Metrol. Meas. Syst., Vol. 33 (2026), No. 1
DOI: 10.24425/mms.2026.158371

METROLOGY AND MEASUREMENT SYSTEMS
Index 330930, ISSN 0860-8229
www.metrology.wat.edu.pl

OPTICAL MEASUREMENTS OF GEOMETRICAL ACCURACY OF GEARS

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Abstract

The article presents the results of comparative tests of gear wheels based on non-contact and contact measurement methods. Comparative tests were performed on selected cylindrical gear wheels with straight teeth, which are spare parts for transmission mechanisms. The paper compares important geometric parameters of gear wheels, such as: total deviation of the tooth line, single and total pitch deviation and radial run-out deviation of the teeth. An optical measurement method was applied using general tools available in the GOM ATOS II coordinate scanner software. The measurement results obtained using the non-contact method were compared with the results of the contact method using a specialized machine for measuring gear wheels Wenzel WGT 600. Based on the conducted analyses, the comparability of the measurement results of gear wheels performed in accuracy class 10 according to the DIN 3961/62 standard was demonstrated for the considered measurement methods, while at the same time indicating significant differences in the geometric parameters obtained between the parts manufactured under the manufacturer's license and commercial substitutes.

Keywords: 3D Vision, gear metrology, 3D scanner, measuring machine, geometric accuracy.

1. Introduction

The precision of gear wheel manufacturing in the manufacturing industry is mainly based on the assessment of their geometric parameters. When designing mechanical gears, the period of time during which the working gear should meet the requirements to a greater or equal degree than assumed is estimated. In the practice of servicing technological machines, repairs are commonly performed using spare parts. In situations where original spare parts are not available from the machine manufacturer, the solution is to use spare parts available in the offers of other manufacturers. In many situations, *e.g.* liquidation of the manufacturing plant, commercial spare parts may be the only alternative for further operation of economically efficient machines. It is important when using them to verify the quality of workmanship by performing appropriate measurements. In the quality control of gear wheels, in addition to strength tests, the geometry of the toothing is of great importance [1]. Geometric precision directly affects dynamic deviations, which cause a lack of smooth operation during the operation of gear wheels [2].

Classical contact methods of measuring the course of tooth shape in metrological laboratories were performed in claw holders using a dial gauge with a specified accuracy or based on involute meters, *e.g.* Carl-Zeiss Jena VG 450. The actual registration of the tooth line shape was performed by moving the wheel, thus maintaining the parallelism of the movement. This allowed for determining the measured parameters and quality control. Similarly, the measurement of the deviations of the radial run-out of the teeth in relation to the axis of rotation

Article history: received October 1, 2025; revised December 2, 2025; accepted February 2, 2026; available online March 13, 2026.

of the wheel was performed. The difference between the largest and smallest deviation of a specially selected measuring element, *e.g.* a shaft of a specified diameter inserted into the groove, was indicated by a dial gauge.

The development of industry resulted in replacing classical measurement methods with automated coordinate measurements [3]. The contact measurement method essentially consists in measuring the coordinates of points, which are subject to computer analysis to determine the values of deviations of individual parameters. Industrial quality control uses specialist machines for measuring gear deviation parameters, such as Klingelnberg PNC 35, Wenzel WGT 600 or coordinate measuring machines with specially developed modules, such as GearPro involute by ZEISS. Currently, a number of works are being carried out on the development and improvement of non-contact gear measurements based on optical technologies and sensors [4]. Coordinate measuring machines such as Leitz Infinity are being built, which have the ability to use both contact and optical heads, for example using a chromatic confocal sensor. Thanks to the possibility of combining data from both heads, the application area of such a machine is significantly expanded.

Apart from coordinate measuring machines, at present there is even more thought about scanning geometry and assessing parameters based on the obtained digital data, than about measuring specific deviations. The development of 3D optical metrology systems has revolutionized the control of gear wheels, providing very precise measurements and enabling the assessment of complex geometries [5, 6]. The advantage of various optical techniques is the ability to collect a large number of measurement points in a short time, and thus a multi-million point cloud representing the measured object can be obtained [7, 8]. Advanced scanning techniques enable the acquisition of detailed surface data. Geometric scanning therefore provides comprehensive data on the geometry of gear elements, which is crucial for predicting application properties such as noise behavior, wear and fatigue. This information helps to identify and correct deviations at an early stage of the manufacturing process, both for cylindrical and bevel gears [9].

Macro-scale scanning of gear surfaces includes various advanced techniques that provide precise measurements and quality control. Among these techniques, optical scanning is increasingly used. Optical scanning methods provide fast data acquisition, significantly reducing the time required for gear inspection. They allow for the evaluation of the entire gear geometry, including complex surfaces, which is not possible in the case of traditional random spot inspections [10]. They are widely used due to their high efficiency and ability to collect relatively detailed geometric data [11]. They consist in collecting point clouds from measured surfaces and matching them to design models in order to reconstruct real surfaces or calculate geometric parameters [12]. In this way, they provide a comprehensive 3D measurement of gears, recording the entire geometry, not specific points [13], although it is also well suited for the analysis of surface defects in specific locations [14].

