metrology

Article

Comparative Studies of the Measurement Accuracy of Basic Gear Wheel Parameters

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Abstract: This article presents the results of comparative tests of gear wheels based on the contactless and contact measurement methods. Measurements of gear wheels in accuracy classes containing deviations within the range of measurement capabilities of the GOM ATOS II optical scanner are proposed. Elementary deviations of teeth related to the involute profile were analyzed. In undertaking a non-contact gear measurement using the GOM ATOS II scanner, a new method was developed to extract parameters from the point cloud, which were then used to determine the total deviation of the profile. The results of the measurements obtained using the non-contact method were compared with the results obtained with the contact method using the Wenzel WGT 600 four-axis machine specialized for measuring gear wheels. Measurement uncertainty was also compared. The result of the conducted tests is the comparability of results for gear wheels made in accuracy class 10 according to DIN 3961/62. The proposed non-contact method shows the possibility of using it to measure gear wheels commonly used in agricultural and construction machines. The information obtained from comparing the measurement model and the nominal wheel model provides additional information about surface defects of the part which result from the production and operation process.

Keywords: gear accuracy; industrial metrology; optical scanners; gear profile deviations

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1. Introduction

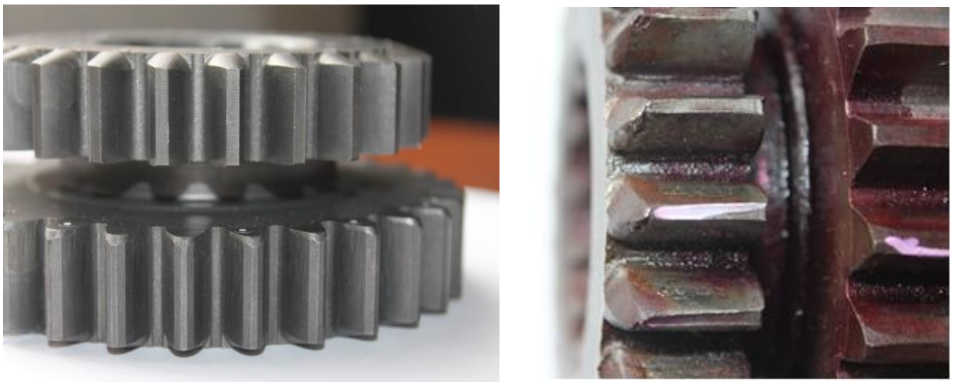
Research conducted in recent years in the area of metrology is increasingly based on the use of non-contact measurement methods [1,2]. Gears occupy a very important area in the machine industry. The quality of the produced mechanical gears and their appropriate service life depend on their performance. Research on the implementation of non-contact measurements using optics is conducted mainly for applications in the aviation industry [3,4] and automotive industry [5]. For many years, work has also been underway on improving non-contact measurement techniques by developing new methods of using the light spectrum in order to increase the accuracy of measuring devices [6,7]. The proposals of conceptual measurement methods are widely known, which consist in using a source of structured light directed at the measured gear and performing scanning using cameras [8–10]. The light falling on the measured gear undergoes deformation, which is observed by cameras. Then, the obtained image is analyzed by a computer program, which, by combining scans taken from many directions, calculates a 3D surface model of the measured gear. A commonly used scanner that uses structured light is the GOM ATOS II scanner. As a result of the measurement, it is possible to reproduce the shape of the measured gear wheel into an editable digital model. Measuring elementary deviations of the gear wheel requires generating a digital model from a point cloud (counted in millions), which is then subjected to appropriate processing using CAD software. An example of this type of software dedicated to the GOM ATOS optical scanner is GOM Inspekt. It provides the ability to compare the measured model of the actual gear wheel with the nominal model as a result of transforming two models into a common coordinate system. Then, as a result of using model matching tools, based on the construction databases of a given gear wheel, the effect of a visual map is obtained presenting the exceedance of nominal dimensions in the form of a color scale. However, this operation does not provide numerical values of elementary deviations of the profile, tooth line and pitches, and run-out; therefore further geometric processing of the model system is required. In the work presented in [11], a method for measuring the tooth profile based on the use of an additional cross-section plane supporting the measurement of profile parameters is graphically presented. Then, in the separated cross-section plane, a tooth outline is generated, which includes the adjusted outline from the measured (real) model and from the nominal model (obtained from the CAD program). The appropriately adjusted outline on the left and right side of the tooth allows for determining the total deviation of the outline on the designated measuring section of the tooth profile. The researchers also presented a method for measuring the total deviation of the tooth line in a similar (graphic) way. The additional plane allows for the isolation of the measured section, which is subject to assessment in accordance with the measurement guidelines included in the adopted standards for gear wheels, e.g., DIN 3961/62. In the work presented in [12], there is a non-contact method for measuring gears using optics to determine the accuracy of gears obtained as a result of production using a rapid prototyping method. This publication discusses the possibilities of using optical measurements to determine the geometric accuracy of gear wheel castings produced in the rapid prototyping process. The tested gear wheel prototype was made and cast from an aluminum alloy. Coordinate optical measurement methods and a GOM scanner were used to test the accuracy of the geometry of gears produced by casting. The obtained measurement results are highly reliable, because the accuracy of castings in the rapid prototyping method is within the limits of the scanner's measurement capabilities. A similar method was described in [13], for measuring the performance properties of polymer gears using coordinate measurement methods. The measurements were performed using the ATOS II Triple Scan optical system. The main imperfection of the measurement method using an optical scanner is obtaining a discontinuous measurement surface. This problem was described in [14], where a method for reconstructing the actual surface from a point cloud was proposed. The researchers used 3D modeling to align the point cloud, which is processed to recreate actual tooth surfaces. A very significant aspect in industrial metrology is obtaining the appropriate measurement accuracy, as well as determining the measurement uncertainty estimate [15]. Publication [16] presents the results of accuracy measurements using a laser triangulation method. The article examines the potential of triangulation and confocal–chromatic sensors for measuring gears. The sources of deviations, such as the angle of inclination between the nominal to the tooth surface and to the sensor axis, the variable surface curvature and the topography of the gear surface, were analyzed. Measurements were carried out on the side surface of a straight-toothed gear wheel and it was shown that optical sensors have the potential to measure the shape of gears, especially confocal–chromatic sensors, which can achieve a measurement uncertainty of less than 10 μm. The geometric shape of gears is another issue for which an appropriate measurement method should be selected. Publication [17] presents the possibility of using the ATOS II optical scanner for measuring aircraft bevel gears. The research presented in the article was carried out based on a non-contact method of measuring bevel gears using a 3D optical scanner for preliminary and quick verification of correctness of execution. Deviations of all individual measurement points are calculated in relation to the nominal value of the geometry. Due to their number, deviations are visualized in the form of a color map. Such an image shows the critical points of the measured gear, which should be carefully analyzed using other—more accurate—methods. Study [18] presents the advantages of using a vision system in metrology, by using a vision-based gear profile measurement system. Thanks to the integration of the camera system with the measuring equipment, accurate registration and subsequent analysis of measurement results are possible. This system has the ability to record videos and save image frames in the JPEG format during the measurement, which allows their later opening and analysis in offline mode. The vision-based inspection system presented in that paper was designed mainly for measuring surface errors of various types of gear wheels. A lot of information about the geometric structure of the gear tooth surface can be obtained by analyzing the surface topography. In paper [19], an experimental optical approach to assessing the deflection of the gear tooth during meshing is presented, which is crucial for understanding the wear and fatigue resistance of gears made of polymers. The features depend on factors such as working load, speed, temperature and lubrication. The proposed approach is an alternative to numerical analyses, such as the finite element method (FEM), and uses image recording from high-resolution cameras and image processing methods.

