

MEASUREMENT SYSTEM FOR ASSESMENT OF MOTOR CYLINDER TOLERANCES AND ROUNDNESS

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Abstract

The paper describes the concept of a novel measurement system designed for quick and inexpensive measurement of tolerances and assessment of roundness, especially suitable for the motor industry. The structure of measurement system and its algorithm of measurement data analysis are described in detail. The system underwent tests with the setting (master) rings of known tolerances and out-of-roundness. The results were compared with those obtained from the reference device PIK-2. The tested system exhibited a very good accuracy and proved to be a good measurement tool. It was implemented in the industrial enterprise.

Keywords: precision, measurement, accuracy, roundness, automation.

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1. Introduction

The measurement of shape errors in the motor industry is a very important issue [1]. The measurement and evaluation of cylindricity errors are essential to ensure proper assembly and good performance [2]. Application of a sophisticated measurement technique, e.g. the modelling with genetic algorithms [4], is considered the crucial requirement in production of industrial elements such as the cylinders [3]. Since cylinders and pistons are the main working internal components of combustion engines, the measurement of their details must be fast and accurate.

Various methods are applied to the out-of-roundness assessment [5], among others the three-point methods [6, 7] and the multi-sensor method for the cylindricity [8]. The V-block measurement of cylindricity and roundness proved to be accurate and useful [9]. It can be used as a two-point, three-point or n-point method, while the most popular type is the three-point method where a V-block provides two supporting points and a measuring sensor collects data in the third point [10]. Its principle was successfully applied in the three-point measurement system based on the air gauges [11], where the measurement data from three independent gauges were collected and then recalculated in order to obtain the results as if the V-block method was applied. It is important to consider all possible sources of errors in this method, e.g. inaccurate calibration of the measuring sensor, a straightness deviation of the guideway axis, a slope of the guideway axis

in relation to the workpiece axis (caused by factors other than inequality of the prisms' angles), and a deflection of the sensor axis from its nominal orientation [12].

A similar V-block-based measurement principle was applied in the presented device, only with two gauges S1 and S2 and two supporting points R1 and R2, as shown in Fig. 1. This innovative type of geometrical solution enables to measure the out-of-roundness and diameter simultaneously, identifying an expected third harmonic that is difficult to measure with the two-point method. The only problem is to properly recalculate the collected measurement data, which was solved successfully, as presented below.

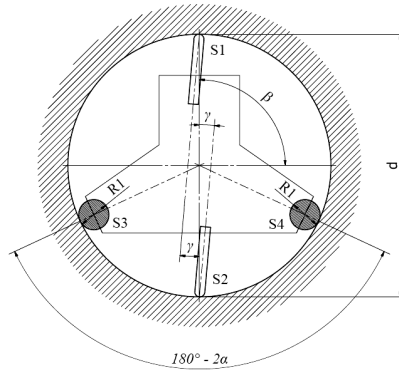


Fig. 1. Geometry of the V-block based cylindricity assessment.

The entire design of the presented measurement device due to innovative aspects is patented in Poland [13]. The patent was granted in 2015.

2. Concept of measurement system

2.1. Requirements to be met

The project was performed in the Division of the Metrology and Measurement Systems (Poznan University of Technology, Poland).

The required accuracy of a measured cylinder implies that the measurement must be performed at least at three levels of the cylinder. The highest accuracy should be in the middle of the cylinder, where the values of dimensional tolerance and out-of-roundness RON_t measured according to the Standard [14] are 0.002 mm and 0.015 mm, respectively. It is usually assumed in metrological practice, that the measurement uncertainty should not exceed 10–20% of the measured tolerance. Thus, the uncertainty $U_{0.95}$ of the device [15] should not exceed 1.5 μm .

Moreover, the device should be reasonably cheap and able to work in the industrial conditions. Another problem to be solved is automation of the system and assuring a proper measurement time. Since the production line provides a new cylinder every minute, it is recommended that the measurement should take less than a minute so that it would not cause any “jam.”

Hence, the requirements of the measurement system for cylinders are formulated as follows:

- the measurement should be performed at three levels,
- the uncertainty $U_{0.95}$ of the device should not exceed 1.5 μm ,
- the process must be automated with the results displayed on a monitor,
- the measurement time should be minimized,
- the price must be reasonably low.

2.2. Structure of measurement system

A block diagram of the proposed measurement system is presented in Fig. 2.