Optical scanning can be performed using different versions of lighting: structured light [15] or laser [16]. Modern scanning techniques, such as laser triangulation, offer high-resolution measurements with minimal deviations, enabling precise detection of surface defects and ensuring the appropriate quality of gear production. Holistically viewed, non-contact measurement methods also provide a fast and relatively accurate assessment of gear wear, without the need to dismantle it. Optical scanning is also used to create digital models of physical objects, as an invaluable support in reverse engineering and quality assurance [17]. It is also used more broadly, to reconstruct three-dimensional models of gear surfaces, through comprehensive registration of wear and damage morphology, where it can be supported by various observation techniques [18], including machine vision [19] and image analysis systems [20]. By providing data on gear wear, geometric scanning supports predictive maintenance strategies, which helps to plan maintenance activities before destructive wear occurs, thus extending the service life of gear components. Advanced scanning systems use automated path planning techniques, optimizing the measurement process and reducing the need for manual intervention [21]. Scanning systems (both optical and contact) can also be integrated with CNC machines, enabling on-machine measurements and real-time corrections during the production process [22]. Such integration improves the overall production efficiency and reduces the probability of errors [23].

Developing the topic of optical gear measurement techniques, in [24] a non-contact method for measuring the radial run-out of the gear tooth profile was proposed, using a single laser displacement sensor. In [25], the authors established a mathematical model of the angle of incidence in order to explain the effect of the angle of incidence of the measuring light, which is verified by simulation analysis. In [26], a method for measuring the tooth shape was proposed, which uses incoherent structured light and allows for measurement accuracy in the range of ±2.2 μm. The presented works clearly indicate the development of optical methods in gear metrology. In measurement applications in the area of geometrical metrology, computed tomography is also increasingly used [27], although the material and the possibility of its X-raying at relatively low power, allowing for high resolution [28], play an important role here. However, it can be stated that optical methods have been accepted by industrial reality and are particularly useful in the case of complex geometries and reverse engineering tasks. However, the challenges, especially related to measurement uncertainty, make it necessary to verify them in relation to the results obtained with a much slower but more accurate, contact coordinate measuring technique on coordinate measuring machines [29]. This is particularly visible in the more accurate classes, for the less accurate ones, the comparisons show satisfactory agreement.

Information techniques are also playing an increasingly important role in the discussed measurements of geometrical quantities, with particular emphasis on augmented reality [30] and artificial intelligence [31].

Taking into account the above analysis, this paper presents measurements of the parameters of the gear teeth of a mechanical transmission, which were carried out for toothed objects manufactured under the manufacturer's license and commercially available substitutes. The comparative measurements carried out for selected parameters of gear wheels using the contact method using the Wenzel WGT 600 specialized machine and the non-contact method using the GOM ATOS II coordinate scanner constitute the next stage of research on the possibilities of using optics in gear wheel metrology. After carrying out comparative studies of the tooth profile deviation parameter using optics [32], measurements of subsequent standardized parameters of tooth geometry deviations related to the tooth line, tooth pitches and radial run-out were undertaken. The measurements carried out using an optical 3D scanner yielded comparable measurement results to the contact method in the range of measured tolerances for a gear wheel manufactured in the 10-th accuracy class.

2. Material and measurement method

Figure 1 shows a model of a double-rimmed gear wheel selected for measurements. The gear wheel is made of chrome-nickel steel for carburizing 15 HGN. The type of gear wheel selected for measurements is a part of a gearbox with a module of 4, which allows for optical measurement of the teeth using structured light. The gear wheel consists of two rims, which create 25 teeth, respectively - rim 1 and 30 teeth - rim 2. In the comparative studies, apart from the methods used, possible differences in the quality of the gear wheel production were also taken into account by obtaining elements for measurement from different manufacturers, whose sales offers for the selected gear wheels - spare parts significantly differed. Gear No. 1 is a part manufactured under the license of the gearbox manufacturer. Gear No. 2 is a commercial replacement.

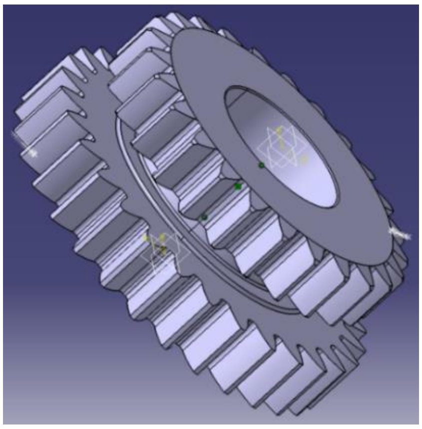

Fig. 1 3D model of a gear wheel made in Catia.

