of transmissions. This is given mostly by temperature of the filling (oil). The influence of this parameter on the form of the map varies depending on construction of the device and oil used, from very low to completely decisive.

For needs of our research in the field of industrial gearboxes for relatively large powers (from hundreds of kW to MW units), the most commonly used type is a projection of the efficiency map determined for the operating temperature of given design into a speed and torque plane. The speed and torque plane is a plane from which the connection of the investigated gearbox with the degree of its load can be seen clearlierst.

Furthermore, other important information can very easily be obtained from the efficiency maps, such as the development of power dissipation depending on a load of examined transmission, etc.

All the above-mentioned partial steps have been a subject of long-term development. As a part of this development, the methodology of tensometric measurement of the efficiency of transmission sets was certified by TÜV NORD Czech, s.r.o. [1].

Experiment

The measurement was performed using the above-mentioned methodology in a cooperation with Škoda Electric a.s. and Wikov MGI et al. The tested gearbox for city rail vehicle was installed in the measuring stand in full compliance with its real installation (Fig. 3).

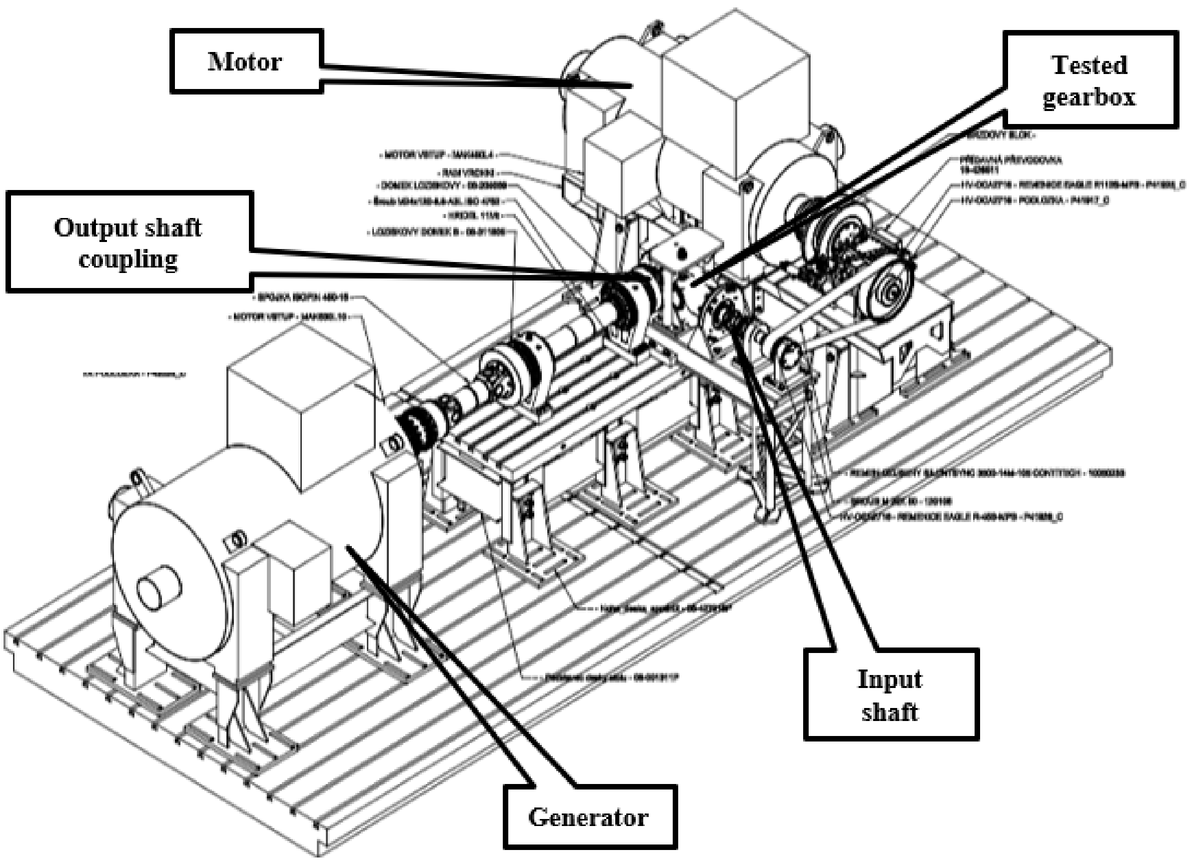

Fig. 3: Testing stand

The measurement was performed according to the following specification (Tab. 1):

Tab. 1: Assignment

Mode	Input speed [1/min]	Mk on the input [Nm]
1	10	10
2	10	330
3	10	660
4	10	1080
5	1840	10
6	1840	330
7	1840	660
8	1840	1080
9	2670	10
10	2670	358
11	2670	710
12	2670	1080
13	4200	10
14	4200	250
15	4200	500
16	4200	775

Based on the analysis of the drawing documentation, places for position of strain gauges and apparatus were selected. The outputs of this phase are clear from Fig. 4.

