EAN 2019
57th conference on experimental stress analysis

Improvement in accuracy of strain gauge measurements for using in high precision measurements of gearboxes efficiency

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Keywords: Notch, Strain gauge, Stress, Torque, FEM, Measurement, Gearbox, Efficiency

Abstract

The paper describes further development in our research from the previous year [1]. We are still focused on finding a method of measuring the torsion on shafts of gearboxes installed in a real machine to determine their actual efficiency. The biggest problem is the limited accuracy of our strain gauge apparatus, because of over-sized design of shafts and thus their very small deformations. We still believe that use of various technological and structural notches is an acceptable solution, whereby the level of recorded signal could be amplified by this way.

Introduction

As part of our work, we try to determine the actual efficiency of gearboxes installed in a real fabric in normal operating conditions. In addition to warming and vibration monitoring, the strain gauge measurements which can be used to detect torques on input and output shafts, seem to be an effective approach. The importance of our measurements increases with the total power transferred when in case of large industrial units a small loss of efficiency may reach tens of kW of lost power. To make our measurement really meaningful, we need to get below 1% of relative error. A reliable way to minimize the relative measurement error is to have a sufficiently strong signal in relation to the sensitivity of the apparatus. Because in real installations it is not possible to make adjustments on the shafts that would "boost" the signal, we need to use some alternative means. These are mostly structural and technological notches that act as natural mechanical stress concentrators. For our measurements, we assume that a higher value of mechanical stress means also a higher corresponding deformation and that we work in the zone of elastic response. In the literature, we can find quite extensive information about stress in the notches and their surroundings and based on this we believe that our assumption on its applicability in functional structures such as gearboxes is justified and true. On the basis of stress analysis, we can also define the requirements for the orientation and location of strain gauges so that the notch is best used from our point of view, i. e. to generate the strongest signal. Because analytical solution of this problem could be very complicated, we used the finite element method (FEM) here. The previous work [1] focused on verification that FEM is also useful for calibrating the strain gauge apparatus when a real calibration is not possible, and we have introduced an approach that allows to use this option in real condition. The current laboratory measurements are primarily used to determine the uncertainty of such a calibration.

Experiment - method

A new measuring stand has been designed for our work. The main change compared to the previous version is a statically certain test shaft mounting (Fig. 1).