The measurement laboratories ensured standardized measurement conditions in accordance with PN-EN ISO/IEC 17025:2018 – 02. The automated specialized machine WENZEL WGT 600 (MPEp = 1,8+L/400 for classical coordinate measurements) was selected to carry out contact measurements. During the measurement, the measuring tip collects the coordinates of points from the tested surface as a result of direct contact with this surface (Fig. 2). Then, this information is processed by computer, as a result of which we obtain the values of deviations of tooth parameters such as: deviations of the tooth profile and line, deviations of pitches and run-out. In the measurement protocols, the obtained deviation values are presented numerically and on graphs for all measured teeth.

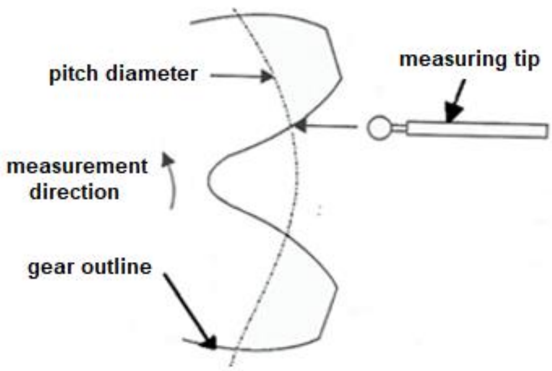

Fig. 2 Contact method of measuring a gear wheel on a specialized machine.

Non-contact measurements of gears involve the assessment of the geometry and quality of the teeth without the need for physical contact with the measured element. They are used to shorten the measurement time and avoid the influence of mechanical forces on the final results. Current technologies enable the use of non-contact methods such as: laser scanning [33], computed tomography [34], industrial photogrammetry [35]. The GOM ATOS II coordinate optical scanner („GOM Acceptance Test" according to VDI/VDE 2634 Part 3, The manufacturer's declared accuracy is less than 0.02 mm) selected for measurements uses structured light emitted by a projector that falls on the object. The projected structure falling on the surface of the object is deformed. Cameras observe the deformation of the image on the measured surface and on this basis, the coordinates of points on the surface of the element are determined, which are combined into a 3D image of the measured element (Fig. 3) [36].

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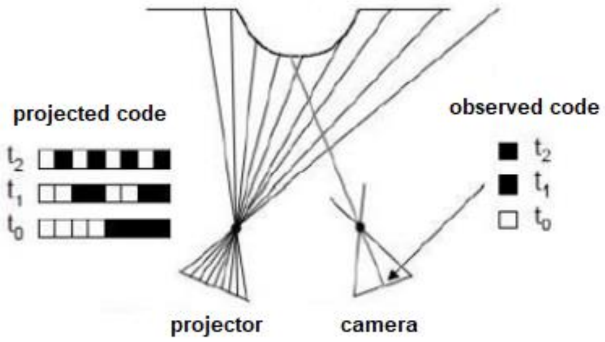

Fig. 3 Non-contact measurement method using a structured light scanner [36].

For the selected measurement methods, measurement uncertainties were estimated according to formula (1), which takes into account U_C the combined measurement uncertainty of both U the standard deviation of the data multiplied by the coverage factor (expanded uncertainty formula (2)) and U_m the machine accuracy (systematic component of combined uncertainty formula (3)) and which can be expressed as the root of the sum of the squares of these two components [37].

$$U_C = \sqrt{U^2 + {U_m}^2}, \tag{1}$$

$$U = k \cdot \sqrt{\frac{1}{(N-1)} \sum_{i=1}^{N} (x_i - \bar{x})^2}, \tag{2}$$

where: $u = \sqrt{\frac{1}{(N-1)} \sum_{i=1}^{N} (x_i - \bar{x})^2}$ is the standard uncertainty resulting from the data dispersion, that is the standard deviation of the data from the distribution of measured values, x_i – single measurement value, $\bar{x}$ – arithmetic mean of all measurements, N – number of all measurements, $\sum_{i=1}^{N}$ – sum of all measurements from 1 to N measurements, k – coverage factor. U_m - is the uncertainty, resulting from the accuracy of the machine or measuring instrument

$$U_m = \frac{a}{\sqrt{3}}, \tag{3}$$

where: a – error value specified by the manufacturer based on the specifications of the measuring device.

3. Measurement of geometric parameters of gears using optics

The basic parameters of the straight-toothed cylindrical gear are shown in Fig. 4.