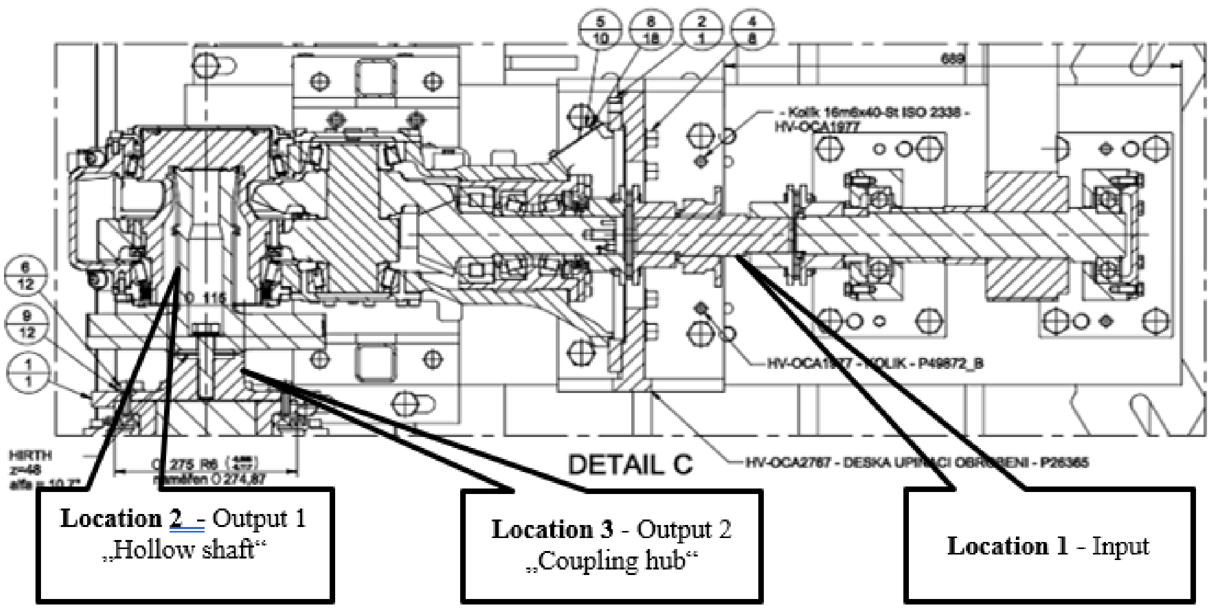

Fig. 4: Drawing with determination of places for application of strain gauges

The second step was the calculation of expected stress for individual load levels and FEM analysis of complicated shapes with notches to ensure virtual calibration even in places for which the analytical calculation does not provide reliable data. Because all the selected locations except for the first third (Fig. 4) are located on smooth circular cross-sections, FEM analysis was applied only to the hub of the used Hirt toothed coupling. We worked with Abaqus software. The FE model is designed as axisymmetric. It brings many benefits in case of meshing and computation time. There are used axisymmetric stress elements CGAX8R with reduced integration and quadratic shape functions. Quadratic elements are chosen to obtain the most precise results.

The FE size sensitivity analysis was carried out to ensure the correctness of the result shear stress at measured place. The obtained values are averaged across the strain gauge active length. The dependency of the result shear stress on the FE size ratio can be seen in the graph. It is evident that the results are very stable and converges quickly to the „exact“ solution. The final FE size is set to 0,5 mm on the surface, the global seed size is 4 mm.

The calibration constant for the Hirt joint measured point is calculated as a ratio of the shear stress of the smooth shaft and the shear stress on the modelled part with realistic shape. The result calibration constant is equal to K=0.902 (Fig. 5).

There is also the inner thread M24 placed in the centre line of the shaft. The influence of this thread to the surface shear stress is negligible.

