THE ANALYSIS OF THE GEAR'S GEOMETRY MEASUREMENT WITH VARIOUS MEASURING SYSTEMS

Analiza pomiaru geometrii koła zębatego różnymi systemami pomiarowymi

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Abstract: The paper presents a comparison between contact and optical measuring systems, which can be implemented to measure the shape and dimensional accuracy. The comparison included the MarSurf XC20 contact system, the iNEXIVE optical microscope and the MCA II measuring arm with the MMDx100 laser head as well as the ATOS II Triple Scane structured light scanner. The measurements were conducted on a part of a gear rim. The assessment of the measuring accuracy in relation to the nominal model was performed in the GOM Inspect software. The parametric model of the gear created in the NX software was adopted as the nominal model. According to the obtained reports, it results that the MarSurf XC20 is the most accurate 2D measuring system whereas the ATOS II Triple Scane is the most accurate 3D measuring system.
Keywords: measuring systems, optical scanners, reverse engineering, gear

Streszczenie: W artykule przedstawiono porównanie pomiarowych systemów; stykowych oraz optycznych, możliwych do wykorzystania przy weryfikacji dokładności wymiarowo-kształtowej. Porównanie obejmowało system stykowy MarSurf XC20, mikroskop optyczny iNEXIVE , ramię pomiarowe MCA II z głowicą laserową MMDx100 oraz skaner światła strukturalnego ATOS II Triple Scane. Pomiary przeprowadzono na fragmencie wieńca koła zębatego. Ocenę dokładności pomiaru w odniesieniu do modelu nominalnego przeprowadzono w programie GOM Inspect. Za model nominalny przyjęto model parametryczny koła zębatego stworzonego w systemie NX. Według otrzymanych raportów wynika, że najbardziej dokładnym systemem pomiarowym 2D jest MarSurf XC20, a systemem pomiarowym 3D ATOS II Triple Scane.
Słowa kluczowe: systemy pomiarowe, skanery optyczne, inżynieria odwrotna, koło zębate

Introduction

Modeling of the elements and machine parts is traditionally carried out with the use of computer aided design systems (CAD), which are presently commonly implemented in the design of industrial products. It all begins with the idea of the designer who then models the part in a virtual environment. The concept is made possible with the use of the techniques, available on the market. Many a time during the design and manufacturing process, there is no full technical, construction or material documentation for a given product. Thanks to the increasing development of coordinate measuring techniques, data processing software [27] as well as modern manufacturing methods, the solution to this problem has become available with the reverse engineering (RE) [12]. The process allows for the reconstruction of a part's geometry in aviation [13], architectural [10] and medical [8] industries. The aim of reverse engineering is to transform the existing model into its digital counterpart, which constitutes the basis of the further work of the designers. The finished digital model can be produced using modern manufacturing techniques [6]. The most common methods include additive [3, 5, 14, 20] and subtractive [20] manufacturing. When creating a gear's model, we may implement one of the two paths (Fig. 1). In the case of the CAD path, the designing of a gear's geometry process is made possible by the tools specially designed for the task. At the design stage, the knowledge of the basic gear's parameters is crucial [25]. In the case of the second path, the gear's geometry is recreated based on the real model measurements.

The selection of the part's recreation path depends on the complexity of the model geometry. CAD modeling of a part from the start is based on the measuring data. The first method is aimed at more experienced and knowledgeable users. The result of the recreation methods is an approximate 3D solid model. Based on the knowledge of how the part works, the part can be designed as a nominal model. At the modeling stage, any signs of wear or technological imperfections that could arise during machining can be removed. A possibility to implement changes in the design of the existing part in order to improve the operation of the device or machine is an important advantage. Based on the 3D model, the documentation can be created as well as the manufacturing of the real part can be programmed. The second method, which is RE, is based on the geometric