Scientific publications also include other methods of measuring gear tooth profiles using incoherently structured light. Publication [20] presents the use of the incoherent linearly structured light method for precise measurement of gear tooth profiles. Inconsistent light, unlike coherent light used in lasers, helps reduce speckle noise, which is a common problem in laser measurements. As a result of the conducted experimental studies, it was shown that the incoherent linearly structured light method provides higher measurement resolution and is less susceptible to speckle noise, compared to traditional laser methods. The tooth profile error for the involute standard measured using the incoherent linearly structured light method was $\pm$2.2 µm. The obtained level of accuracy of the method allows its industrial application, where precise measurements of gear tooth profiles are required. Publication [21] presents 3D measurements of gears using a linear laser enabling quick acquisition of full 3D data of the tooth surface. That method, called LL3DMG, allows for the representation of the complex 3D topography of the tooth surface, including the size and modification of the gears, and compensates for the limitations of traditional measurement techniques that rely on a limited number of points on the tooth surface. In publication [22], the focus was on 3D measurement of gears based on linear light sensors. Measured 3D point cloud data were used to calculate the profile error and then compared with the results obtained from traditional contact measurements obtained using a Klingelnberg P26. The results obtained proved the agreement between measurements with a structured light sensor and reference measurements, which allows to conclude that, using a 3D point cloud measurement system, it is possible to perform fast and accurate measurements of gears, which is an innovative system for measuring involute for specified accuracy of gears.

This article presents the results of research conducted on the measurement of gear wheel profiles using the non-contact optical method and the contact method. The article is organized as follows: after the Introduction, in Section 2, the gear wheels are characterized and the measurement methods used in the research are described. Then, in Section 3, the measurement results are presented. In Section 4, the obtained results are commented on. In Section 5, the main conclusions from the research are presented.

2. Material and Methods

For comparative tests of the accuracy of gear wheels using the non-contact optical method and the contact method, two gear wheels made in the 10th accuracy class according to the DIN 3961/62 standard were selected. The first of the wheels was made as a brand-new wheel in accordance with the drawing documentation (Figure 1a). The second of the wheels used for measurement was dismantled from the gearbox mechanism in which it worked and was used (Figure 1b). The photos were taken in such a way as to show the difference in the profiles of brand-new and used teeth.

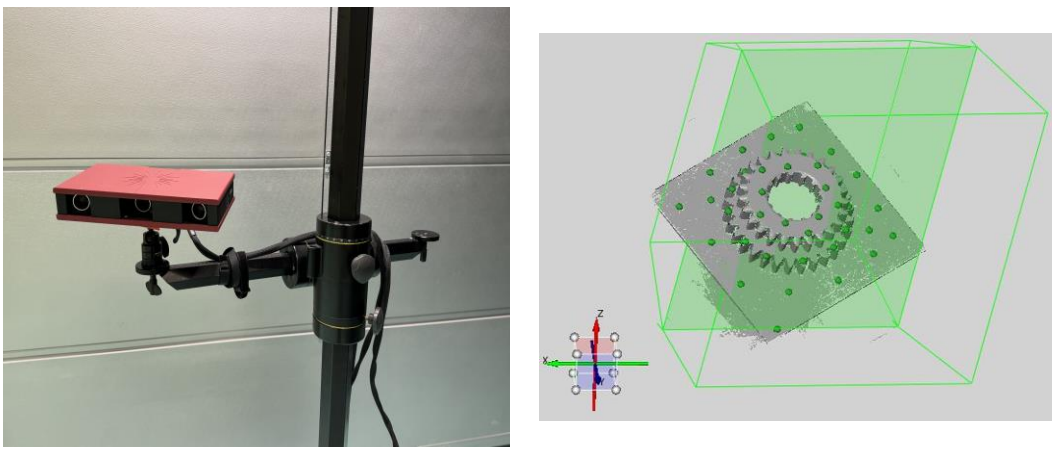


(**a**) (**b**)

Figure 1. Gears: (**a**) brand-new teeth, (**b**) used teeth. Ring 1: number of teeth 25; module 4; pressure angle 20°; tooth width 19.6 mm. Ring 2: number of teeth 30; module 4; pressure angle 20°; tooth width 21.5 mm.