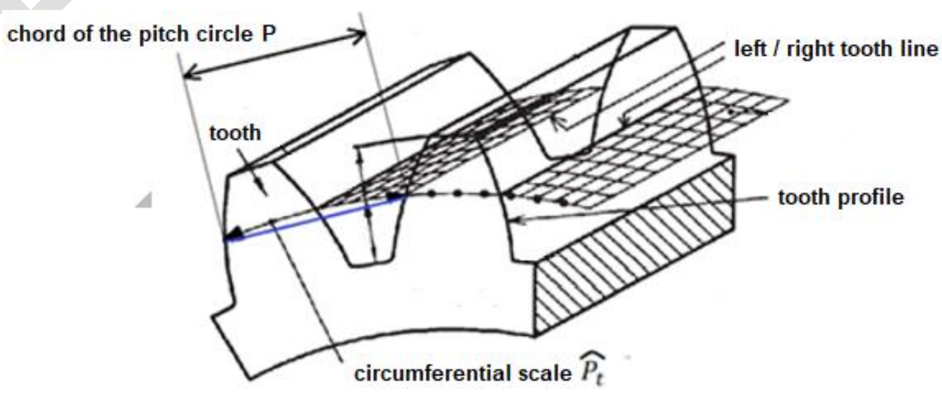

Fig. 4 Interpretation of gear wheel parameters [38].

The developed algorithm for the evaluation of geometrical parameters of a gear is presented in the block diagram (Fig. 5)

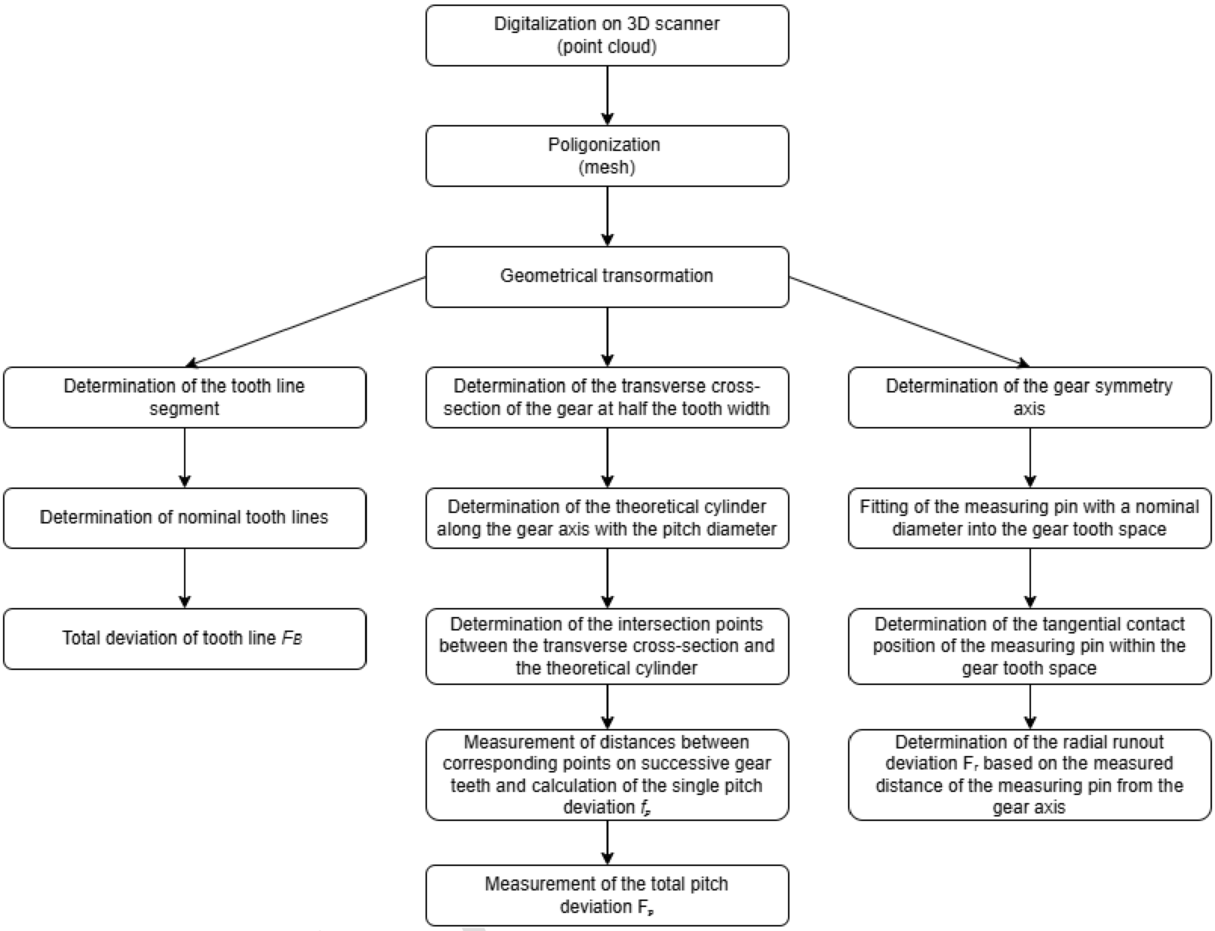

Fig. 5 Block diagram of the procedure for determining gear parameters from 3D scanning.