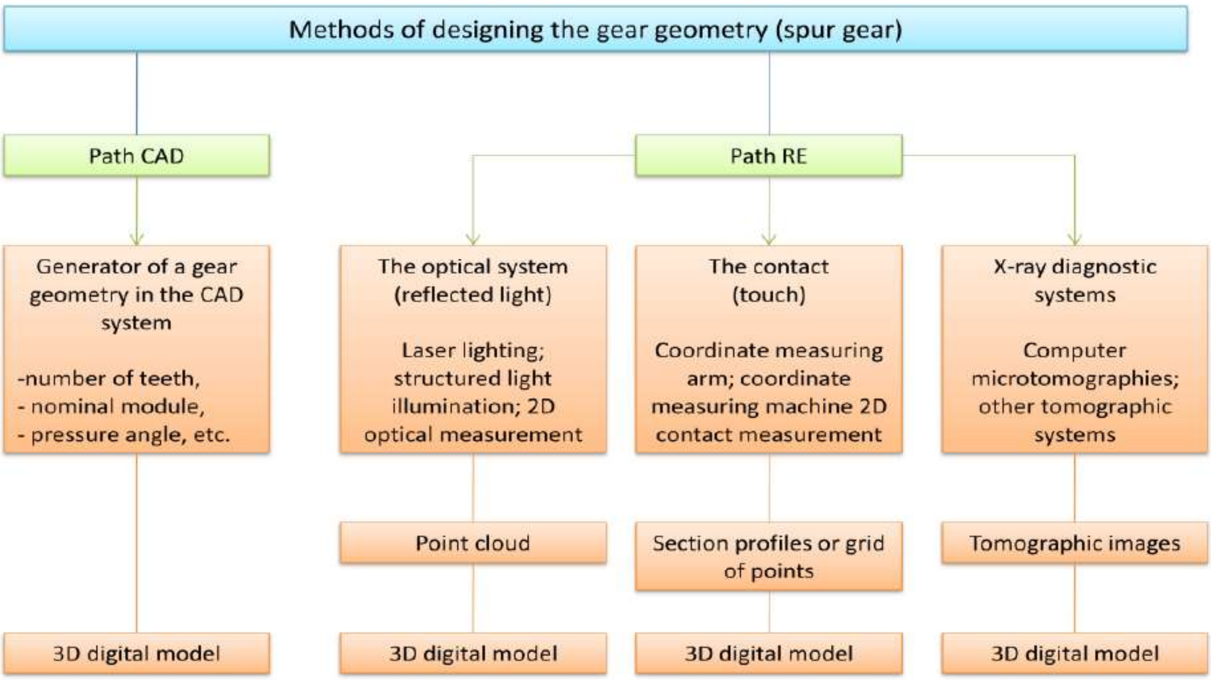


Fig. 1. Gear geometry design methods

outline of the part approximation, and then creating a surface between the generated curves. The advantages of this method include the high model accuracy as well as the short time needed to create the model. Among the disadvantages, one can include the common difficulty of creating the surface based on the measured results. Assuming that the real part has any signs of wear, they are unfortunately reproduced in the digital part. Thus, for parts that show signs of wear, the first method of CAD modeling from the start is used. The repair of worn parts is of great importance in the aviation industry in order to prolong the life cycle of aircraft elements [4, 15, 28, 31].

The increase in the manufacturing accuracy of gear's geometry needs to meet the development of modern industrial solutions. The shape and dimensional verification is conducted mainly with the use of contact coordinate measuring systems [7]. Nowadays, increasing development in optical systems based on the reflected light, as well as tomographic systems are observed. 3D optical scanning systems are commonly used and compared with each other [2, 16, 21]. Contactless techniques are increasingly used due to their advantages. With optical systems, it is possible to conduct measurements without interrupting the manufacturing process and the measuring process is performed during machining at the same station. Measurements on the CMM measuring machine require stopping the machining process [26]. Guerra [18] worked on measuring techniques suitable for the verification and repair of parts. In his work, he compared optical systems. The comparative analysis was performed for four laser scanners: linear scanner LLS, structured light scanner SLS, photogrammetric scanning system with rotational table PSSRT and laser scanning arm LSA. Both concave and convex surfaces were analyzed. The scanned surface had a high reflection coefficient in order to identify weaknesses in optical systems. Guo [19] performed 3D measurements of the shape of a gear tooth surface with a system based on a light sensor with a linear structure with a rotational table. The gear profile errors in relation to the contact system were analyzed. He found, that the optical system was fast and accurate. Peters et al. analyzed the measurement of gears using a linear light sensor with the 2000 structure [24]. Leopold et al. and Chen et al. designed measuring devices based on the laser triangulation system [9, 22].