- Optical measurement methodology

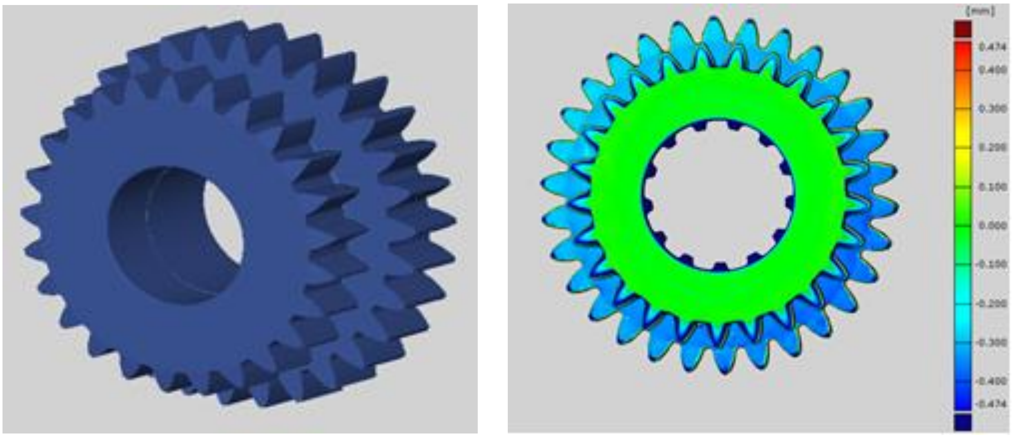
The first stage of the wheel tests was measurement using the GOM ATOS II optical coordinate scanner (Figure 2a). The Atos system allows the transfer of three-dimensional geometry of physical objects to the computer, thus providing a complete digital model that can be edited and processed by the CAD/CAM program [23]. In order to perform optical measurements using the non-contact method, appropriate preparation of selected gear wheels was required. In the first step, the gear wheels had to be thoroughly cleaned and degreased of any dirt, oils and liquids that could disrupt the scanning process and affect the accuracy of measurements. Then, black and white reference points, which are used for scanners using structured light, were glued to the surface of the gear wheels. The size of the markers is selected depending on the size of the measurement space. They serve as markers of three-dimensional objects during digitization. In the second step, the gear wheels were properly mounted on the measuring table to ensure stability and obtain accurate positioning during scanning. Before starting the scanning, the scanner was calibrated and the scanning parameters, such as resolution, scanning speed, etc., were set. During the measurement, the software controlled the scanner accordingly and measurement data (points) were collected for processing and analysis of the results. Individual scans were transformed into one common coordinate system. A spatial model of the measured object was obtained from the point cloud (as a result of the polygonization process) (Figure 2b).



(**a**) (**b**)

Figure 2. (**a**) GOM ATOS II optical coordinate scanner, (**b**) 3D surface model of the gear wheel obtained after polygonization.

In the next step, a nominal model of the gear wheel was generated in CATIA (Figure 3a). Then, both models were transformed to one common coordinate system and matched with each other in relation to the appropriate technological databases. As a result of this matching, a map of deviations was obtained (Figure 3b).



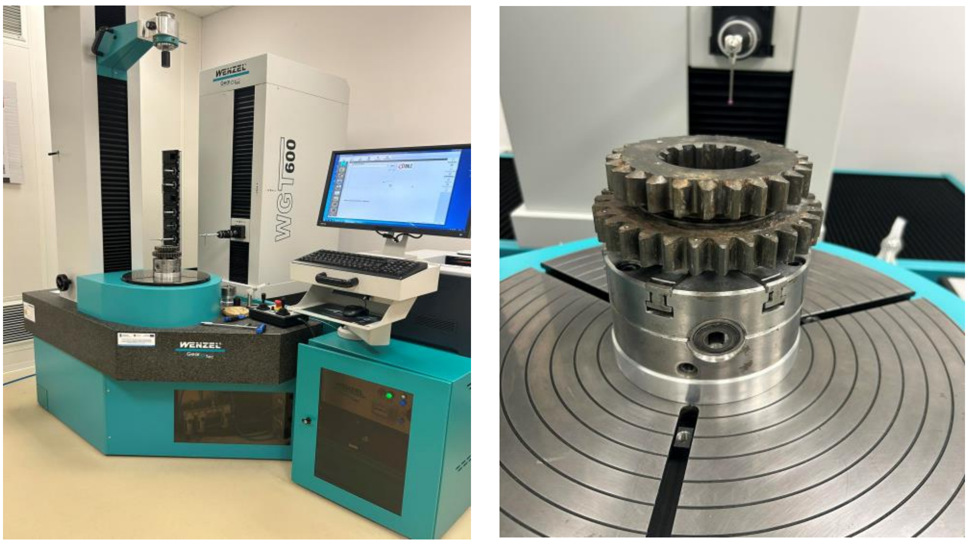
(**a**) (**b**)

Figure 3. (**a**) View of the nominal CAD model of the gear in CATIA, (**b**) view of the map of deviations of the surface model from the nominal values.

Data processing was performed using tools available in the GOM Inspekt scanner software based on the method presented in publication [8].

- Contact measurement methodology

For comparative tests, contact measurement was used with a specialized four-axis gear wheel machine, a Wenzel WGT 600. The measuring machine is equipped with computer numerical control (CNC) and is designed to control workpieces (cylindrical and bevel gears, worms, worm wheels, stepped shafts, camshafts, compressor rotors). It also allows measurement of gear wheels of unknown geometry and tools for their production in the range of teeth of up to 600 mm in diameter and with a maximum weight of 4000 N. The measuring machine is equipped with a RENISHAW SP600M scanning head. The photos show the test stand with the Wenzel WGT 600 measuring machine (Figure 4a) and gear wheels prepared for contact measurements (Figure 4b).



(**a**) (**b**)

Figure 4. Measuring machine: (**a**) test stand, (**b**) with a gear wheel prepared for contact measurements.

The measurement of gears using the contact method also required preparatory activities, which began with the use of an ultrasonic cleaner to clean and degrease the entire gear ring. The measurement was performed by mounting the gear in a three-jaw chuck on the internal base diameter. Then, the measured gear was referenced before the actual measurement.