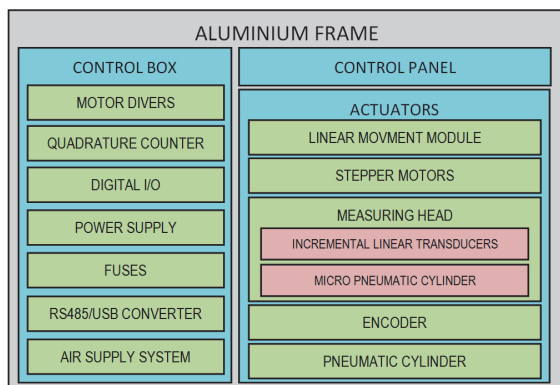


Fig. 2. A block diagram of the designed system.

It is clear that it is impossible to make strict boundaries between mechanical, electronic, electric and pneumatic units. Thus, the global mechatronic system approach was necessary from the very beginning. The iteration method was applied, where in subsequent stages the details were worked out more accurately to find optimal solutions according to the requirements specified above.

Fig. 3 presents a scheme of the mechanical construction of measurement system. It consists of an aluminium frame, a measurement unit, a control box and a control panel. The frame is made from aluminium angle bars and dedicated joints to obtain a stable construction able to bear the expected load.

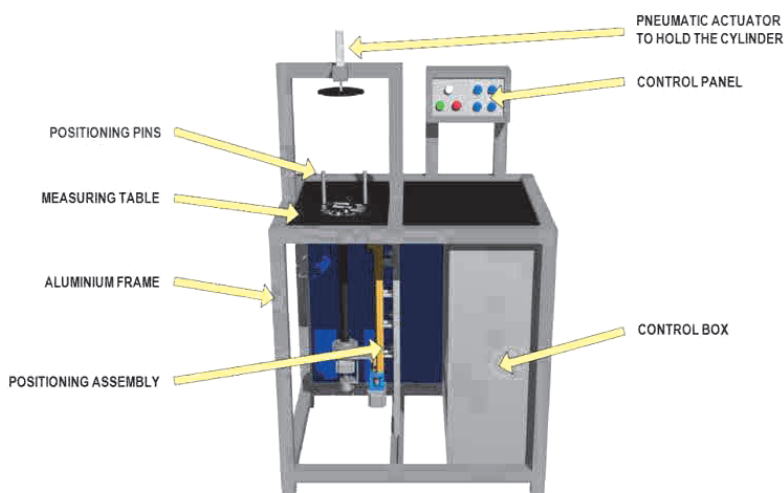


Fig. 3. A scheme of the mechanical construction.

2.3. Mechanical and control units

The main mechanical parts are inseparably fixed to the aluminium frame. There are two most important mechanical units:

- the automatic unit to perform mechanical movement tasks (linear and rotational movements of the gauge head),
- the gauge head where the gauges (sensing units) are placed and moved toward the surface of measured cylinder during the measurement.

Most of the applied parts and subunits were standard ones available in the market, but some of them were made especially for the designed system.

The task of the automatic unit is to move the gauge head to a proper level inside the measured cylinder (upper, middle and lower ones) and to turn it around to collect measurement data from the entire profile circle. The movements must be precise and smooth.

The gauge head is the most important unit. It contains, besides the gauges, the mechanical subunits that support the head in a chosen position and another subunit that puts the gauges into a measurement position. In a working cycle, the pneumatic servo-motor moves the gauge head into the cylinder. When the head reaches its proper position, the gauges get in contact with the cylinder's surface and the gauge head performs rotational movement. The so-called "floating head" is a patented solution that secures the proper positioning of the gauge head regarding the cylinder's surface. In the main box of the construction shown in Fig. 3, there are placed the control units, as well as the electrical and pneumatic devices. The latter comprise pressure reducers and regulators, control valves etc. The main and emergency switches are available from the outside. Inside the box, the subunits are arranged according to their importance and functions.

2.4. Software

The control and measurement software procedures were prepared in the environment of Visual Basic with a Visual Studio 2010 Express compiler. This environment was chosen because it enables to create new applications in a short time with no need of deep understanding its programming language. The experience with graphic interface and basic object-oriented programming is sufficient to prepare quickly a good program. The software in the measurement system was divided into several modules of independent code and the main part controlling all the modules. The module structure of the programme enables to introduce some modifications into the working algorithms, and to use them in further projects.