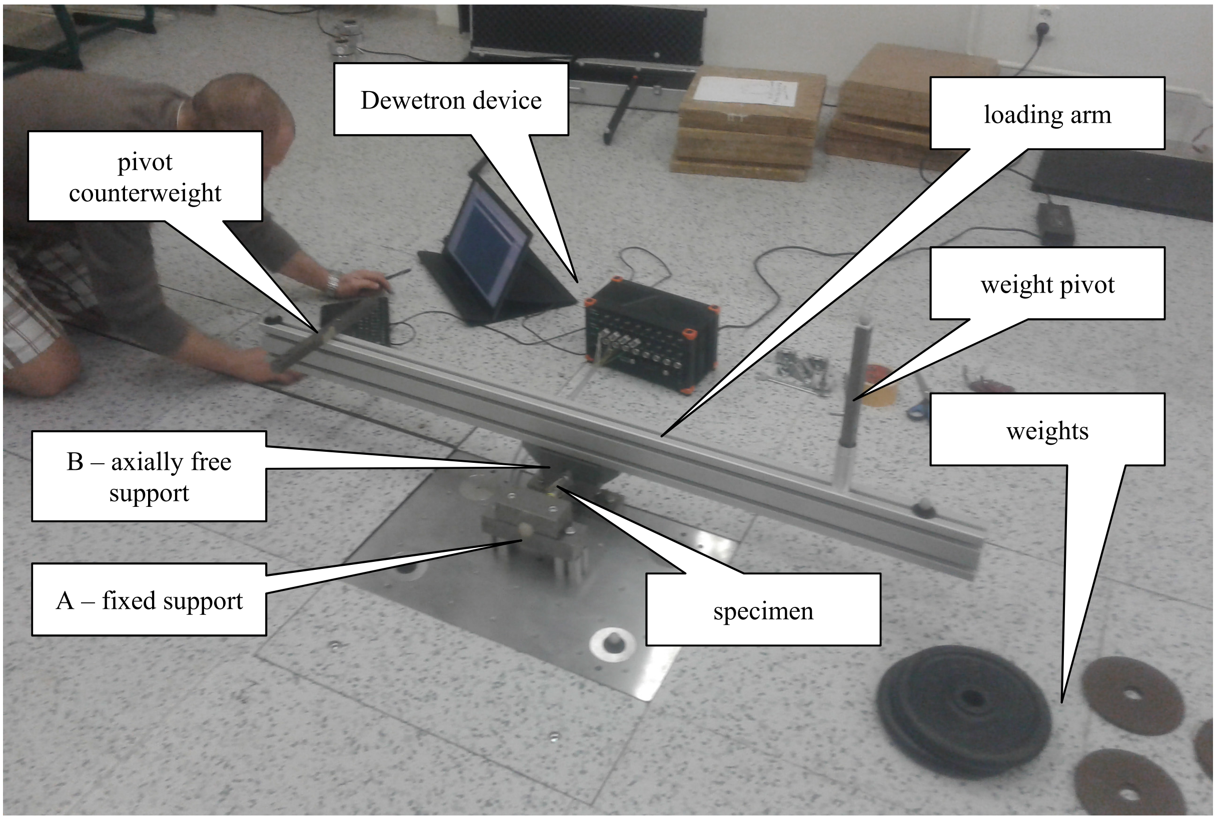
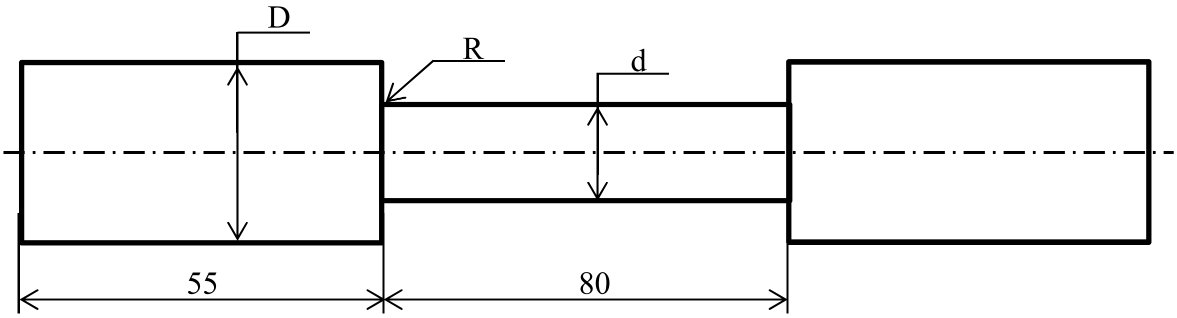


Fig. 1: Measuring place

One end (A) is mounted to a fixed part of the stand while the other end (B) is mounted on ball rollers with rolling contact. Thus, the measured shaft is loaded by torsion only. The loading of the specimens was induced by weights in steps of 0, 10, 15, 17.5 and 20 kg placed on the arm of defined length.

Three specimens of E355 steel [2] without chemical-theraml treatment were prepared for the measurement – see Fig. 2.



Specimen	D [mm]	d [mm]	R [mm]
1	25	15	2
2	25	15	4
3	25	20	2

Fig. 2: Specimen specification

Measurements were made using HBM LY11-0.6/120 strain gauges [3] installed by special application foil on the specimens acc. to Fig. 3.