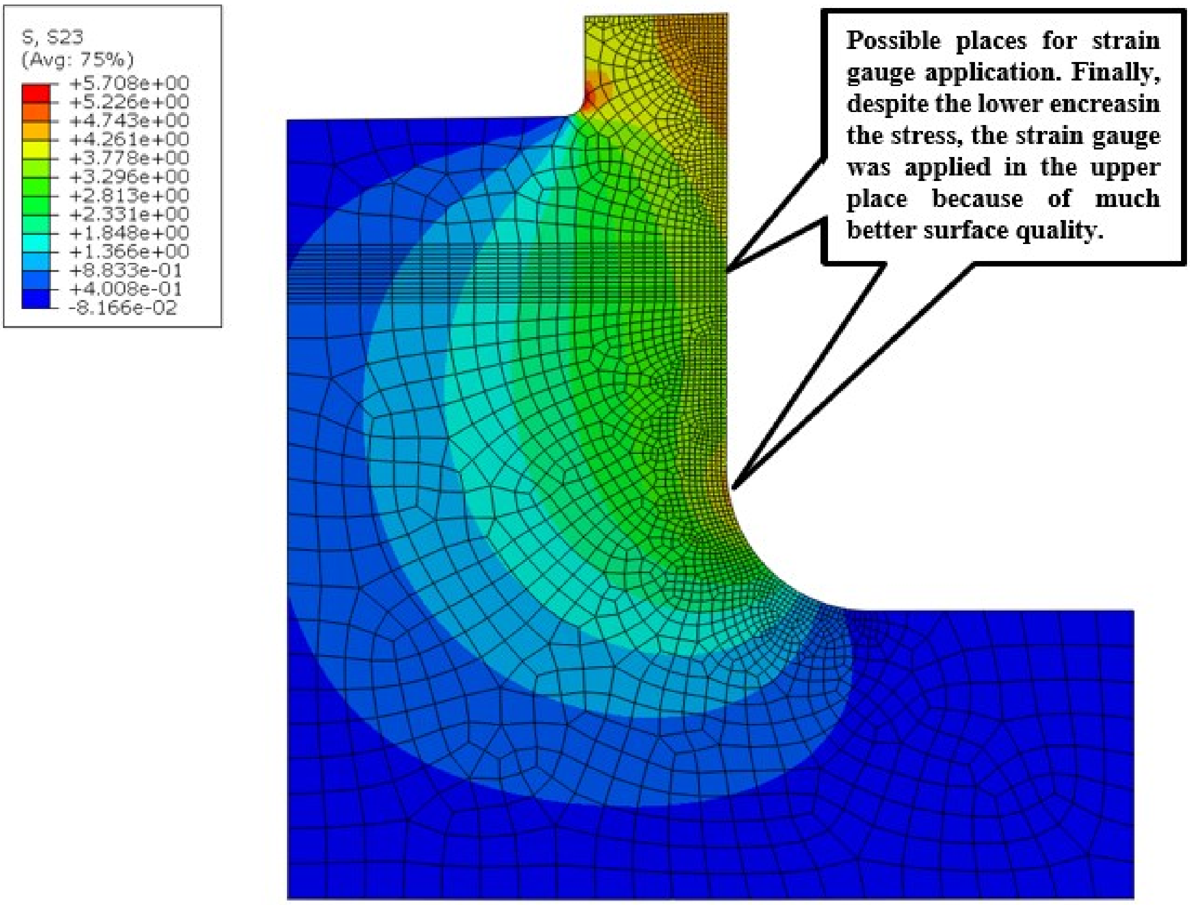

Fig. 5: FEM analysis use

The outputs of this calculation were subsequently used also for the above mentioned final calibration during data processing.

After confirming that selected places are well usable for the installation of strain gauges, the phase of preparation of installation foils took place on the basis of the processing of local geometry. This is followed by the installation of strain gauges on site. In this case, the output shaft was varnish coated and it was necessary to remove the varnish at gluing place for the strain gauge. The outputs of these phases can be seen in Figs. 6 and 7.

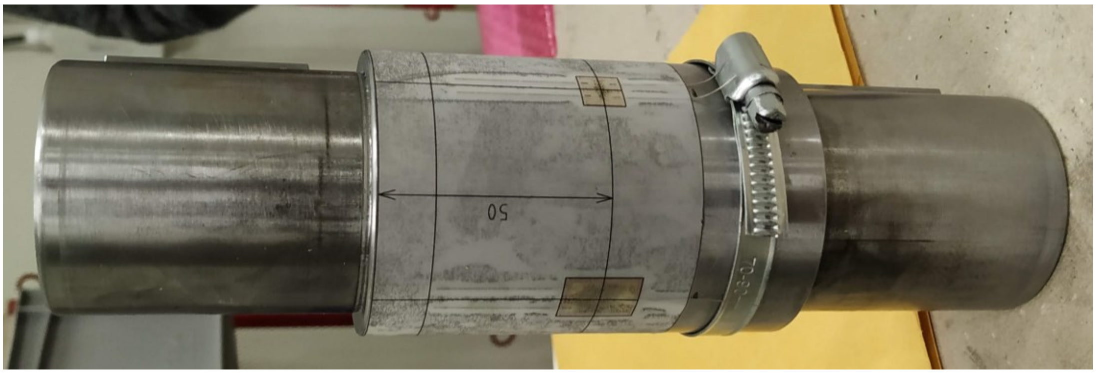

Fig. 5: Applied application foil with strain gauges on the input shaft (Location 1 in Fig. 4)