In order to process the measurement data, a class "Analysis" was created to convert the measured points into real-time ones. Appropriate arguments should be introduced to the class, like a table with radius values, a table with respective angles for those radiuses, coefficients to scale the obtained data dependent on the applied gauge, and a correction for the master gauge scaling. In order to obtain results in the form of harmonic compounds, proper coefficients, amplitudes and phases are calculated. The resulting table is one-dimensional because of interpolation limiting any collected number of probed points to 3,600. This number is set permanently in the program, assuring an angle resolution of 0.1° , which is sufficient for obtaining the required measurement accuracy.

The aim of the main program is to control the above-mentioned modules and to present the obtained results on a monitor. The role of operator is just to start a measuring cycle with the button START, and – in case of emergency – to interrupt its work with the button STOP. When the measurement is completed, the programme uses the signal analysis module and presents results

as radial graphs for three measured levels and values of out-of-roundness. Since harmonic data are also available, the dominating type of form deviation is determined (oval and lobe shapes).

After starting the application, the main menu appears on the monitor screen (Fig. 4). There are 5 modes available: the setting, archive, test, calibration and measurement ones.

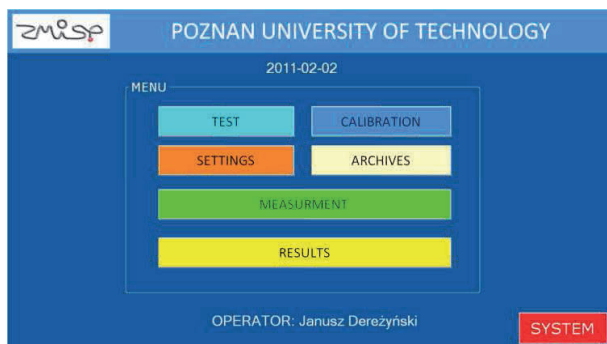


Fig. 4. The main menu of the control program.

The screen colour is different for each mode, so the operator can always visually distinguish which mode is currently in work.

3. Acquisition of measurement data

The collected measurement data are to be processed and then presented in the user-friendly form. The datasheet consists of three columns of values: an angle φ , a respective indication of gauge 1 for the angle φ , and a respective indication of gauge 2 for the angle φ . The number of rows corresponds with the number of samples collected during the measurement. The raw data are further processed according to a procedure shown in Fig. 5.

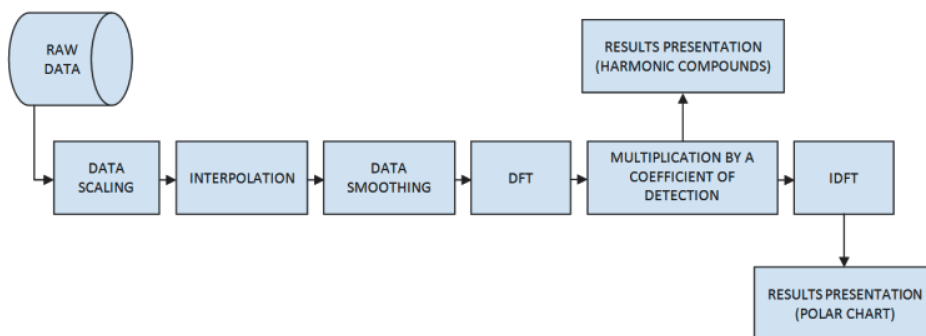


Fig. 5. A block diagram of the data processing procedure.

3.1. Data scaling

Because the measurement range of the gauges is 12 mm, their indications must be related to the actual diameter of cylinder. For that purpose, a special setting master was made of a diameter

different from the nominal diameter of cylinder (131 mm). The roundness measurement of the setting master provides the reference data for the further measurement of the cylinders. In order to reduce uncertainty propagation, the setting master should be very precise, with deviations within 10% of the uncertainty of the calibrated measurement system.

Apart from calibration, it should be considered that the gauges in the gauge head are not perpendicular to the measured surface. A declination angle to the surface is $\gamma = 6^\circ$. A proper scaling coefficient is calculated from the following formula:

$$r_s(\varphi) = r(\varphi) \cos(\gamma). \quad (1)$$

3.2. Data smoothening

The obtained values of radiuses should undergo a smoothening procedure in order to eliminate gross errors. The smoothened data may further become the object of digital operations like interpolation, integration or differentiation.