The deviations of the tooth profile (right flank and left flank) of the cylindrical gears with straight teeth were measured. The number of controlled teeth in the measurement of the involute profile was, respectively, for the ring 1—25 teeth, for the ring 2—30 teeth. The results of the measurements were the following:

- Total profile deviation (Fα), which is the derivative of the superposition of the profile inclination deviation and the tooth profile shape deviation. This deviation provides information on how the actual gear tooth profile deviates from the intended profile, taking into account both the angle (inclination) and the shape (form) of the deviation. For the measured profiles of the 1st and 2nd gear rims made in the 10th accuracy class, the permissible total deviation was 56 µm.

All measurements were performed in accordance with the DIN 3961/62 standard and corresponded to the same number of teeth for which measurements were previously performed using the non-contact method.

3. Results

The results of the measurements of gears using the non-contact method for deviations of the surface model of the tooth profile are presented in the form of a deviation map (Figure 5). Figure 6 presents a detailed protocol of optical measurements with the result of the total deviation of the profile for the left and right flank of the selected tooth. Figure 7 presents a fragment of the protocol of contact measurements performed on a Wenzel WGT 600 machine.

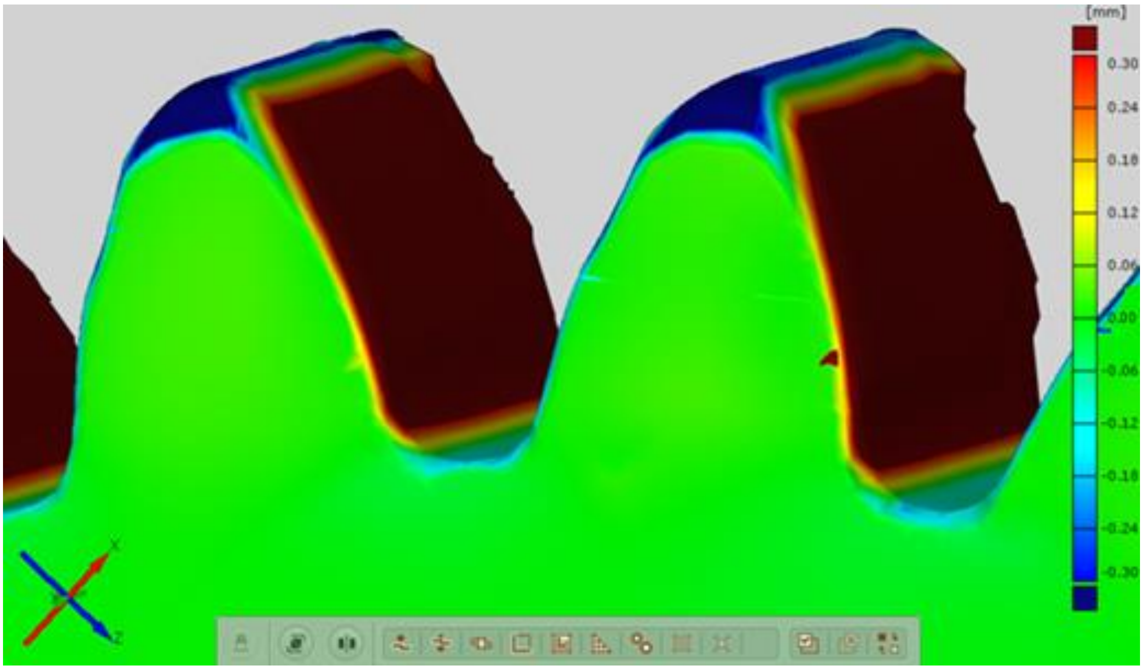
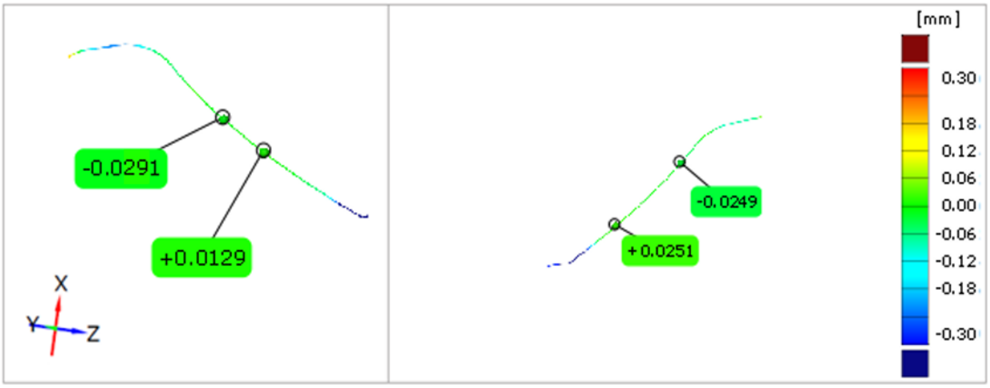


Figure 5. View of the scale of deviations of the actual model from the nominal model as an example of a non-contact measurement.



F_α = 0.042 [mm] = 42 [μm] F_α = 0.05 [mm] = 50 [μm]

Figure 6. View of the scale of deviations of the real model from the nominal model.