There are however no descriptions of the conducted experiments pertaining to a comparative analysis of the gear measuring accuracy with various contact and optical systems in the literature. The following experiments may help with the selection of such an optical measuring system, which would result in the lower measuring errors during verification of a gear geometry model. Each of the optical systems is described by parameters, such as camera resolution, depth of field or errors resulting from external sources, such as ambient light [23, 33] or surface roughness and colours [11] having an impact on the results.

Experimental results

The primary aim of the experimental tests was to compare different measuring systems used in the industry. For this purpose measuring systems with various characteristics were selected: 2D and 3D measurements, contact and optical, manual and automatic measurements.

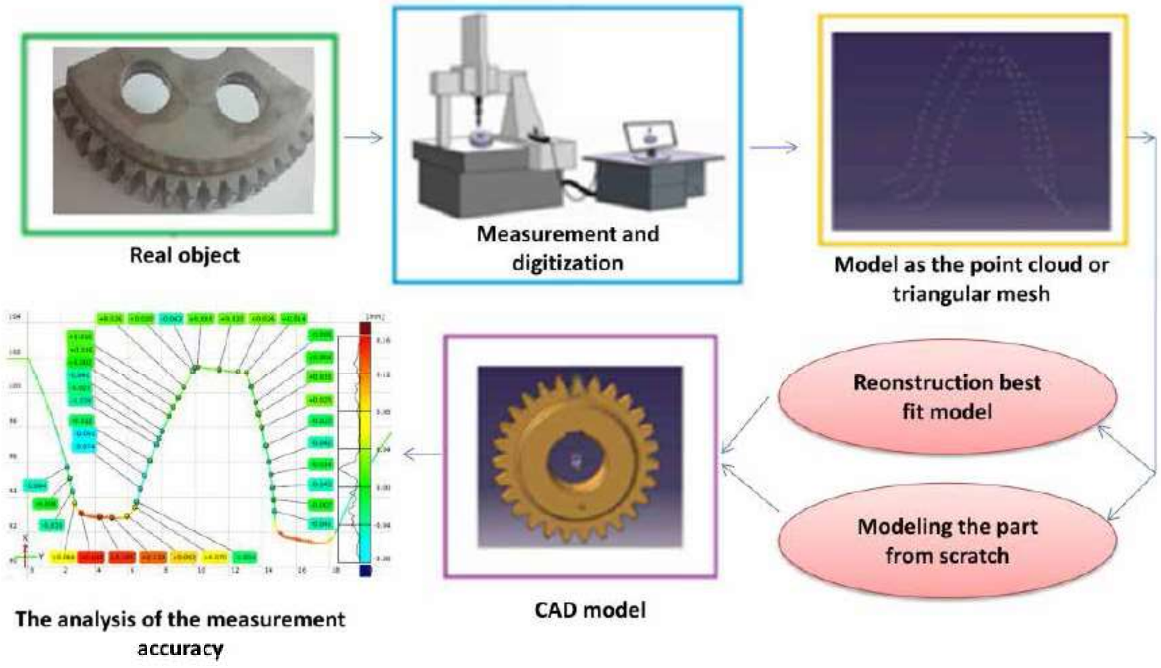


Fig. 2. Experimental tests' plan

The comparison between the systems was conducted based on the measurement of the gear part presented in Figure 2. The basic parameters of the gear are included in Table 1.

The experimental test methodology (Fig. 2) included a series of measurements of the test model using four systems of coordinate metrology and spatial reconstruction. The reconstruction was based on a point cloud in the software dedicated to the measurement system. The numerically created, based on the solid measurement were compared with the reference model in GOM Inspect software with the use of the Best fit method. As a reference, the parametric CAD model of the gear was adopted. The CAD model of the gear was created in NX 12.0 software based on the known mathematical dependencies presented in Table 1.

Table 1. Gear parameters

Lp.	Parameter	
1	Normal module	m = 4
2	Number of teeth	z = 49
3	Pressure angle	α = 20°
4	Helix angle	β = 0°
5	Material	17CrNi6-6,

The measurements were conducted at a constant ambient temperature of 20°C. For the purpose of comparing the measurement systems, the constant value of the measurement resolution was adopted. The measured surface was covered with a thin, uniform, white layer of anti-reflective coating.