3.1. Total deviation of the tooth line F_β

The total tooth line deviation F_β is interpreted as the distance between two nominal tooth lines that tangentially encompass the tooth flank within its evaluation range (Fig. 6).

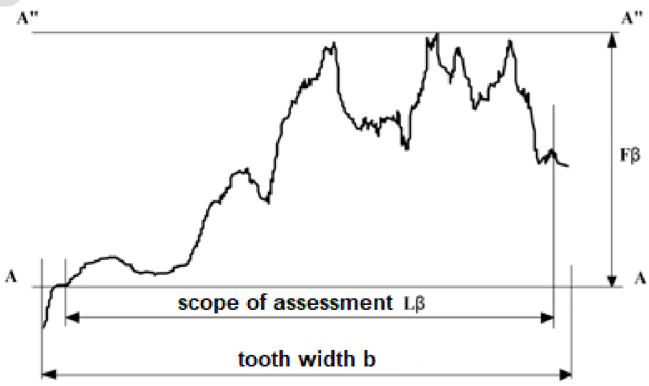

Fig. 6 Graphic interpretation of the total deviation of the F_β line [20] AA, A"A" – nominal tooth lines surrounding the real side, F_β - deviation of the tooth line position, L_β – range of the tooth line assessment, b – width of the toothing.

Figure 7 shows a view of the gear wheel measurement analysis in the Inspekt GOM program.

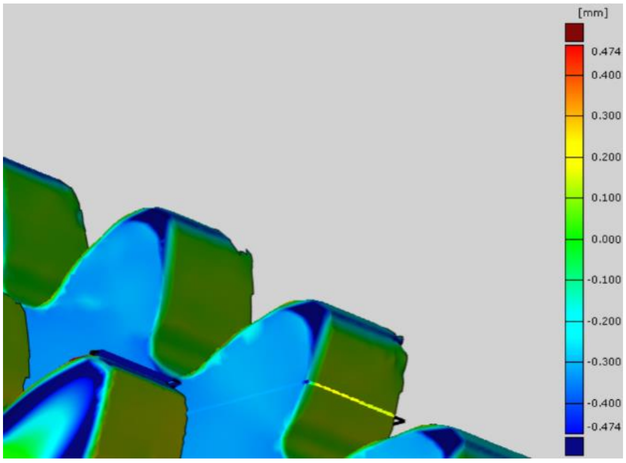

Fig. 7 View of the F_β tooth line in the Inspekt GOM program.

In order to determine the total deviation of the tooth line F_β. An image of the object (gear wheel) was analyzed, in which the tooth line intended for measurement was isolated and the measuring section of the actual line was determined, which is taken into account when assessing the parameters (Fig. 8). Then, a nominal line was determined in the plane of the isolated tooth line to obtain auxiliary data for calculating the total result, which is the value (F_β).

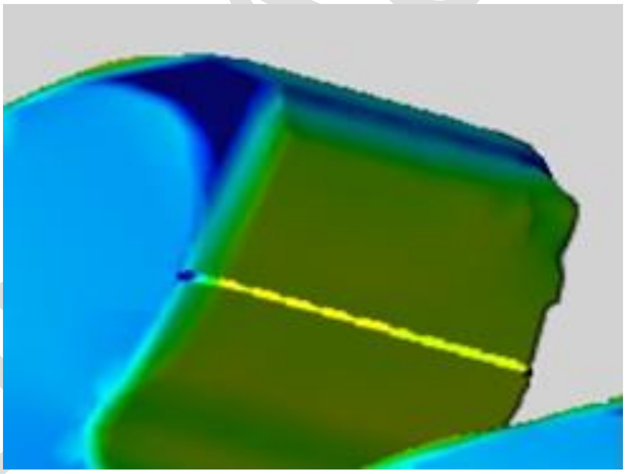

Fig. 8 Real model tooth line for measurements.

3.2. *Deviations of the circumferential pitch*

The circumferential pitch is the distance between teeth measured on the pitch circle diameter. The basic pitch parameters are the single pitch deviation f_p and the total pitch F_p. In order to determine the single pitch deviations, measurement points were determined on the tooth profile. For this purpose, local cross-sections of the profiles were determined at the middle of the tooth width and a coaxial cylinder with the pitch diameter of the gear wheel. Additional geometric elements created points at the intersection of their edges with the measured gear wheel, the appropriate distances of which were measured (Fig. 9).

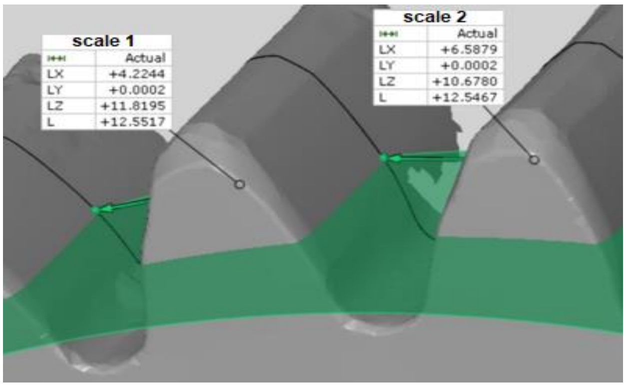

Fig. 9 Measurement of the chord of the pitch circle of a gear – GOM Inspect.