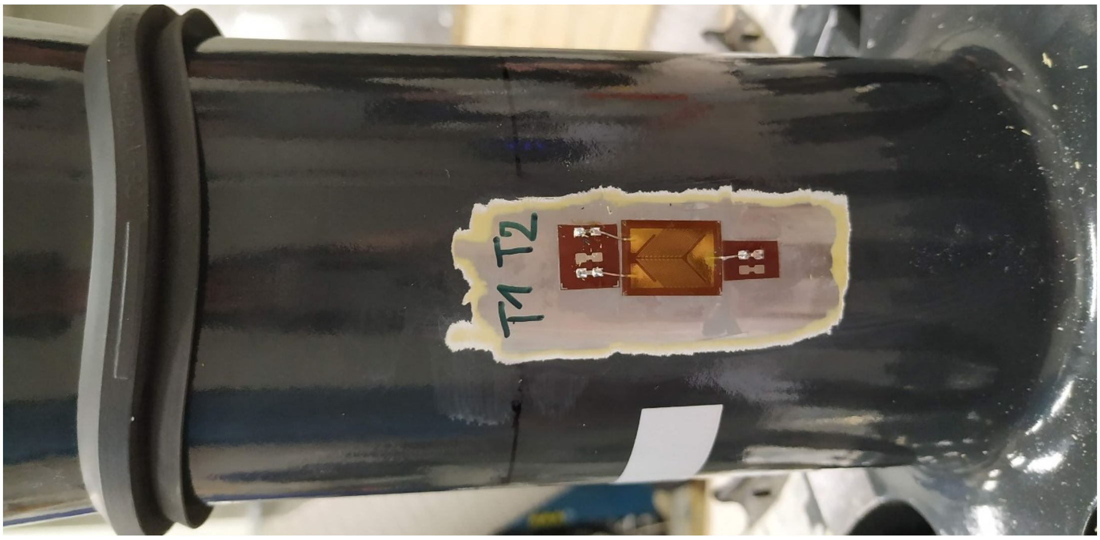

Fig. 6: Applied measuring strain gauge after removing the foil and installing the soldering fields on the hollow output shaft (Location 2 in Fig. 4)

After wiring, the parts were handed over to the mechanics and laboratory technicians of Wikov MGI company. They installed all the measuring parts prepared into the tested stand. The installation of data loggers and batteries followed. In order to ensure permanently unchanged position of data loggers and accumulators on the surface of rotating measured shafts, a strong adhesive tape with textile fibers in the adhesive line was applied (Figs. 7 and 2).