Characteristics of measuring systems

The gear geometry was measured with the use of various measurement systems, such as: the iNEXIVE optical coordinate measuring system by NIKON, the MarSurf XC20 contact system, the MCA II measuring arm with the MMDx100 laser head, the Atos II Triple Scan – structural light – Fig. 3.

The iNEXIVE optical system by NIKON (Fig. 4a) is equipped with a camera recording the outline of the element in the single measuring plane. The measurement with this method consists of determining the point cloud based on the vectors perpendicular to the measuring object's outline.

The MarSurf XC20 conturograph is a machine that allows for registering points as the measuring contact tip moves along the surface of the part. The conturograph determines single cross-sections in a given plane. The measuring tip moves at a constant speed and the displacements of the element are converted into an electrical signal. MarSurf XC20 is a technologically advanced device for the analysis of curvilinear contours. The result of the measurement is a point cloud in the x-y system – Fig. 4b.

The measuring arms MCA II (Fig. 4c) are portable devices, thanks to the appropriate design and

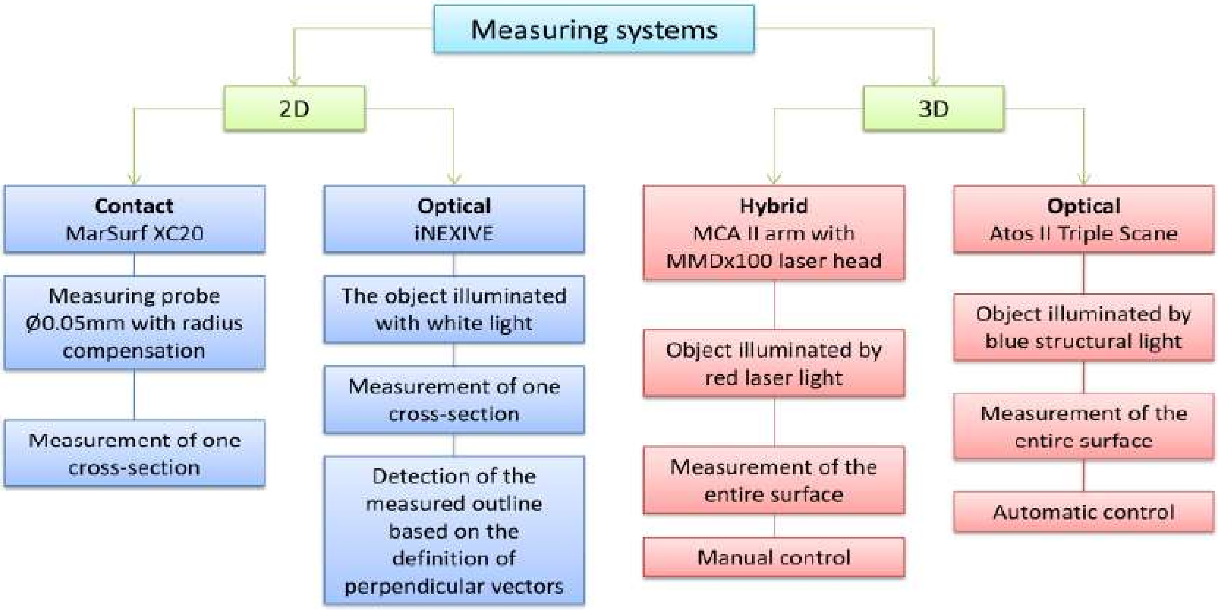
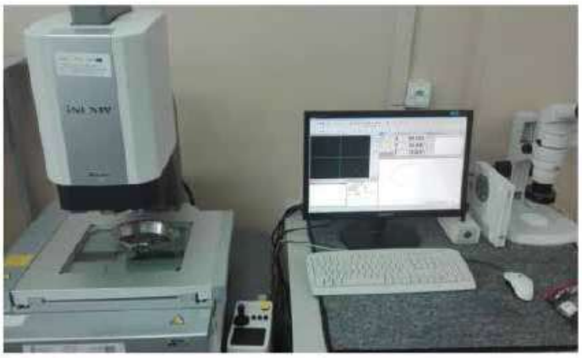