The measured values of P (the chord of the pitch circle) after insertion into formula (4) allow obtaining the measurement result of the circumferential pitch P_t (the length of the arc defined by the chord) between successive teeth (Fig. 10). The single pitch f_p was determined by subtracting the nominal pitch value P_n from the measured value of the circumferential pitch P_t, according to formula (5):

$$P_t = \frac{4 \cdot \pi \cdot r \cdot \arcsin(\frac{P}{2r})}{360}, \tag{4}$$

$$f_p = P_t - P_n. \tag{5}$$

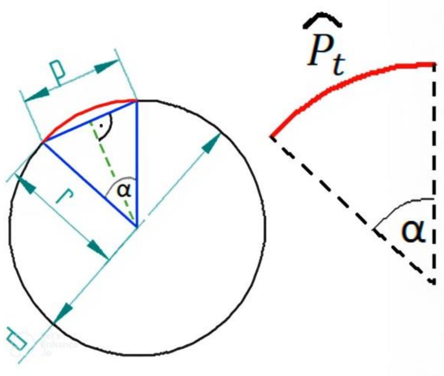

Fig. 10 Graphical interpretation of dependencies.

From the obtained values of deviations of subsequent pitches we can generate a graph of single and total pitch deviations (Fig. 11), from which it is possible to read the total pitch value expressed in µm by adding the maximum absolute values obtained from summing the single pitch deviations.

3.3. Radial run-out deviation F_r

The measurement of the tooth run-out consists of programmatically inserting a cylinder of a specified diameter into the notch between the teeth, tangent to the sides of the tooth. Then we measure the distances from the axis of the inserted cylinder to the designated wheel axis (Fig. 12). The difference between the values of the largest and smallest distances gives the total deviation of the radial run-out F_r.

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Fig. 11 Total pitch deviation graph.

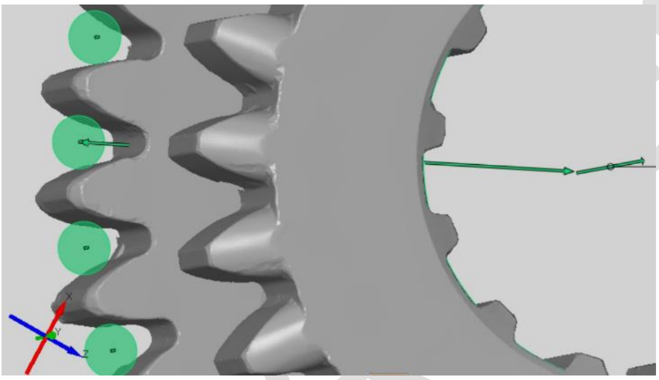

Fig. 12 Distance measurement to determine radial run-out.

4. Measurement results and comparative analysis

The measurements were carried out on double gears wheel made in the 10th accuracy class according to the DIN 3961/62 standard.

Tables 1-12 present the measurement results of the F_β parameter - the total tooth line, developed by the non-contact measurement method and, for comparison purposes, by the contact method. In accordance with the industrial practice used in quality control departments, the assessment was carried out for 3 teeth, which are evenly distributed over the entire gear wheel. Permissible total deviation of the tooth line $F_{\beta MAX}$ = 45 µm.

Tables 13 and 14 compare the measurement results of the parameters f_p - single pitch and F_p - total pitch using the developed non-contact measurement method and, for comparison purposes, using the contact method. The results for the single pitch are presented taking into account the maximum values for a given wheel and a given rim (for example 1/1 - wheel 1, rim 1). Permissible deviations of the single pitch f_{pmax}= 40 µm and total F_{pmax}= 125 µm.

Table 1. Measurement results of the total tooth line deviation F_β for gear wheel no. 1 – ring 1.

	Wenzel WGT 600		**GOM ATOS II**	
Tooth number	**Right side**	**Left side**	**Right side**	**Left side**
	µm		µm	
1	20,4	7,3	25,1	18,9
8	9,8	9,3	19,3	19,9
16	11,8	7,8	17,3	12,4

Table 2. Calculation results of the standard deviation and measurement uncertainty of the total tooth line deviation F_β for gear wheel no. 1 – ring 1 (Wenzel WGT 600).

	Wenzel WGT 600			
Tooth number	u	U_C	u	U_C
	Right side		Left side	
	μm		μm	
1	0,117	1,804	0,215	1,813
8	0,158	1,807	0,192	1,810
16	0,112	1,803	0,238	1,816

Table 3. Calculation results of the standard deviation and measurement uncertainty of the total tooth line deviation F_β for gear wheel no. 1 – rim 1 (GOM ATOS II).