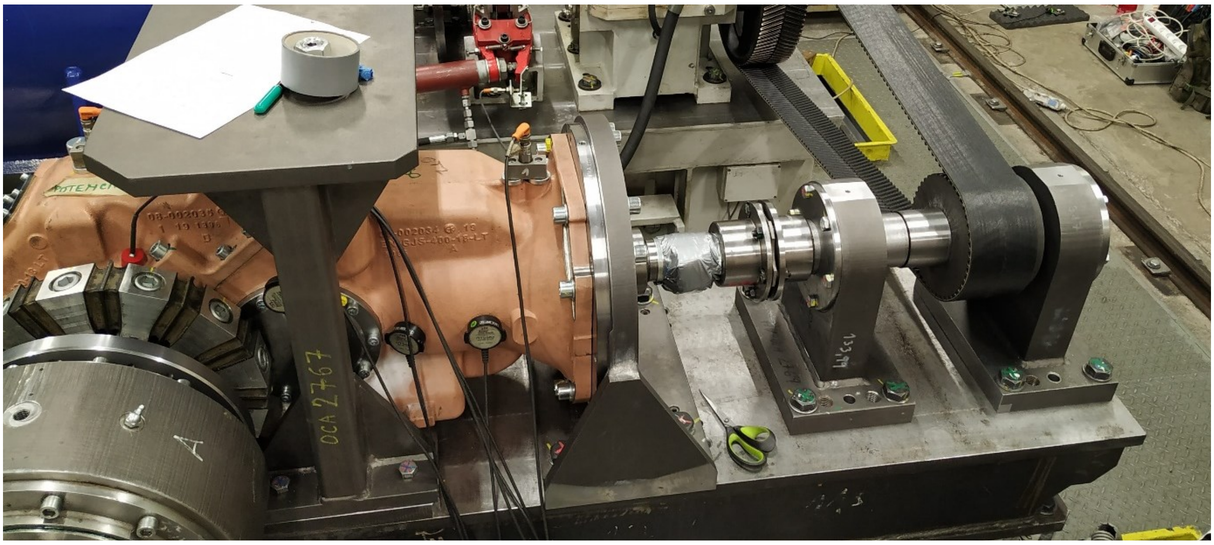

Fig. 7: Completed installation of the apparatus on the input shaft

The measurement was performed without physical presence of workers in the area of the gearbox measured. Progress of the measurement was monitored by means of video camera on computer monitor in a control room of the testing laboratory. The setting of required operating modes was performed by an experienced employee of Wikov MGI company. Tab. 2. provides an overview of the measured modes. These have been implemented within the possibilities offered by the laboratory equipment, respecting of operating conditions of the gearbox operation (especially the oil temperature).

Tab. 2: Overview of implemented measured modes

Mode	Input speed [ot/min]	M_k on the engine [Nm] (indicatively)	No. of measurement	Measurement start	Measurement time [s]	Oil temperature [°C]
1	12,2	10	9	16:56	35	48
2	12,2	330	10	16:57	35	46
3	12,2	660	11	16:59	35	45
4	12,2	1080	12	17:00	20	45
4	12,2	1080	12a	17:54	20	42
5	1840	10	1	16:04	40	44
6	1840	330	2	16:09	40	45
7	1840	660	3	16:11	40	48
8	1840	1080	4	16:14	40	49
9	2670	10	5	16:17	40	50
10	2670	358	6	16:19	40	53
11	2670	710	7	16:22	40	55
12	2670	1080	8	16:24	40	56
13	4200	10	13	17:58	30	42
14	4200	250	14	17:59	30	44
15	4200	500	15	18:00	30	45
16	4200	775	16	18:01	30	46

Mode no. 4 was repeated because control of operation of the unit reached limit of laboratory equipment. Moreover, online monitored control data did not show stable character. The delay between modes 12 and 13 was caused by oil cooling to operating temperature. Data on input torque in Tab. 2 is for guidance only - this data come from motor control converter. RPM reading is accurate. It was obtained from an external speed sensor located on the transmission input shaft.

Measurement time in Tab. 2 is for guidance only. It is a time for which the unit worked exclusively in the operating mode set.

Data recording was provided by data loggers with 24-bit AD converters. These convertors stored data on an SD card with sampling frequency of 1000 Hz per channel. At the same time, these data were sent via wireless interface X-Bee with a frequency of 10 Hz to a notebook. These data were there displayed online to check the operation of the apparatus.

The purpose of data processing before final evaluation is to identify and eliminate artifacts and errors which have been introduced during the measurement. Furthermore, readings from strain gauges have to be converted to Nm.

The actual data processing was preceded by detailed determination of dimensions of measured components at the strain gauge application site.

Data obtained after removal of artifacts and conversion to Nm using the data of gear ratios are presented graphically for individual modes according to tab. 2 (an example in Fig. 8).

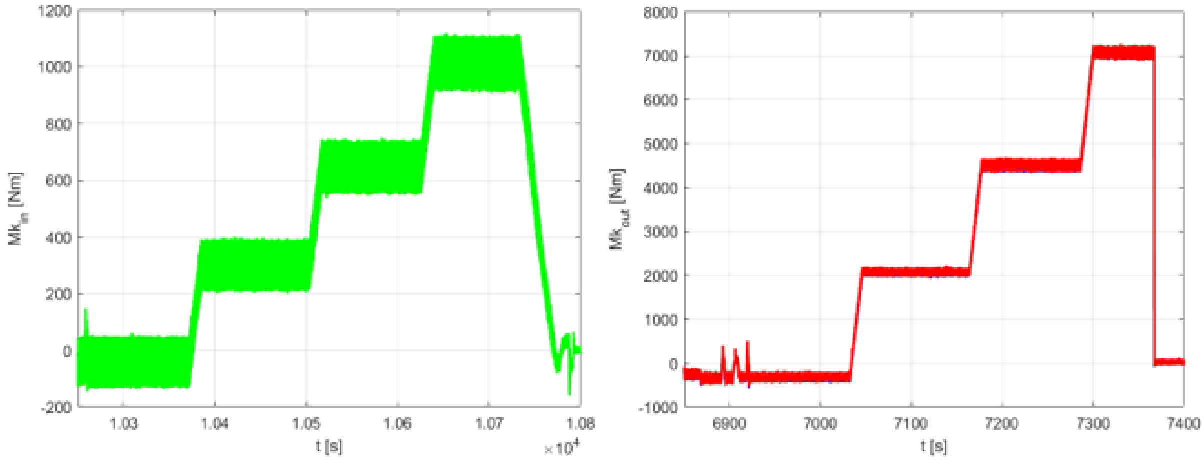

Fig. 8: Exapmple of torque recording for modes 9, 10, 11 and 12
(input - green, outputs - red, blue)