Fig. 3. Features of the compared measurement systems

a)



b)

c)

d)

Fig. 4. The measuring stations: a) NIKON iNEXIVE optical coordinate system, b) MarSurf XC20 contact system, c) MCA II measuring arm with the MMDx100 laser head, d) Atos II Triple Scan –structured light

measurement procedure allow for work in the immediate vicinity of the element. They are used in automotive and aviation industries, and even in workshops that repair parts [27]. Systems such as measuring arm can be equipped with laser triangulation head, which enables to measure elements that are not possible to be measured with the contact methods, i.e. soft materials. The measuring arm belongs to the hybrid systems family of products. By hybrid products, one assumes measurement using the contact method as well as the optical one. For contact measurement, a head ending with a steel or sapphire ball is used, whereas in the case of optical measurement, i.e. laser heads are adopted [29]. The MMDx100 system obtains the data from the measured geometry as a result of illuminating the object with red laser light. Laser triangulation is considered to be one of the best techniques of 3D object measurement. The technique is based on the knowledge of the geometrical dependencies between the laser beam and the coordinates of the image recorded in the detector [30]. The width of the laser beams is 100 mm, the measurement error is 10 μm and the number of scanned points on one line is 1000 at a scanning frequency of 33-150 Hz. The permissible errors of the MCA II measuring arm equipped with the laser head MDD × 100 system estimated at the confidence level of 95% are ±0,03 mm [17]. The result of the measurement is a spatial cloud of points.

The ATOS II Triple Scan Blue Light system by GOM (Fig. 4d) enables to measure the model geometry by illuminating it with a blue light and analyzing the deflection of the light lines in a series of fringe images projected on the object. The deflection of the fringes is recorded by cameras and then processed by algorithms into measuring data in the form of a set of x, y, z coordinate points that represent the measured surface. The adoption of the blue light allows for measurement regardless of the intensity of daylight or artificial (white) light. This enables to include the measurement system into a production cycle without the necessity of creating special measuring conditions. The application of blue light in the scanning process also allows for a significant reduction in the measurement time, i.e. thanks to reducing the influence of the environment on the scanning process [11, 23, 33].

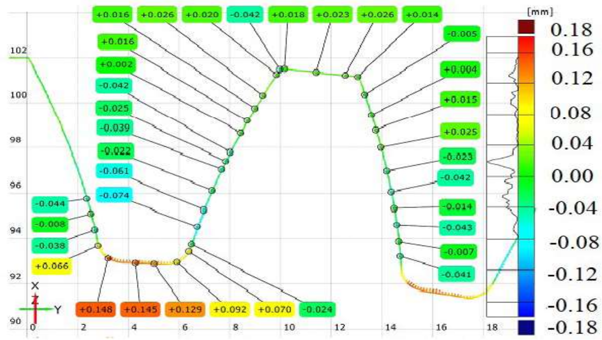
Regardless of the measurement system, the data analysis process was the same. It consisted of collecting the data in the form of point cloud coordinates. Further processing consisted of removing the areas that significantly differed from most of the results, filtering by removing noise and reducing artifacts. When data optimization was completed, the coordinate system was determined. The point cloud was triangulated and as a result, the surface mesh model was obtained.

The accuracy of the measurement systems has been tested according to dedicated standards, i.e. coordinate measuring arm is tested in relation to the ASME B89.4.22 standard [1], whereas the Atos II Triple Scan is tested according to the VDI/VDE 2634 standard [32].

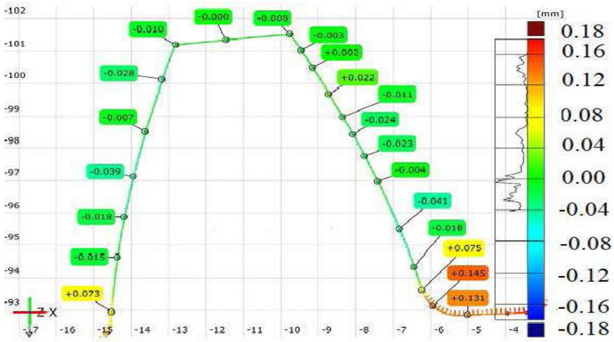
Test results and discussion

The obtained measurement results allow a comparison between the measurement systems on the basis of a gear measurement to be presented. The analysis of the accuracy of geometrical dimensions of the gear was conducted with the use of the GOM Inspect V7.5 software [17]. The results of the measurement are presented in a detailed deviations map in selected profiles of the gear rim cross-sections in the plane normal to its axis. The analyzes were conducted by comparing the nominal gear CAD model with the selected point clouds obtained as a result of measurements with selected measurement systems (Fig. 5, 6).