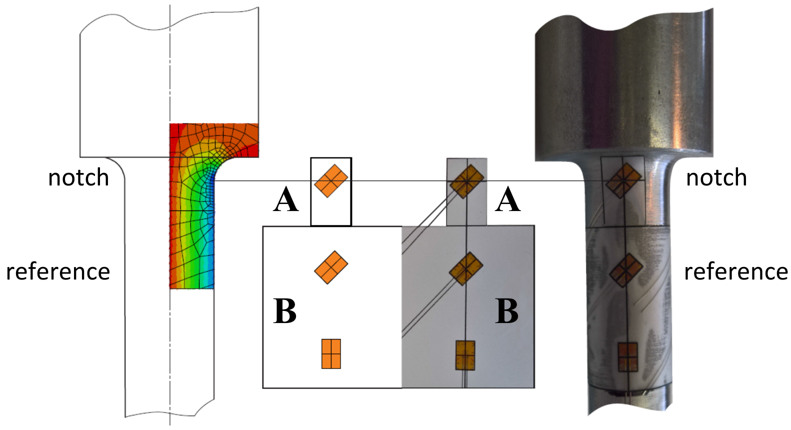


Fig. 3: Application foil design (left side) and use (right side – photo)

The left part of the figure shows a technical drawing of the shaft specimen with the deformation field determined by FEM and the drawing of the application foil with strain gauges. In the right part of the picture, there is real arrangement. The correct position of the foil is determined by the part marked B, which is applied to the available cylindrical part of the shaft. The part marked with A carries strain gauges placed in the area of the measured notch. In the B-part, the strain gauges for checking the data from the smooth cylindrical part are seen. From them, we get the magnitude of the torsional deformation. There are also other strain gauges for checking presence of pressure, tension and bending in the load applied on the tested shaft.

After several testing measurements, it became obvious that the halfbridge is an entirely satisfactory solution for the given purpose because of its installation simplicity and lower price. Also, strain gauges for checking the presence of tension or bending were found unnecessary and were not used in the final measurements.

The strain gauges were connected to the Dewetron Sirius station. The sampling frequency was set to 500 Hz with low pass filter on 10 Hz. The excitation voltage was 10 V and the amplifier sensitivity was 1 mV/V.

Experiment – data processing

The data processing procedure is presented on an example of one specimen. Fig. 4 presents an example of the recorded data (specimen No. 2, Fig. 2).

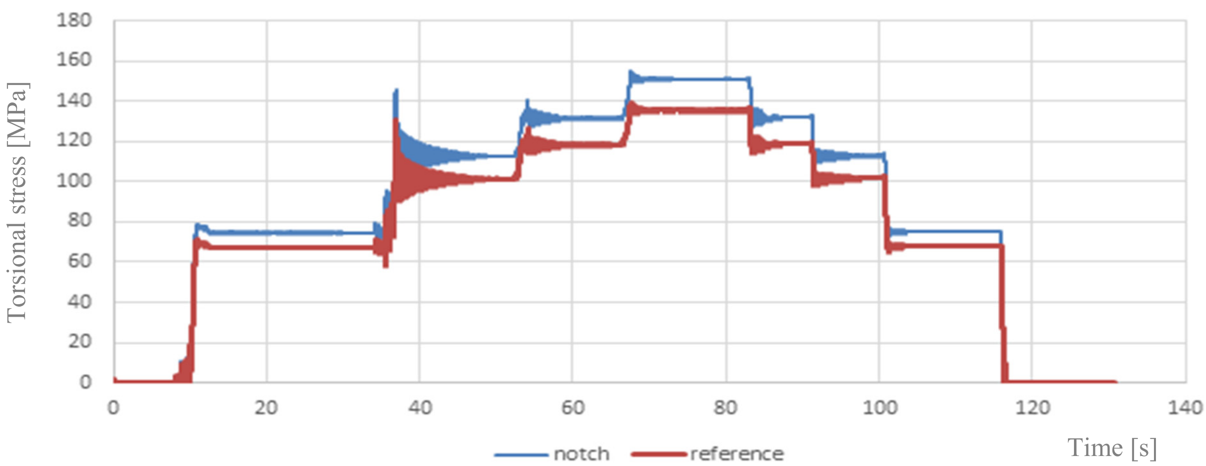


Fig. 4: Obtained data

From the measured quantity, which was the half-bridge voltage U [mV] related to the excitation voltage Un [V], it is possible to calculate the deformation (strain) of active part of the strain gauge using the definitional formula:

Strain = 2 x (U/Un) / (Gauge Factor from [3] = 1.74) (1)

Then, using next definitional relation:

Torsional stress = G x Strain, (2)

where G is appropriate modulus of elasticity for shear loading of measured shaft (81 GPa, [2]), the presented torsional stress is determined. For its calculation, it is, of course, possible to use the relation between torque and stress in the smooth middle section of the measured shafts as well:

Torsional stress = Torque / Wk, (3)

where Wk is modulus of cros-ssection for torsion.

Based on comparison the results of experimental data processing (2) with the results of the analytic calculations based on the known applied torque (3) and the outputs of the FEM analysis, the correctness and accuracy of the measurement is checked.

In the graph in Fig. 4, the distance of the stress levels measured at the notch and at the smooth cylindrical part of the specimen can be seen very well. This difference is described as the ratio of the values in the notch to the values of the smooth part. In terms of applicability of our approach for measuring different levels of gear shafts loading by torque, it is very important that this ratio remains constant as the graph in Fig. 5 shows.

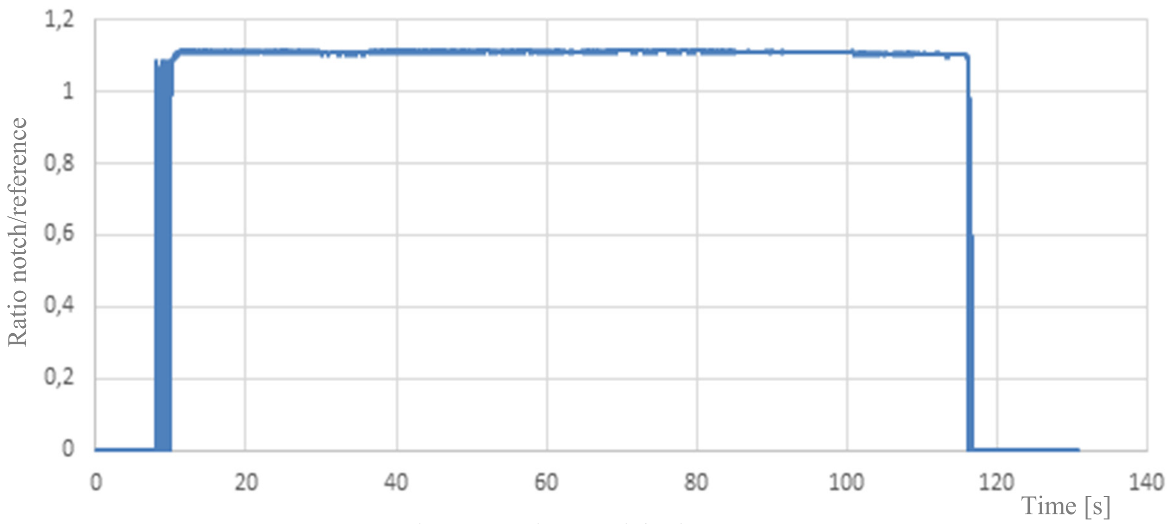


Fig. 5: Ratio notch/reference

Since we are very far from the yield point of the shaft material in our measurements, this graph can be taken for granted. It is, in fact this shape that is important for practical measurements. Any deviation from that pattern means that the data we would be obtaining becomes unreliable and their processing would be difficult if not impossible. As for possible causes, deviation from its individual but constant values would suggest that the notch becomes plasticized and further measurement and data processing would be problematic.

Results

Tab. 1 presents an overview of data processing outputs for measured specimens. The data in the table shows the average values from stable parts for each loading level. The right column gives the "Stress concentration factor" Kt values determined from the Peterson’s charts [4] at the eFatique.com portal [5].