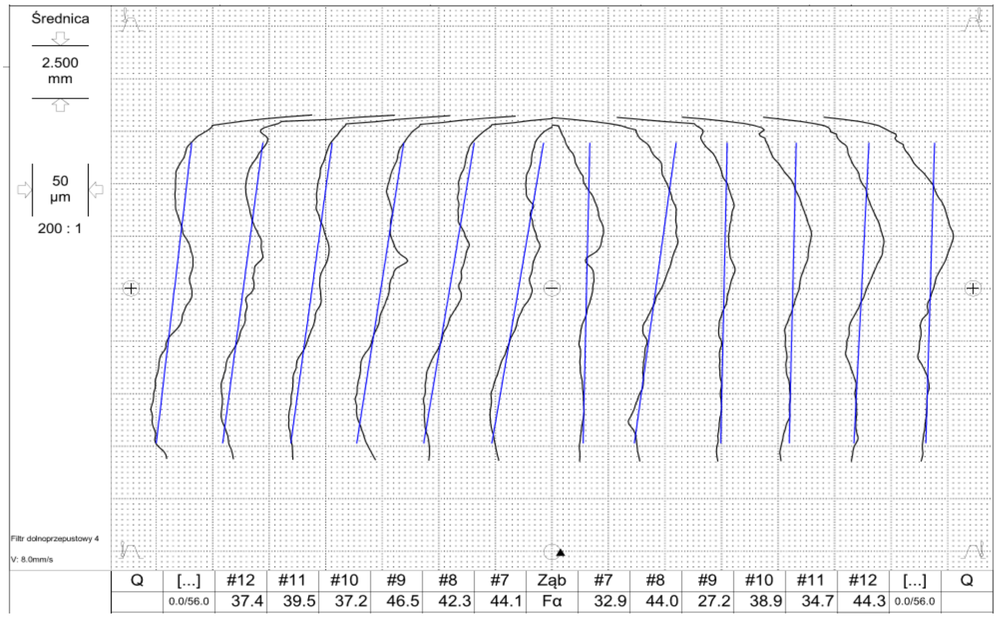


Figure 7. A view of a fragment of the protocol from contact measurements with the total profile deviation for selected teeth.

The following protocols contain the results of the total profile deviation for an example tooth of a factory-new gear wheel, rim 1, tooth 8, right and left flank.

The measurement results of the specialized four-axis Wenzel WGT 600 coordinate measuring machine and the GOM ATOS II optical scanner are presented in Tables 1–4. The exceedance of the total profile deviation is highlighted in red. Tables 5–12 present the results of calculations of standard deviation and measurement uncertainty based on five times the measurements of the right flank and the left flank for each tooth. Measurement uncertainties were calculated taking into account the maximum permissible error, which for the WEZNEL WGT 600 measuring machine is 1.8 μm and for the GOM ATOS II scanner is 15 μm.

Table 1. Measurement results of the total profile deviation Fα for gear wheel no. 1—rim 1.

	Wenzel WGT 600		GOM ATOS II	
Tooth Number	**Right Flank**	**Left Flank**	**Right Flank**	**Left Flank**
	μm	**μm**	**μm**	**μm**
1	34.0	68.1	30.0	60.5
2	93.4	42.7	85.6	40.3
3	23.3	39.5	20.3	44.5
4	28.9	39.7	28.1	35.6
5	37.8	37.0	35.6	38.5
6	31.2	38.5	30.2	39.5
7	44.1	32.9	41.3	31.4
8	42.3	44.0	50.0	42.0
9	46.5	27.2	45.6	23.4
10	37.2	38.9	39.2	35.6
11	39.5	24.7	41.3	23.5
12	37.4	44.3	36.7	42.3
13	42.8	49.9	40.3	46.4
14	40.3	31.4	40.1	27.9
15	38.6	37.2	39.1	35.6
16	27.9	36.2	29.1	33.5
17	27.1	44.8	30.5	40.7
18	23.2	38.2	20.3	42.6
19	30.9	36.5	29.1	39.7
20	26.0	40.1	28.6	42.8
21	25.9	46.9	24.1	47.6
22	19.7	40.1	25.5	42.8
23	22.3	56.6	24.3	57.8
24	32.6	39.2	30.5	38.1
25	12.6	95.5	20.4	100.4

Table 2. Measurement results of the total profile deviation Fα for gear wheel no. 1—rim 2.

	Wenzel WGT 600		GOM ATOS II	
Tooth Number	**Right Flank**	**Left Flank**	**Right Flank**	**Left Flank**
	μm	**μm**	**μm**	**μm**
1	29.9	41.0	28.7	42.5
2	28.6	36.8	25.7	35.6
3	50.8	42.4	48.0	40.0
4	51.8	41.1	54.6	39.8
5	35.1	40.0	36.7	42.6
6	38.7	31.3	39.5	31.6
7	30.3	20.2	27.9	23.5
8	43.0	5.3	42.3	18.6
9	54.1	7.0	52.1	21.5

Table 2. *Cont.*

	Wenzel WGT 600		GOM ATOS II	
Tooth Number	**Right Flank**	**Left Flank**	**Right Flank**	**Left Flank**
	µm	**µm**	**µm**	**µm**
10	35.9	11.8	36.5	19.9
11	29.1	12.5	28.4	20.5
12	39.7	11.3	38.1	23.6
13	41.6	7.8	43.5	22.6
14	43.0	11.0	43.8	20.3
15	29.1	12.6	30.3	24.3
16	22.6	15.1	24.5	21.4
17	26.1	23.9	25.1	23.7
18	36.8	28.2	35.2	28.1
19	36.2	23.7	35.4	23.9
20	29.8	21.9	27.3	22.6
21	23.7	27.2	21.5	28.5
22	24.9	26.8	25.7	24.7
23	42.7	32.0	41.5	30.2
24	34.7	30.2	33.6	28.8
25	30.8	31.4	30.1	28.9
26	19.8	24.5	23.5	22.4
27	36.4	23.1	40.1	20.1
28	43.3	25.1	45.3	23.5
29	40.6	40.6	42.6	38.0
30	32.9	35.8	33.9	37.9

Table 3. Measurement results of the total profile deviation $F\alpha$ for gear wheel no. 2—rim 1.