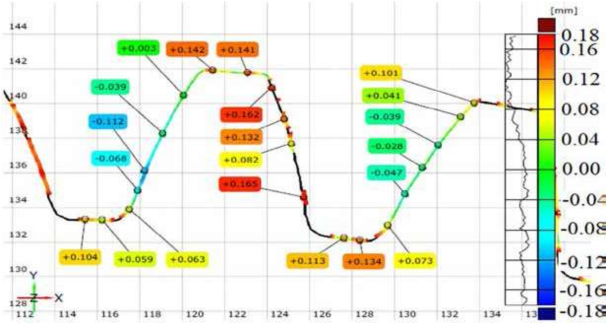
a) iNEXIVE optical system



b) MarSurf XC20 contact system



c) MCA II measuring arm with the MMDx100 laser head



d) Atos II Triple Scane optical system

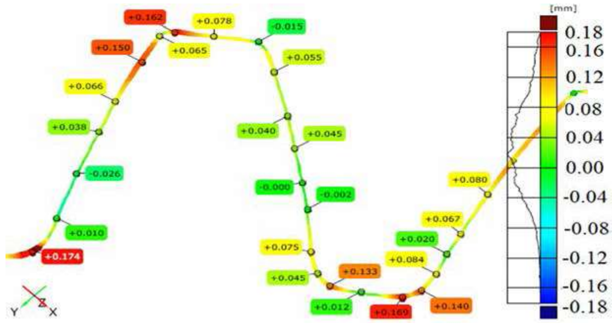


Fig. 5. The comparative analysis of measuring systems: a) iNEXIVE optical microscope, b) conturograph MarSurf XC20, c) MCA II measuring arm with the MMDx100 laser head, d) Atos II Triple Scan

Table 2. Measured deviations of the gear

Measuring Systems	Maximum/Minimum deviations		Average deviation	Standard deviation
iNEXIVE	+0,148 mm	-0,074 mm	0,026 mm	0,0698 mm
MarSurf XC20	+0,145 mm	-0,041 mm	-0,012mm	0,0472 mm
MCA II MMDx100	+0,178 mm	-0,121 mm	-0,061mm	0,1113 mm
Atos II Triple Scane	+0,174 mm	-0,084 mm	-0,054 mm	0,0915 mm

Based on the deviation maps, negative values of deviation were observed on the side of gear teeth, which can indicate wear of the tested part. Positive values of deviations were observed at the root of the tooth, which can result from the CAD model of the reference element – Fig. 5, Table 2.

The presented analysis of the gear geometry accuracy obtained by comparing the model acquired from the measurement with the NIKON iNEXIVE optical system with the reference model proved, that the deviations are in the range of +0.148 mm to -0,074 mm and the standard deviation is equal to 0.0698 mm – Fig. 5a.

The shape errors resulting from the comparison of the model obtained from the measurement with the MarSurf XC20 contact system with the reference model are in the range of +0,145 mm to -0,041 mm, whereas the standard deviation is equal to 0,0472 mm – Fig. 5b.

The map containing the shape errors obtained from the comparison between the model acquired from the MCA II optical system with the MMDx100 laser head with the reference model shows that the errors are in the range of +0,178 mm to -0,121 mm, with the standard deviation of 0,1113 mm. Based on the analysis, it was observed that in the case of the measurement with the measuring arm – laser head system, the system is not suitable for the measurement of the elements such as gears, because it does not register continuous surfaces, which leads to an incomplete model of the analyzed geometry (Fig. 5c). The incomplete point cloud proved fit to the reference model with the best fit method difficult.