Tab. 1: Results - overview

Specimen	Loading [Nm]	Experiment Smooth part [MPa]	Experiment Notch [MPa]	FEM analysis Smooth part [MPa]	FEM analysis Notch [MPa]	Analytics Smooth part [MPa]	Kt
1	0	0	0	0	0	0	1.30
	47.6766	70.5525	89.7071	70.5255	89.6975	70.5252	
	71.5149	105.7734	134.5606	105.7883	134.5463	105.7879	
	83.4341	123.4007	157.0221	123.4197	156.9707	123.4192	
	95.3532	141.0601	179.4306	141.051	179.395	141.0505	
	83.4341	123.4108	157.0208	123.4197	156.9707	123.4192	
	71.5149	105.7879	134.5700	105.7883	134.5463	105.7879	
	47.6766	70.5606	89.7105	70.5255	89.6975	70.5252	
	0	0	0	0	0	0	
2	0	0	0	0	0	0	1.18
	47.6766	67.7899	75.3401	67.796	75.3348	67.7955	
	71.5149	101.7003	113.0111	101.694	113.0022	101.6933	
	83.4341	118.6393	131.8325	118.6431	131.836	118.6422	
	95.3532	135.6026	150.6803	135.592	150.6696	135.5911	
	83.4341	118.6400	131.8376	118.6431	131.836	118.6422	
	71.5149	101.6999	113.0099	101.694	113.0022	101.6933	
	47.6766	67.7912	75.3399	67.796	75.3348	67.7955	
	0	0	0	0	0	0	
3	0	0	0	0	0	0	1.35
	47.6766	29.0308	36.6728	29.026	36.6947	29.0260	
	71.5149	43.5309	55.0092	43.539	55.04205	43.5390	
	83.4341	50.8008	64.1774	50.7955	64.21576	50.7955	
	95.3532	58.0399	73.3456	58.052	73.3894	58.0520	
	83.4341	50.7997	64.1774	50.7955	64.21576	50.7955	
	71.5149	43.5401	55.0092	43.539	55.04205	43.5390	
	47.6766	29.0311	36.6728	29.026	36.6947	29.0260	
	0	0	0	0	0	0	

Presented results show very good agreement between measured data, results of the FEM analysis and from analytical calculation in a smooth cylindrical part of samples. The FEM analysis is perfectly matched also to the measured data in the notch - the worst ratio of these values does not exceed 0.06 % of the FEM values (Tab. 2).

Tab. 2: Results – comparison, average values

Spc.	Experiment/FEM analysis Smooth part [MPa] average	Experiment/FEM analysis Smooth part [MPa] worst	Experiment/FEM analysis Notch [MPa] average	Experiment/FEM analysis Notch [MPa] worst	Experiment/Analytics Smooth part [MPa] average	Experiment/Analytics Smooth part [MPa] worst
1	1,000082189	1,000497692	1,000197136	1,000327328	0,999914053	0.999498304
2	0,999997100	0,999910024	1,000048839	0,999973611	0,999995785	0,999915193
3	1,000022527	0,999791566	0,999403012	0,999402585	0,999977324	1,000208477
total	1.000033939	1.000497692	0.999882996	0.999402585	0.999962387	0.999498304

None of the measurements achieved the values resulting from the above mentioned Stress Concentration Factor. This, if fact, further supports relevance and reliability of data obtained by the described method.

Conclusions

Based on the above results, it appears that the aim less than 1% of the uncertainty of the strain gauge output is achievable, thus our method can actually be used to monitor the efficiency of big industrial gearboxes.

The results confirm that the use of structural and technological notches may bring the necessary "amplification" of the strain gauge signal.

With regard to small deviations found, we can also confirm applicability and feasibility of the FEM analysis as a method of virtual calibration of strain gauge set-outs.

It is also interesting to note that for stepped shafts with simple radiuses in steps loaded by torsion, the maximum mechanical stress is located at the transition of the smaller cylindrical part and the notch radius.

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