	Wenzel WGT 600		GOM ATOS II	
Tooth Number	**Right Flank**	**Left Flank**	**Right Flank**	**Left Flank**
	µm	**µm**	**µm**	**µm**
1	284.5	94.4	290.5	91.6
2	193.9	89.5	195.6	90.1
3	236.1	89.6	234.6	92.4
4	164.3	94.2	161.6	92.7
5	168.2	62.2	165.7	64.9
6	199.6	41.5	196.3	42.5
7	147.5	23.3	155.9	20.5
8	139.1	14.8	143.1	21.4
9	161.5	10.2	156.3	22.5
10	309.0	11.0	310.5	21.0
11	174.4	21.5	171.4	24.9
12	168.9	45.6	170.2	49.3
13	183.7	64.4	185.8	65.4

Table 3. *Cont.*

	Wenzel WGT 600		GOM ATOS II	
Tooth Number	Right Flank	Left Flank	Right Flank	Left Flank
	μm	μm	μm	μm
14	160.5	81.8	162.4	84.3
15	159.1	105.9	161.5	108.5
16	168.9	115.5	170.5	117.3
17	181.1	113.2	182.5	115.3
18	194.1	112.3	201.4	114.3
19	156.5	100.9	158.3	103.2
20	144.6	106.5	148.4	102.9
21	224.5	113.1	230.5	110.2
22	139.5	110.8	135.2	106.4
23	304.5	100.4	310.2	95.3
24	177.0	103.0	183.2	101.4
25	167.6	99.5	165.3	95.4

Table 4. Measurement results of the total profile deviation $F\alpha$ for gear wheel no. 2—rim 2.

	Wenzel WGT 600		GOM ATOS II	
Tooth Number	Right Flank	Left Flank	Right Flank	Left Flank
	μm	μm	μm	μm
1	23.0	31.2	25.6	30.5
2	87.4	65.8	89.1	62.6
3	9.1	171.8	20.2	175.9
4	132.8	143.7	135.8	142.8
5	78.0	61.5	81.3	63.9
6	24.3	46.1	23.6	46.9
7	27.7	42.3	25.2	41.8
8	26.9	41.3	24.9	43.9
9	17.9	45.0	18.1	47.9
10	21.2	45.4	20.2	40.9
11	38.7	60.2	39.9	61.0
12	106.3	78.3	110.0	79.1
13	16.1	73.1	21.5	75.9
14	71.4	67.5	65.9	65.4
15	11.4	56.0	23.4	55.3
16	80.7	67.6	84.3	67.3
17	38.7	83.2	39.1	85.4
18	44.6	80.1	47.5	85.3
19	41.6	54.1	43.7	52.3
20	56.5	45.9	57.0	44.2
21	65.7	42.7	69.4	45.6

Table 4. *Cont.*

	Wenzel WGT 600		GOM ATOS II	
Tooth Number	**Right Flank**	**Left Flank**	**Right Flank**	**Left Flank**
	µm	**µm**	**µm**	**µm**
22	69.9	32.9	70.1	35.1
23	37.4	26.8	34.6	24.2
24	49.4	29.1	51.3	26.9
25	65.2	33.1	63.5	30.6
26	16.6	64.4	21.5	60.2
27	17.6	49.1	20.4	52.6
28	53.7	40.0	54.6	41.2
29	31.2	49.4	30.3	45.3
30	24.8	40.5	25.6	39.1

Table 5. Calculation results of standard deviation and measurement uncertainty for gear no. 1—rim 1 (Wenzel WGT 600).

	Wenzel WGT 600			
Tooth Number	**Standard Deviation**	**Measurement Uncertainty**	**Standard Deviation**	**Measurement Uncertainty**
	Right Flank		**Left Flank**	
	µm		**µm**	
1	0.172	1.808	0.215	1.813
2	0.229	1.815	0.292	1.824
3	0.148	1.806	0.334	1.831
4	0.269	1.820	0.274	1.821
5	0.384	1.841	0.311	1.827
6	0.303	1.825	0.396	1.843
7	0.733	1.944	0.217	1.813
8	0.726	1.941	0.394	1.843
9	0.554	1.883	0.255	1.818
10	0.760	1.954	0.180	1.809
11	0.438	1.853	0.269	1.820
12	0.618	1.903	0.268	1.820
13	0.433	1.851	0.217	1.813
14	0.229	1.815	0.148	1.806
15	0.206	1.812	0.180	1.809
16	0.497	1.867	0.295	1.824
17	0.286	1.823	0.224	1.814
18	0.334	1.831	0.228	1.814
19	0.324	1.829	0.192	1.810
20	0.224	1.814	0.460	1.858
21	0.510	1.871	0.485	1.864

Table 5. *Cont.*

	Wenzel WGT 600			
Tooth Number	**Standard Deviation**	**Measurement Uncertainty**	**Standard Deviation**	**Measurement Uncertainty**
	Right Flank		**Left Flank**	
	µm		**µm**	
22	0.217	1.813	0.224	1.814
23	0.316	1.828	0.418	1.848
24	0.354	1.834	0.206	1.812
25	0.274	1.821	0.342	1.832

Table 6. Calculation results of standard deviation and measurement uncertainty for gear no. 1—rim 1 (GOM ATOS II).

	GOM ATOS II			
Tooth Number	**Standard Deviation**	**Measurement Uncertainty**	**Standard Deviation**	**Measurement Uncertainty**
	Right Flank		**Left Flank**	
	µm		**µm**	
1	0.279	15,003	0.349	15,004
2	0.274	15,003	0.296	15,003
3	0.229	15,002	0.303	15,003
4	0.224	15,002	0.286	15,003
5	0.148	15,001	0.332	15,004
6	0.228	15,002	0.192	15,001
7	0.311	15,003	0.286	15,003
8	0.269	15,002	0.286	15,003
9	0.286	15,003	0.255	15,002
10	0.485	15,008	0.303	15,003
11	0.444	15,007	0.217	15,002
12	0.324	15,003	0.316	15,003
13	0.228	15,002	0.255	15,002
14	0.447	15,007	0.255	15,002
15	0.606	15,012	0.250	15,002
16	0.384	15,005	0.324	15,003
17	0.356	15,004	0.303	15,003
18	0.572	15,011	0.334	15,004
19	0.238	15,002	0.363	15,004
20	0.442	15,007	0.339	15,004
21	0.433	15,006	0.259	15,002
22	0.296	15,003	0.311	15,003
23	0.669	15,015	0.268	15,002
24	0.296	15,003	0.334	15,004
25	0.303	15,003	0.522	15,009

Table 7. Calculation results of standard deviation and measurement uncertainty for gear no. 1—rim 2 (Wenzel WGT 600).