The comparison between the model obtained with the Atos II Triple Scane system and the reference model is presented using the deviation map – Fig. 5d. Shape errors are in the range of +0,174 mm to -0,084 mm, whereas the standard deviation is equal to0,0915 mm.

The analysis of the deviation values obtained with various measurement systems (Fig. 6) proved that the lowest deviations were registered with the MarSurf XC20, which indicates that the contact system the most accurately reproduced the measured surface profile. The highest deviation values were obtained during the measurement with the MCA II MMDx100 system, which results from the point cloud with discontinuities and overscans. Among the three optical systems, one may distinguish the iNEXIVE optical microscope as well as the Atos II Triple Scane. The iNEXIVE measures only in one measuring plane using the white light, and the Atos II Triple Scane constitutes the blue light system that measures 3D surfaces

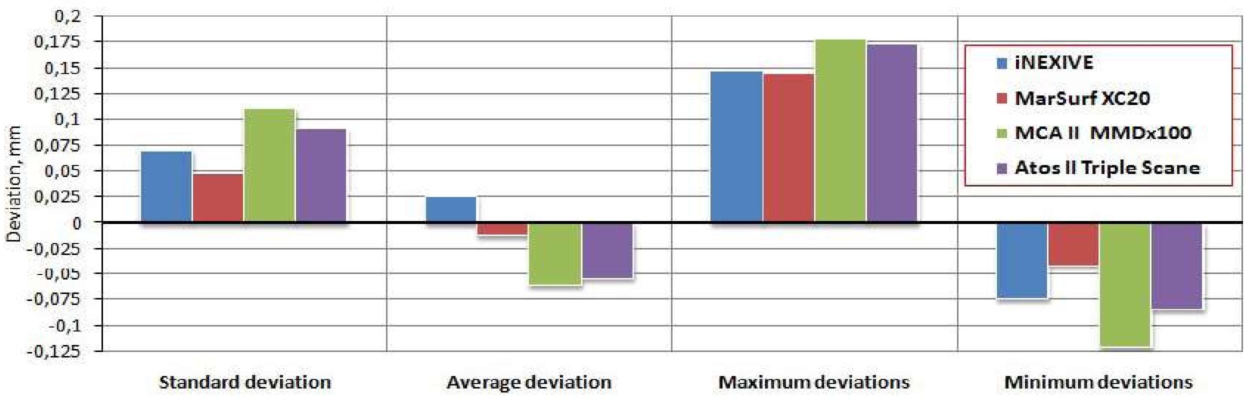


Fig. 6. The comparison between the deviations obtained from the gear measurement with various systems

Conclusions

Based on the conducted in four measurement systems experimental tests, different characteristics of the mapping deviations distribution were observed. The measurement with the MarSurf XC20 contact system proved to be the most accurate. The standard deviation and the mean deviation are the lowest. The NIKON iNEXIVE optical microscope and the MarSurf XC20 with a contact measuring probe are 2D measuring systems, which do not require the application of an anti-reflective layer. The measurement with the NIKON iNEXIVE allows for the measurement of the complete shape by changing the position of the measuring head as well as is equipped with a continuous image sharpness adjustment by changing the object illumination. In the case of the MarSurf XC20 system with a contact tip, the measurement is difficult due to the limited range of movement of the measuring probe as well as the shape of the measuring tip. In the case of the optical systems: the MCA II arm with the MMDx100 laser head and the Atos II Triple Scane, a lack of surface continuity was observed, leading to an incomplete model of the analyzed geometry, which results from the re-selectivity of the measured surface and from the difficulty for a light beam to reach all the surfaces. In the case of measurements with the MCA II arm with the MMDx100 laser head, the recorded point cloud was tainted with noise and artifacts. The measurement with the Atos II Triple Scane system using structured light is suitable for the measurement of the complex surface, because in the case of the gear measurement the resulting point cloud was uniform and continuous. The histograms for individual measurement systems have different forms. For the MarSurf XC20 contact system, the histogram is bimodal, and for the Atos II Triple Scane the histogram is in the symmetrical form.

Among the analyzed measurement systems, the most preferred optical system for 2D solids shape measurement is the NIKON iNEXIVE microscope, whereas for 3D shapes the Atos II Triple Scane system using structured light.

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