ARCH. MECH. TECH. MATER.VOL. 40, (2020) 1-6

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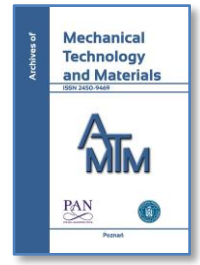

The use of Gage R&R in suitability analysis of a CMM used at FAMOT Pleszew

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A R T I C L E I N F O

Received 18 February 2020
Received in revised form 24 June 2020
Accepted 14 July 2020

K E Y W O R D S

CMM
R&R analysis
measuring system ability

A B S T R A C T

The subject of the article is the suitability analysis of a measuring system, specifically the Zeiss MMZ T 20 30 16 coordinate-measuring machine utilizing an extended procedure.
The article outlines the measurement preparation process and presents the research station as well as the procedure for determining Repeatability & Reproducibility (R&R).

1. INTRODUCTION

The coordinate-measuring technology is increasingly used in the industry for gauging objects of different configurations [3] and is currently one of the more universal measurement methods [1, 2]. It is most often utilized in the automotive, aerospace and machine industries. The use of coordinate machines becomes an indispensable condition for ensuring the required quality of the manufactured products as well as for demonstrating this quality [4]. Controlling the quality of the manufactured products not only using CMM is a conscious and deliberate activity of manufacturers. It is not possible to carry out an appropriate analysis of the quality of the products without the properly functioning measuring system. To recognize this, such a system should be constantly monitored. The assessment of the system should be based on identification of the relevant characteristics, which affect the quality of the products and on their comparison with the required nominal values. Such an action requires the definition of a suitable scope and a reliable method of collecting the system data. The assessment of the effectiveness of the measuring system can be carried out using the R&R method [5, 7, 8].

1.1 Measurement system errors

The quality of the measuring system directly affects the quality of the obtained test results, and thus the quality of the analyses that are carried out on the basis of these data.

In a broad sense, a good measuring system is one, where a dozen consecutive measurements of the same item yield identical or very similar results [4]. The quality of the measuring system is most often described using statistical values, such as the accuracy of the data position in relation to

DOI: 10.2478/amtm-2020-0001

the nominal value and variance (variability) showing the data span [6]. A common cause of low data quality is the high variance of the measurement results. Typically, the reason for this is the lack of resistance of the measuring system to changes occurring in its surroundings. Measurement system errors can be described by five categories:

- **accuracy**, which is defined as the deviation of the mean value of the measurements from the actual size of the measured property and is affected by: calibration error, consumption of the measurement instrument, incorrect calibration, improper operation;
- **repeatability**, which is the variance of the variability of the results of the measurements obtained by a given operator during the measurement of one and the same part, several times under the same measuring conditions and is affected by: the summing of random interference suffered by different elements of the measuring system, variable boundary and initial conditions, environmental instability;
- **reproducibility** that is the variability between the average values from the measurements conducted by different operators during the measurement of the same element, using the same measuring instrument, resulting from differences in the preparation and the skills of the operators;
- **stability** that is the total variability obtained when measuring a given property over a long period of time, which is influenced by the variable environmental conditions and the usage of the measurement apparatus;
- **linearity**, which is the variability of the measurement accuracy determined in relation to the measurement size, e.g. the larger the dimension to be measured, the lower the accuracy of the measurement. The reason for the linearity errors is the imperfection of the method or the measurement apparatus [4, 5, 6].

1.2. The essence of the R&R analysis

Due to its efficiency, the repeatability and reproducibility analysis (R&R) is the most frequently used method to assess the suitability of measuring systems dedicated to perform specific metrological tasks [9]. The key aim of this approach is to determine the repeatability and reproducibility coefficient by measuring a selected item. The obtained measurement results can be used to investigate variability of the measurement process and allow for the interpretation and minimization of the impact of these reasons on the variability of the process [9, 10]. The R&R analysis consists of several series of measurements of a given dimension measured for a randomly selected batch of elements by several operators.

The following three types of the R&R method are distinguished:

Type 1 – analysis of the capability of the measuring means, the aim of which is the initial qualification of the measuring instrument by assessing its capability, by determining the capability of the Cg and Cgk indicators of the measuring apparatus;

Type 2 – analysis of the capacity of the measuring means, a simplified version, the purpose of which is a fast, ad hoc assessment of the capability of the measuring instrument, the result of which is the resultant of the repeatability and reproducibility containing the repeatability of the instrument (EV) and reproducibility of the operators (AV);

Type 3 – analysis of the capacity of the measuring means, this is an extended version that allows for a full assessment of the ability of the measuring system, and takes into consideration the delimitation of the impact of the instrument (repeatability EV) and operators (reproducibility AV) on the dispersion of the indications (R&R) of the measuring system [8, 9].