	Wenzel WGT 600			
Tooth Number	**Standard Deviation**	**Measurement Uncertainty**	**Standard Deviation**	**Measurement Uncertainty**
	Right Flank		**Left Flank**	
	µm		µm	
1	0.286	1.823	0.361	1.836
2	0.269	1.820	0.148	1.806
3	0.334	1.831	0.327	1.829
4	0.370	1.838	0.367	1.837
5	0.403	1.845	0.776	1.960
6	0.296	1.824	0.268	1.820
7	0.224	1.814	0.626	1.906
8	0.255	1.818	0.507	1.870
9	0.334	1.831	0.224	1.814
10	0.646	1.912	0.377	1.839
11	0.406	1.845	0.286	1.823
12	0.438	1.853	0.487	1.865
13	0.502	1.869	0.430	1.851
14	0.238	1.816	0.461	1.858
15	0.296	1.824	0.472	1.861
16	0.303	1.825	0.512	1.871
17	0.295	1.824	0.466	1.859
18	0.370	1.838	0.731	1.943
19	0.461	1.858	0.374	1.838
20	0.430	1.851	0.433	1.851
21	0.308	1.826	0.672	1.921
22	0.412	1.847	0.763	1.955
23	0.585	1.893	0.541	1.880
24	0.304	1.825	0.415	1.847
25	0.350	1.834	0.250	1.817
26	0.274	1.821	0.384	1.841
27	0.377	1.839	0.477	1.862
28	0.269	1.820	0.606	1.899
29	0.286	1.823	0.406	1.845
30	0.418	1.848	0.403	1.845

Table 8. Calculation results of standard deviation and measurement uncertainty for gear no. 1—rim 2 (GOM ATOS II).

	GOM ATOS II			
Tooth Number	**Standard Deviation**	**Measurement Uncertainty**	**Standard Deviation**	**Measurement Uncertainty**
	Right Flank		**Left Flank**	
	µm		**µm**	
1	0.492	15,008	0.487	15,008
2	0.295	15,003	0.180	15,001
3	0.334	15,004	0.320	15,003
4	0.303	15,003	0.250	15,002
5	0.456	15,007	0.377	15,005
6	0.705	15,017	0.482	15,008
7	0.377	15,005	0.370	15,005
8	0.296	15,003	0.238	15,002
9	0.461	15,007	0.596	15,012
10	1.135	15,043	0.384	15,005
11	0.364	15,004	0.660	15,015
12	0.406	15,005	0.442	15,007
13	0.206	15,001	0.356	15,004
14	0.335	15,004	0.540	15,010
15	0.224	15,002	0.746	15,019
16	0.370	15,005	0.356	15,004
17	0.507	15,009	0.512	15,009
18	0.464	15,007	0.224	15,002
19	0.415	15,006	0.438	15,006
20	0.296	15,003	0.334	15,004
21	0.517	15,009	0.238	15,002
22	0.572	15,011	0.430	15,006
23	0.238	15,002	0.471	15,007
24	0.543	15,010	0.349	15,004
25	0.536	15,010	0.238	15,002
26	0.521	15,009	0.450	15,007
27	0.426	15,006	0.482	15,008
28	0.455	15,007	0.524	15,009
29	0.723	15,017	0.485	15,008
30	0.396	15,005	0.296	15,003

Table 9. Calculation results of standard deviation and measurement uncertainty for gear no. 2—rim 1 (Wenzel WGT 600).

	Wenzel WGT 600			
Tooth Number	**Standard Deviation**	**Measurement Uncertainty**	**Standard Deviation**	**Measurement Uncertainty**
	Right Flank		**Left Flank**	
	μm		**μm**	
1	0.319	1.828	0.527	1.876
2	0.187	1.810	0.192	1.810
3	0.367	1.837	0.192	1.810
4	0.311	1.827	0.432	1.851
5	0.354	1.834	0.311	1.827
6	0.217	1.813	0.192	1.810
7	0.286	1.823	0.259	1.819
8	0.304	1.825	0.286	1.823
9	0.320	1.828	0.269	1.820
10	0.415	1.847	0.427	1.850
11	0.250	1.817	0.274	1.821
12	0.364	1.836	0.577	1.890
13	0.304	1.825	0.303	1.825
14	0.482	1.863	0.394	1.843
15	0.487	1.865	0.269	1.820
16	0.334	1.831	0.335	1.831
17	0.383	1.840	0.432	1.851
18	0.311	1.827	0.350	1.834
19	0.415	1.847	0.311	1.827
20	0.292	1.824	0.472	1.861
21	0.415	1.847	0.249	1.817
22	0.148	1.806	0.402	1.844
23	0.255	1.818	0.229	1.815
24	0.418	1.848	0.324	1.829
25	0.238	1.816	0.286	1.823

Table 10. Calculation results of standard deviation and measurement uncertainty for gear no. 2—rim 1 (GOM ATOS II).

	GOM ATOS II			
Tooth Number	**Standard Deviation**	**Measurement Uncertainty**	**Standard Deviation**	**Measurement Uncertainty**
	Right Flank		**Left Flank**	
	μm		**μm**	
1	0.512	15,009	0.354	15,004
2	0.192	15,001	0.817	15,022
3	0.229	15,002	0.229	15,002
4	0.205	15,001	0.286	15,003

Table 10. *Cont.*

	GOM ATOS II			
Tooth Number	**Standard Deviation**	**Measurement Uncertainty**	**Standard Deviation**	**Measurement Uncertainty**
	Right Flank		**Left Flank**	
	µm		**µm**	
5	0.192	15,001	0.334	15,004
6	0.238	15,002	0.217	15,002
7	0.367	15,004	0.255	15,002
8	0.296	15,003	0.255	15,002
9	0.383	15,005	0.286	15,003
10	0.224	15,002	0.461	15,007
11	0.148	15,001	0.224	15,002
12	0.274	15,003	0.224	15,002
13	0.192	15,001	0.320	15,003
14	0.238	15,002	0.316	15,003
15	0.192	15,001	0.192	15,001
16	0.212	15,001	0.500	15,008
17	0.458	15,007	0.361	15,004
18	0.238	15,002	0.415	15,006
19	0.304	15,003	0.320	15,003
20	0.192	15,001	0.229	15,002
21	0.268	15,002	0.406	15,005
22	0.192	15,001	0.217	15,002
23	0.269	15,002	0.383	15,005
24	0.259	15,002	0.311	15,003
25	0.228	15,002	0.356	15,004

Table 11. Calculation results of standard deviation and measurement uncertainty for gear no. 2—rim 2 (Wenzel WGT 600).