From the presented total course, the sections of the constant load in individual working modes are excluded for the determination of the mean values of the acting moments (example in Fig.9).

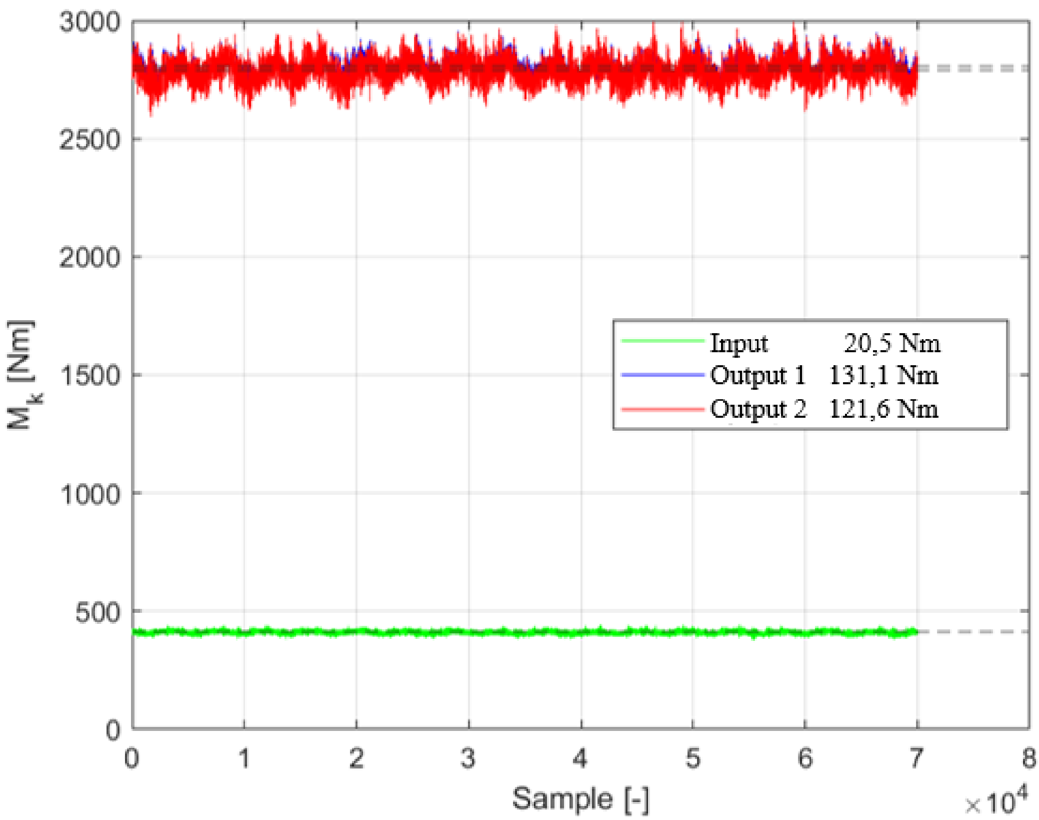

Fig. 9: Example of evaluated torque record for one mode
(input - green, outputs - red, blue)

The data are interesting in terms of frequency also but from current point of view, we use them primarily to calculate the searched efficiency. The interpretation of reached results is clear from Tab. 3 and 4. They give an overview of torque values for the input and output hollow shaft and actuall transmission efficiency in studied modes. The relative deviation of efficiency evaluation of the tested transmission is assessed using a theory of error folding as the square root of squares of relative errors of the input and output torque in each mode. Relative error means the ratio of the standard deviation and the average value of the monitored quantity.