	GOM ATOS II			
Tooth number	u	U_C	u	U_C
	Right side		Left side	
	μm		μm	
1	0,256	15,002	0,206	15,001
8	0,206	15,001	0,286	15,003
16	0,383	15,005	0,421	15,006

Table 4. Measurement results of the total tooth line deviation F_β for gear wheel no. 1 – rim 2.

	Wenzel WGT 600		**GOM ATOS II**	
Tooth number	**Right side**	**Left side**	**Right side**	**Left side**
	μm		μm	
1	36,5	22,9	41,2	22,1
10	35.1	2,9	36,5	17,4
20	13,3	24,4	22,7	33,9

Table 5. Calculation results of the standard deviation and measurement uncertainty of the total tooth line deviation F_β for gear wheel no. 1 – rim 2 (Wenzel WGT 600).

	Wenzel WGT 600			
Tooth number	u	U_C	u	U_C
	Right side		Left side	
	μm		μm	
1	0,219	1,813	0,483	1,864
10	0,296	1,824	0,332	1,830
20	0,316	1,828	0,24	1,816

Table 6. Calculation results of the standard deviation and measurement uncertainty of the total tooth line deviation F_β for gear wheel no. 1 – rim 2 (GOM ATOS II).

	GOM ATOS II			
Tooth number	u	U_C	u	U_C
	Right side		Left side	
	μm		μm	
1	0,376	15,005	0,372	15,005
10	0,229	15,002	0,229	15,002
20	0,374	15,005	0,259	15,002

DOI: 10.24425/mms.2026.158371

Table 7. Measurement results of the total tooth line deviation F_β for gear wheel no. 2 – ring 1

	Wenzel WGT 600		**GOM ATOS II**	
Tooth number	**Right side**	**Left side**	**Right side**	**Left side**
	µm		µm	
1	67,5	91,9	70,6	90,3
8	148,0	2,7	161,2	18,9
16	97,3	4,4	109,2	18,6

Table 8. Calculation results of the standard deviation and measurement uncertainty of the total tooth line deviation F_β for gear wheel no. 2 – rim 1 (Wenzel WGT 600).

	Wenzel WGT 600			
Tooth number	$\boldsymbol{u}$	$\boldsymbol{U_C}$	$\boldsymbol{u}$	$\boldsymbol{U_C}$
	Right side		Left side	
	µm		µm	
1	0,293	1,824	0,297	1,824
8	0,217	1,813	0,224	1,814
16	0,349	1,834	0,35	1,834

Table 9. Calculation results of the standard deviation and measurement uncertainty of the total tooth line deviation F_β for gear wheel no. 2 – rim 1 (GOM ATOS II).

	GOM ATOS II			
Tooth number	$\boldsymbol{u}$	$\boldsymbol{U_C}$	$\boldsymbol{u}$	$\boldsymbol{U_C}$
	Right side		Left side	
	µm		µm	
1	0,232	15,002	0,185	15,001
8	0,32	15,003	0,274	15,003
16	0,394	15,005	0,634	15,013

Table 10. Measurement results of the total tooth line deviation F_β for gear wheel no. 2 – rim 2.

	Wenzel WGT 600		**GOM ATOS II**	
Tooth number	**Right side**	**Left side**	**Right side**	**Left side**
	µm		µm	
1	53,0	103,8	56,4	108,3
10	118,1	72,4	102,1	79,4
20	7,0	174,0	18,1	184,3

Table 11. Calculation results of the standard deviation and measurement uncertainty of the total tooth line deviation F_β for gear wheel no. 2 – rim 2 (Wenzel WGT 600).

	Wenzel WGT 600			
Tooth number	$\boldsymbol{u}$	$\boldsymbol{U_C}$	$\boldsymbol{u}$	$\boldsymbol{U_C}$
	Right side		Left side	
	µm		µm	
1	0,232	1,815	0,206	1,812
10	0,364	1,836	0,377	1,839
20	0,367	1,837	0,238	1,816

Table 12. Calculation results of the standard deviation and measurement uncertainty of the total deviation of the tooth line F_β for gear wheel no. 2 – rim 2 (GOM ATOS II).

	GOM ATOS II			
Tooth number	u	U_C	u	U_C
	Right side		Left side	
	µm		µm	
1	0,358	15,004	0,344	15,004
10	0,292	15,003	0,438	15,006
20	0,295	15,003	0,332	15,004

Table 13. Measurement results of single pitch deviation f_p.

	Wenzel WGT 600		**GOM ATOS II**	
Wheel number/Rim number	**Right side**	**Left side**	**Right side**	**Left side**
	µm		µm	
1/1	74,2	44,9	82,4	51,4
1/2	29,2	28,9	28,9	23,8
2/1	101.5	84,6	113,6	75,6
2/2	45,4	47,9	41,3	44,1

Table 14. Measurement results of the total pitch deviation F_p.