After completing the smoothening procedure, the following conditions must be attained:

- the same surface under the curve,
- the abscissa of the centre of area,
- the inertial momentum of the area related to any line parallel to the Y-axis.

Among many available graphical and digital methods, the Least Squares Method was chosen for the designed system, because it proved to be successful in a similar application based on air gauges [16]. The principle is to find a polynomial of j degree fitting the collected data, so that the squares of differences between the data and model are minimal [17].

3.3. Interpolation

During the roundness measurement, it is not sure whether the sampling provides a steady distribution of points on the assessed circle. That is so because of several influencing factors, among others an inaccuracy of the step motors' positioning and a variable movement resistance that results in varying the rotational speed. The Bessel's theoretical assumptions [18] proved to be sufficient, and the following formula is based on it:

$$f(x) = f(x_0) + k\Delta_0 - k_1(\Delta_1 - \Delta_{-1}), \quad (2)$$

$$k = \frac{x - x_0}{h}, \quad k_1 = \frac{k(1 - k)}{4}. \quad (3)$$

3.4. Fourier analysis

In measurements similar to those performed with the V-block method, the acquired data should be transformed into the actual profile of measured detail. To perform it, the amplitudes of harmonic compounds should be multiplied by appropriate coefficients. So the data collected on the measured profile should be rewritten as a Fourier's series. Because the sampled signal is discrete, the Discrete Fourier Transform should be applied.

$$R(\varphi) = R_0 + \sum_{k=1}^n A_n \cos n\varphi + \sum_{k=1}^n B_n \sin n\varphi. \quad (4)$$

The above equation shows that in the orthogonal coordinates the measured profile can be represented by the sum of sines and cosines multiplied by respective coefficients A_n and B_n . These values help also in calculations of amplitudes and phases of particular harmonics.

The obtained values of amplitudes C_n and phases γ_n are so-called “measured” ones, which – in the case of the proposed method – are different from the actual values. Therefore, they must be further processed using specific coefficients of recognisability, which show the relation between the measured and actual amplitudes:

$$K_n(\alpha, \beta) = \frac{C_{Fn}}{C_{Rn}}. \quad (5)$$

3.5. Recognisability coefficients

The values of those coefficients depend on the measurement scheme geometry, i.e. angles α and β shown in Fig. 1. Moreover, as it is seen from the equation (6) below, the indications ΔW depend not only on the measured diameter, but also on the position of the supporting points.

$$\Delta W = \Delta R_3 - \Delta W_p - \Delta W_0, \quad (6)$$

$$\Delta W = \frac{\Delta R_1}{\cos \alpha}, \quad (7)$$

$$\Delta W = \frac{\Delta R_2 - \Delta R_1}{2 \cos \alpha}, \quad (8)$$

$$\Delta W = R_3 - \frac{\Delta R_2 + \Delta R_1}{2 \cos \alpha}. \quad (9)$$

When the results are presented as harmonics, then the formula for gauge indications becomes as follows:

$$\Delta W = \sum_{n=2}^k \left(1 - \frac{\cos n\alpha}{\cos \alpha} \right) C_n \sin(k\varphi + \varphi_n). \quad (10)$$

The formula (10) reveals that the amplitude of each harmonic is either strengthened or weakened by a recognisability coefficient which is:

$$K_n = 1 - \frac{\cos n(180 - \alpha)}{\cos \alpha}, \quad (11)$$

$$C_{Rn} = \frac{C_{Fn}}{K_n} = \frac{C_{Fn}}{1 - \frac{\cos n(180 - \alpha)}{\cos \alpha}}. \quad (12)$$

Thus, the actual dimensional variations of the measured radius in any point of the circle can be calculated from the formula (13). The obtained values may undergo the metrological analysis and be presented as measurement results.

$$\Delta R = \sum_{n=2}^k C_{Rn} \cos n(\varphi - \varphi_n). \quad (13)$$

3.6. Synthesis of Fourier series

To obtain the actual measured profile, the Fourier series must be synthesized. The actual compound amplitudes are processed with the formula (4) in a modified form:

$$R_r(\varphi) = R_0 + \sum_{n=2}^k C_{Rn} \cos n(\varphi - \varphi_n). \quad (14)$$

After completing the calculations for angles $\varphi = \langle 0, 360^\circ \rangle$, the obtained profile can be presented as a diagram in the radial coordinates. The diagram may present either the out-of-roundness values or the variations of the cylinder's radius.