Tab. 3: Evaluated data for hollow output shaft

mode	Input			Hollow shaft			
	Speed	Average	Std. dev.	Average	Std. dev.	Efficiency	Std. dev.
	1/min	Nm	Nm	Nm	Nm	%	%
1	12.2	20.46	0.620	131.07	3.609	**89.89**	17,898
2	12.2	409.95	0.750	2808.87	4.258	**96.14**	1,055
3	12.2	756.13	0.701	5169.80	3.698	**95.93**	0,498
4	12.2	1106.13	0.758	7607.35	4.233	**96.50**	0,389
5	1840	-39.94	2.972	-347.03	3.623	**82.02**	-11,733
6	1840	271.82	2.940	1853.23	4.221	**95.66**	1,892
7	1840	595.86	3.034	4128.51	6.444	**97.22**	1,195
8	1840	1007.57	3.019	7018.25	5.688	**97.73**	0,639
9	2670	-35.93	4.049	-322.31	2.876	**79.45**	-13,823
10	2670	304.77	4.076	2071.48	2.959	**95.37**	1,653
11	2670	651.44	4.101	4509.53	5.155	**97.13**	1,011
12	2670	1016.67	4.188	7080.37	5.719	**97.72**	0,697
13	4200	-54.89	1.327	-507.55	2.478	**77.08**	-5,121
14	4200	181.76	1.452	1147.52	2.599	**88.58**	1,638
15	4200	428.56	1.452	2888.15	2.903	**94.56**	0,757
16	4200	700.97	1.466	4803.84	3.011	**96.16**	0,478

In modes 5, 9 and 13, the power flow reversed in the direction from the generator to the motor. This was reflected in a change in the polarity of the signal from the measured components. To calculate the efficiency in these cases, the output of the gearbox was therefore considered as an input and, conversely, the input was considered as an output.

Tab. 4 presents similar data for the input shaft and the hub of the output shaft coupling.

Tab. 4: Evaluated data for coupling hub in the output shaft

mode	Input			Clutch hub – Hirt			
	Speed	Average	Std. dev.	Average	Std. dev.	Effieciency	Std. dev..
	1/min	Nm	Nm	Nm	Nm	%	%
1	12.2	20.46	0.620	121.57	4.082	**83.37**	20,180
2	12.2	409.95	0.750	2789.57	4.752	**95.48**	1,174
3	12.2	756.13	0.701	5144.14	4.203	**95.46**	0,564
4	12.2	1106.13	0.758	7570.35	4.731	**96.03**	0,433
5	1840	-39.94	2.972	-386.87	4.463	**73.57**	-13,425
6	1840	271.82	2.940	1813.00	4.859	**93.58**	2,089
7	1840	595.86	3.034	4083.77	6.839	**96.16**	1,256
8	1840	1007.57	3.019	6963.65	6.206	**96.97**	0,685
9	2670	-35.93	4.049	-345.10	3.672	**74.20**	-15,213
10	2670	304.77	4.076	2043.42	3.319	**94.07**	1,725
11	2670	651.44	4.101	4478.72	5.388	**96.47**	1,039
12	2670	1016.67	4.188	7038.89	6.058	**97.14**	0,724
13	4200	-54.89	1.327	-520.35	4.499	**75.18**	-8,545
14	4200	181.76	1.452	1125.83	4.368	**86.91**	2,532
15	4200	428.56	1.452	2859.89	4.544	**93.63**	1,113
16	4200	700.97	1.466	4772.37	4.673	**95.53**	0,699

A graphical representation of the development of efficiency of the tested gearbox in all operational modes is presented as a fundamental output of the measurement (Fig. 10 - without presented uncertainties/errors).