	Wenzel WGT 600			
Tooth Number	**Standard Deviation**	**Measurement Uncertainty**	**Standard Deviation**	**Measurement Uncertainty**
	Right Flank		**Left Flank**	
	µm		**µm**	
1	0.331	1.830	0.432	1.851
2	0.350	1.834	0.497	1.867
3	0.269	1.820	0.286	1.823
4	0.269	1.820	0.192	1.810
5	0.274	1.821	0.150	1.806
6	0.650	1.914	0.229	1.815
7	0.296	1.824	0.477	1.862

Table 11. *Cont.*

	Wenzel WGT 600			
Tooth Number	Standard Deviation	Measurement Uncertainty	Standard Deviation	Measurement Uncertainty
	Right Flank		Left Flank	
	μm		μm	
8	0.320	1.828	0.250	1.817
9	0.316	1.828	0.354	1.834
10	0.148	1.806	0.694	1.929
11	0.374	1.838	0.187	1.810
12	0.384	1.841	0.532	1.877
13	0.304	1.825	0.383	1.840
14	0.460	1.858	0.158	1.807
15	0.311	1.827	0.464	1.859
16	0.217	1.813	0.286	1.823
17	0.238	1.816	0.460	1.858
18	0.286	1.823	0.311	1.827
19	0.524	1.875	0.927	2.025
20	0.286	1.823	0.287	1.823
21	0.229	1.815	0.383	1.840
22	0.492	1.866	0.328	1.830
23	0.797	1.969	0.334	1.831
24	0.497	1.867	0.415	1.847
25	0.826	1.980	0.374	1.838
26	0.364	1.836	1.011	2.064
27	0.536	1.878	0.304	1.825
28	0.652	1.914	0.295	1.824
29	0.432	1.851	0.259	1.819
30	0.507	1.870	0.303	1.825

Table 12. Calculation results of standard deviation and measurement uncertainty for gear no. 2—rim 2 (GOM ATOS II).

	GOM ATOS II			
Tooth Number	Standard Deviation	Measurement Uncertainty	Standard Deviation	Measurement Uncertainty
	Right Flank		Left Flank	
	μm		μm	
1	0.329	15,004	0.637	15,014
2	0.374	15,005	0.909	15,028
3	0.286	15,003	0.634	15,013
4	0.604	15,012	0.665	15,015
5	0.295	15,003	0.743	15,018

Table 12. *Cont.*

	GOM ATOS II			
Tooth Number	**Standard Deviation**	**Measurement Uncertainty**	**Standard Deviation**	**Measurement Uncertainty**
	Right Flank		**Left Flank**	
	µm		**µm**	
6	0.292	15,003	0.589	15,012
7	0.259	15,002	0.667	15,015
8	0.396	15,005	0.671	15,015
9	0.356	15,004	0.812	15,022
10	0.455	15,007	0.536	15,010
11	0.229	15,002	0.776	15,020
12	0.485	15,008	0.765	15,019
13	0.320	15,003	1.108	15,041
14	0.374	15,005	0.745	15,018
15	0.381	15,005	0.723	15,017
16	0.572	15,011	0.652	15,014
17	1.608	15,086	0.778	15,020
18	0.966	15,031	0.676	15,015
19	0.795	15,021	0.630	15,013
20	0.394	15,005	1.125	15,042
21	0.987	15,032	0.997	15,033
22	0.522	15,009	0.640	15,014
23	1.003	15,033	0.461	15,007
24	0.432	15,006	0.841	15,024
25	0.622	15,013	0.512	15,009
26	0.549	15,010	0.522	15,009
27	0.515	15,009	0.634	15,013
28	0.903	15,027	0.364	15,004
29	0.354	15,004	0.374	15,005
30	0.911	15,028	0.320	15,003

4. Discussion

Based on the results presented in Tables 1–12, it can be stated that the use of the optical method for gears made in the 10th accuracy class according to the DIN 3961/62 standard gives results comparable to the contact method. The optical scanner for teeth no. 1, 23 and 30 of gear no. 1—rim 1 indicated that the permissible total deviation of the profile was exceeded. This indication was confirmed by measurements carried out on the Wenzel WGT 600 measuring machine, where the obtained values also indicate that the permissible deviation was exceeded. The remaining results for both rims of gear no. 1 are within the permissible tolerance limits, which was observed for both non-contact and contact measurement results.

Based on the analysis of the measurement results using an optical scanner for both rims of gear wheel no. 2, it was found that the permissible tolerances were significantly exceeded, which results from the wear of the tooth profiles as a result of operation. Exceedance of the permissible deviations was also observed in comparative measurements performed using the contact method.

The obtained tooth profile deviation map provides much more 3D spatial information about the tooth profile dimensional deviation compared to contact measurements in one plane.

5. Conclusions

As a result of comparative studies using the non-contact measurement method for basic parameters of gear wheels using an optical scanner, it can be stated that the proposed method can be an alternative to classic contact measurement methods for accuracy classes of gear wheel manufacturing, which are within the range of the scanner's measurement accuracy. It should be noted, however, that the non-contact measurement method is burdened with measurement uncertainty that is several times greater than the contact measurement method. Optical measurement is a measurement that not only provides much more information about the measured object, but also allows for a quick assessment of the wear and tear of gear wheels. Colored deviation maps created on the basis of measurements enable quick control of the correctness of the workmanship of details. The presented solutions included in the automatic control of gear wheels can be used to segregate the controlled gear wheels or to select gear wheels for measurement using other methods in the event that the permissible deviations of selected parameters are exceeded.

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