4. Measurement system accuracy test

4.1. Reference circle measurement

After assembling and programming the measurement system prototype, a series of functionality tests were performed. The system carried out 30 measurement cycles in the automatic mode, as well as in the manual mode. To perform the accuracy tests, two master rings were measured (Fig. 6) and their out-of-roundness values were assessed. In both rings, the measurement was made at the same level (middle), with 20 repetitions. For each gauge head rotation, 8,500 probing points were collected and then reduced down to 3,600 to achieve an angle resolution of 0.1° as it has been explained earlier (Section 2.4).



Fig. 6. The gauge head inside the master ring during tests.

After execution of the procedures described in Chapter 2, the harmonic analysis was performed. In order to reveal a possible angular error generated by the rotating system of gauge head, repetitions were made after turning the master ring by 90° . The results are presented in Table 1.

Table 1. Reference ring measurement results.

Parameter:	Reference Ring 1	Reference Ring 2
RON _t [μm]	2.3	4.5
RON _p [μm]	3.4	5.1
RON _v [μm]	5.7	9.6

For the obtained values of out-of-roundness RON_t, statistical parameters were calculated in order to evaluate the uncertainty concerned with the Method A [19]. Table 2 presents the values of mean, median, range, standard deviation, standard deviation of mean, and expanded measurement uncertainty $U_{0.95}$, calculated from 20 repetitions. The values of mean and median close to each other prove that the distribution type is symmetric. The uncertainty $U_{0.95} = 0.2 \mu\text{m}$ lies far below the required value of $1.5 \mu\text{m}$.

Table 2. Statistics of the obtained measurement results.

Parameter	Ring 1 [μm]	Ring 2 [μm]
Mean value:	5.7	9.6
Median:	5.6	9.55
Range:	1.4	1.0
Standard Deviation:	0.4	0.3
Standard deviation of the mean:	0.1	0.05
Measurement uncertainty $U_{0,95}$:	0.2	0.1

4.2. Comparative analysis of reference device

To verify the obtained results, the same two master rings of diameter 131 mm, corresponding to the upper and lower tolerances of cylinders, respectively, were measured first with the prototyped device, and next with the reference roundness measurement device dedicated to laboratory measurements, produced by Warsaw Technical University, type PIK-2. Figs 7 and 8 present examples of radial diagrams obtained with both devices for the same ring marked 1.

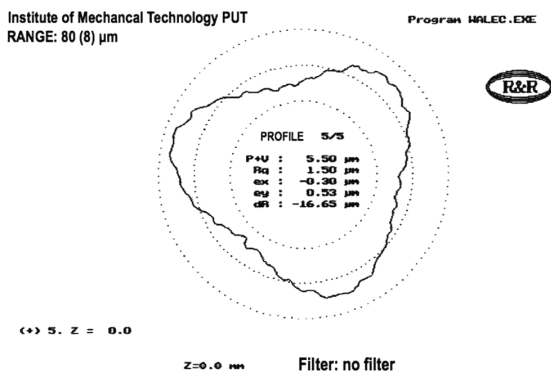


Fig. 7. The results of the ring 1 measurement with PIK-2 device.

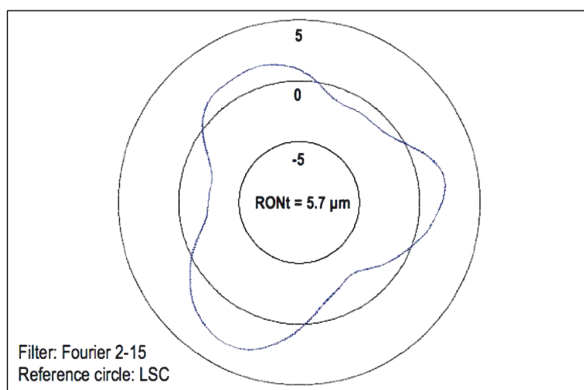


Fig. 8. The results obtained with the tested system for ring 1.