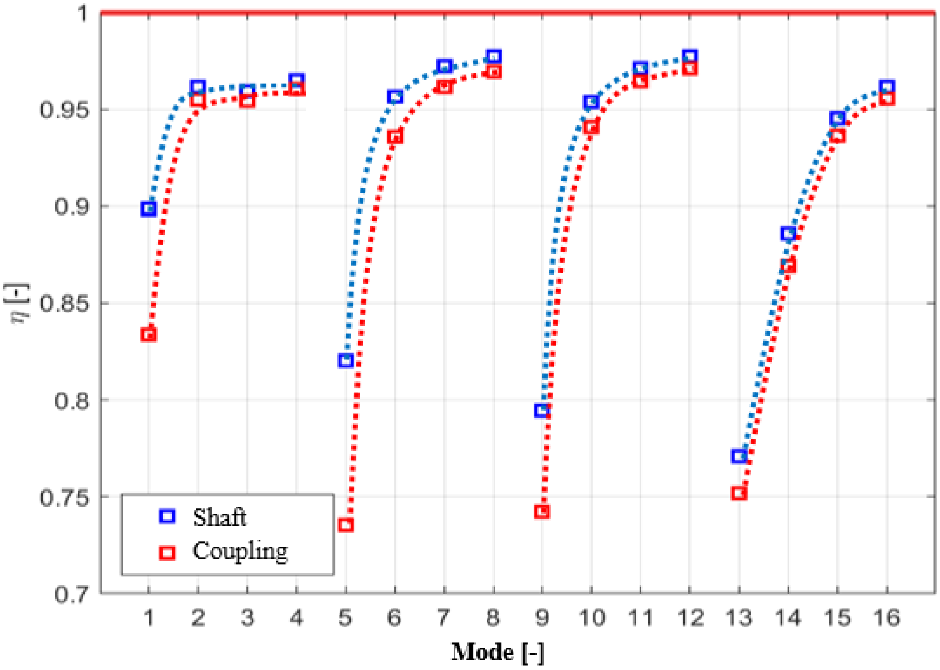

Fig. 10: Gearbox efficienty – trend curves for constant RPM

Smooth trend lines of marked points were added to the graph in Fig. 10 to show the development of efficiency of tested gearbox for individual measured modes in connection with the growth of the gearbox load at constant RPM.

If trend lines of marked points corresponding to each other across the modes are added to the same graph, it is possible to monitor the development of the efficiency of the tested gearbox in connection with the increase of RPM for a constant load level (Fig. 11).

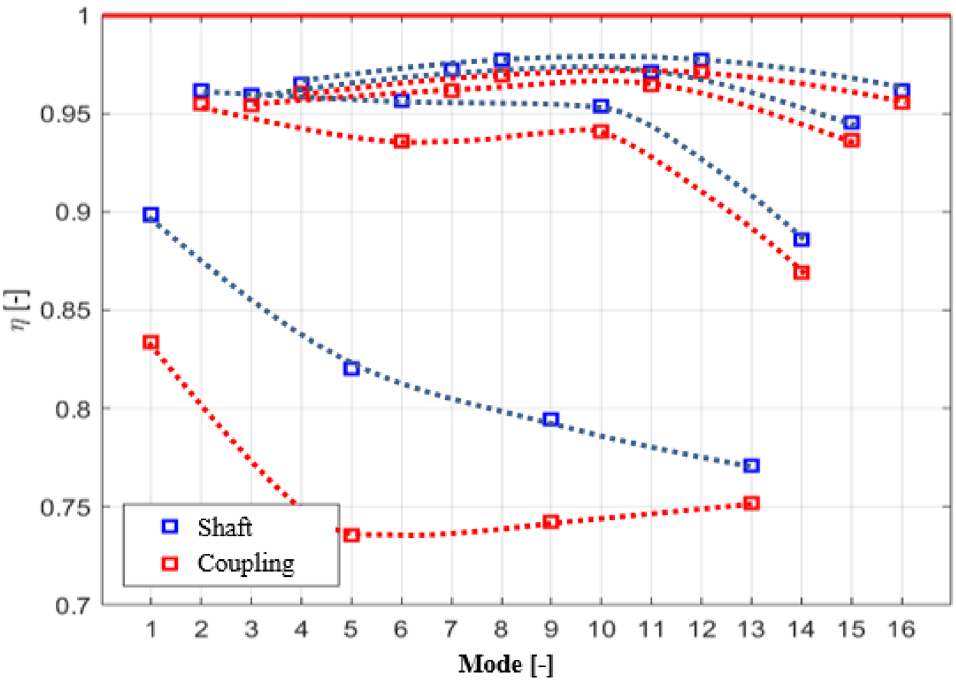

Fig. 11: Gearbox efficienty – trend curves for constant load level

With reference to the results presented above, it can be stated in general that the presence of flexible coupling on the output shaft (Figs. 2 and 7) which reduces the overall efficiency of the tested gearbox compared to the efficiency measured directly on the hollow shaft inside the gearbox.

Conclusions

The purpose of this study was to present a functional approach to measuring the efficiency of transmissions by direct application of conventional foil strain gauges. We aimed to draw attention to pitfalls that accompany it. To clearly document described phases of the whole process, the procedure was presented on an example of concrete measurement. In connection with this, it can be stated that the efficiency map above corresponds well with expectations of the gearbox manufacturer and, above all, it matches well with theoretical assumptions.
An important outcome of our work is the confirmation that with a suitable constellation of apparatus and the use of notches for the installation of strain gauges where possible, it can be obtained reliable interpretation of results from measurements with conventional foil wire strain gauges far beyond their commonly reported sensitivity at the level of about 2 MPa. Furthermore, it brings a proposal how to define realistic uncertainities of the measured data considering calculated directly from raw data set without any filtering or other processing to eliminate the noise or in contrary highlight the points of interest.

Acknowledgements

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