	Wenzel WGT 600		**GOM ATOS II**	
Wheel number/Rim number	**Right side**	**Left side**	**Right side**	**Left side**
	µm		µm	
1/1	96,2	188,6	101,6	198,6
1/2	171.1	166.8	127,7	193,3
2/1	667,5	612,2	590,5	740,6
2/2	344,3	356,0	370,2	302,5

Table 15 presents the measurement results of the parameter F_r – radial run-out deviations, developed by the non-contact measurement method and for comparison purposes, by the contact method. The permissible radial run-out deviation of the teeth F_{rmax}= 90 µm.

Table 15. Measurement results of the tooth run-out deviation F_r.

Wheel number/Rim number	**Wenzel WGT 600**	**GOM ATOS II**
	µm	µm
1/1	192,3	181,4
1/2	147,2	113,7
2/1	636,8	657,2
2/2	319,8	302,4

While analysing the results of comparative tests of significant parameters of gear wheels related to the tooth line, tooth pitches and radial run-out of the teeth, it is noted that the results of measurements of the tooth line and single pitch are comparable for the adopted methods: non-contact using the GOM ATOS II scanner and contact using the Wenzel WGT 600 machine.

The differences in the result values of individual deviations are related to the accuracy of the adopted measurement methods.

The results of detailed measurements of the total tooth line for gear wheel 1 – manufactured under the manufacturer's license – did not show exceeding the permissible value of deviations of the measured teeth. Compliance was detected using both the contact and non-contact methods. For gear wheel 2 – which is a commercial replacement – there are significantly more inconsistencies, as shown in Tables 7 and 10. A similar analogy can be concluded by comparing the results of the single pitch deviations, total pitch deviations and radial run-out. For the total pitch deviation parameter F_p, the result of which is influenced by the measurement of individual tooth pitches, the measurement results contain the sum of errors made when measuring a single pitch. For gear wheel no. 1, the single pitch deviation was exceeded for individual teeth, which also caused the total pitch deviation to be exceeded. Errors of this type usually occur on teeth that are input or output for the machining tool. On the other hand, the deviation values for gear wheel no. 2 significantly different from the permissible tolerances may indicate that the gear wheel finishing was abandoned – tables 13 – 15. The calculated standard deviation and measurement uncertainty are acceptable for the 10th class of gear wheel manufacturing accuracy – tables 2, 3, 5, 6, 8, 9, 11 and 12.

5. Summary

The application of an optical 3D scanner in comparative investigations enabled the acquisition of significantly more detailed information about the examined gears compared to the traditional measurement method performed with a contact gear measuring machine. The use of optical technology made it possible not only to obtain a more comprehensive representation of the tooth surface geometry, but most importantly to considerably reduce the measurement time, even by several times in relation to the contact method.

Exporting the results in the form of deviation maps, with color-coded dimensional discrepancies, allowed for a rapid visual assessment of the manufacturing quality of the tested components. Such a graphical representation of differences between the nominal and actual models provides an effective inspection tool within the production process and facilitates the identification of areas requiring machining corrections.

To evaluate the applicability of the optical method, an algorithm for the geometrical assessment of gears was developed in a manner analogous to the methodology used for determining gear parameters on a contact gear measuring machine. By comparing the results obtained from both instruments, the adequacy of the optical method for evaluating the geometrical accuracy of gears was assessed. Based on the obtained measurements of the fundamental geometrical deviations (such as total tooth line deviation, single pitch deviation, total cumulative pitch deviation, and radial runout deviation), the following observations were made:

- Gears manufactured under the original producer's license have higher dimensional accuracy and meet the requirements of **accuracy class 10** according to **DIN 3961/62**.
- Commercial replacement gears show a higher number of exceeded tolerance parameters, indicating lower machining precision.

In particular, the commercial replacement gear exceeded the permissible limits for class 10 in terms of:

- total tooth line deviation,
- single and total pitch deviations, and
- radial runout deviation.

The observed deviations resulted primarily from inaccuracies in the machining process, such as improper tool alignment, cutter wear, fixturing errors, or insufficient temperature control during cutting. Such deviations can lead to deteriorated transmission performance manifested by increased noise, vibrations, and accelerated wear of mating components. Therefore, the use of low-quality replacement gears in mechanical transmissions may result in the recurrence of failures after a short operating period, thereby reducing the reliability of the entire drive system.

The conducted analyses showed that the calculated measurement uncertainties remain within acceptable limits for the applied measurement methods, confirming the reliability of the results obtained using the optical scanner. The high repeatability and accuracy of the optical technique indicate that this measurement approach can be effectively applied to the evaluation of gears with higher accuracy classes (*i.e.*, better than class 10 according to DIN 3961/62), particularly when using modern scanners equipped with high-precision scanning heads.

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Metrol. Meas. Syst., Vol. 33 (2026), No. 1
DOI: 10.24425/mms.2026.158371

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