As it was expected, the third harmonic was dominating. It was successfully identified by the measurement system prototype. The tested prototype performed the measurement of the same rings and provided results of $5.7 \mu\text{m}$ and $9.6 \mu\text{m}$, respectively, compared with the values of out-of-roundness – $5.5 \mu\text{m}$ for ring 1 and $8.4 \mu\text{m}$ – for ring 2, obtained from PIK-2 (the measurement uncertainty was $0.2 \mu\text{m}$). Figs 9 and 10 show diagrams provided by the tested measuring system for rings 1 and 2, so that the measurement results of two different rings can be compared. Figs 11 and 12 present the measurement results for each ring, obtained by the proposed device in comparison with the reference measurement results.

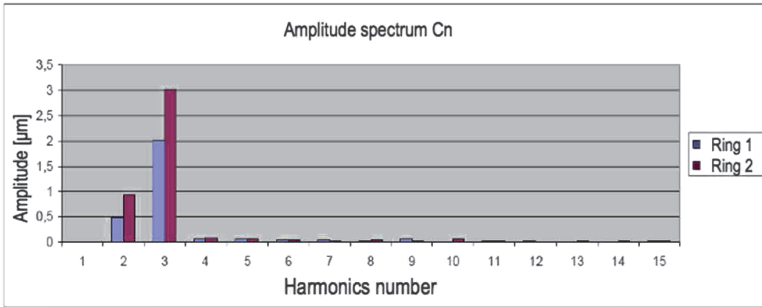


Fig. 9. Values of C_n obtained with the tested system for measured rings 1 and 2.

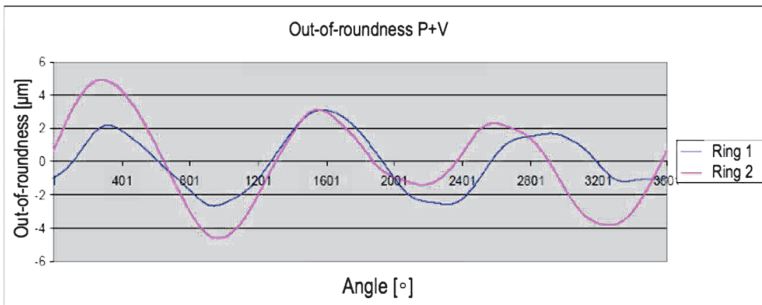


Fig. 10. Results of the out-of-roundness measurement obtained for rings 1 and 2.

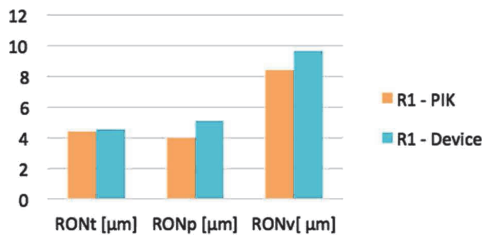


Fig. 11. Comparison of ring 1 measurement results obtained with the tested system and the reference device PIK-2.

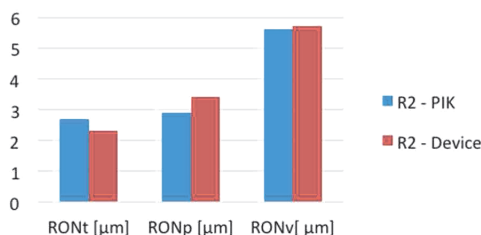


Fig. 12. Comparison of ring 2 measurement results obtained with the tested system and the reference device PIK-2.

The results of out-of-roundness appear to be satisfactory. In the next verification stage, the diameter measurement will be checked and its uncertainty estimated.

5. Conclusions

The presented tests are just an initial stage of evaluation of the proposed measurement system capabilities. The initial results do not give the final overall uncertainty of the system. The differences between results obtained with the reference device PIK-2 and the tested prototype require further analysis and corrections. In successive tests, more repetitions should be made in order to collect more statistical data. The calculated uncertainty should be related to different parts of the measurement range, and must be determined separately for the dimensional measurements (diameter or radius). Furthermore, the impact of gauging forces in the gauge head should be closer analysed.

Anyway, the built and checked prototype proved that the main constructional and data processing assumptions were correct. The method of measurement based on the modified V-block principle provided good results, even though it is not widely applied in industrial measurements of cylindricity and roundness. The overall expenses indicate that the measurement system may provide quick and accurate results for a reasonable price in dedicated industrial applications.

The automatization of measurement process is an additional advantage of the device. It minimizes the operator's subjective impact on the measurement procedure and interpretation of the obtained data. Moreover, the automatized process always completes the measurement cycle in the same time securing fluent and smooth flow of produced parts.

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