1.3. Description of the station and the study object

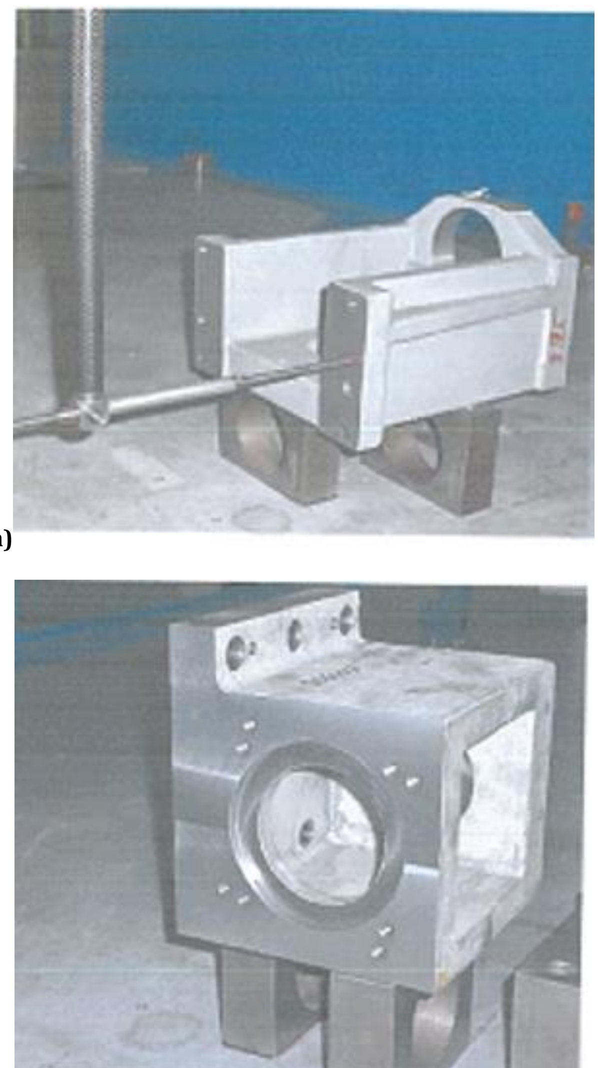
The research was carried out on the portal coordinate-measuring machine [11, 13] Zeiss MMZ T with a stationary measuring table located in the measurement laboratory of FAMOT PLESZEW Sp. z o.o. shown in Figure 1. It is a coordinate machine with measuring range X, Y,Z, 2000 mm/3000mm/1600mm, designed to measure large and precise parts, such as gears, spindle bodies, bearings, and other machine parts. It is also ideal for measuring parts in the energy sector (elements of wind power plants). This machine can operate directly in production halls at high temperatures and under polluted atmosphere as well as in specially separated air-conditioned rooms. The measuring machine contains computer-calculated adjustments of all dynamic impacts on the machine. This allows for the achievement of optimum precision during quick scanning. Unlike most measuring machines, the construction of the guides is based on roller bearings and linear guides, which makes the system invulnerable to external impacts. The employed design and materials result in good vibration damping characteristics and the possibility to abandon special foundations. The main construction material of the machine is steel. The CMM design has been optimized for rigidity and resistance to temperature changes.

Fig. 1. CMM MMZ 203016

1.4. Selection of items and quality features

The bodies that have been selected by the authors in the present article are the basic components of the lathe and milling machine. The first body is Y – Flansch used in the DMC 635V milling machine as the housing of the ball screw drive on the Y-axis. The second body is also the housing of a ball screw drive on the Z-axis of the Engine Console used in the NEF 600 lathe. These machine components act as a skeleton to ensure adequate strength and rigidity and contain anchor and support points for cooperating structural components [12]. The evaluated elements are subjected to geometric conditions and linear dimensions by the constructor. Due to the labor intensity of the measurements, and the works associated with the measurements ensuring continuity of production, the authors of the work selected only three characteristics that were used to assess the measuring system.

For the Y — Flansch body, the flatness condition of 0.015 mm, and the linear dimension of 220 ± 0.2 were selected, while for Engine Console, the perpendicular condition of 0.03 mm was selected.



a)

b)

Fig. 2. Measurement on a CMM: a) Engine Console; b) Y – Flansch

1.5. Preparation of measurements

A calibration pattern was installed on the CMM measuring table prior to the test to calibrate the measuring head. By calibration we are gaining certainty that the performed measurements will not be affected by errors from the measuring head. After performing this action, the selected quality features were measured.

In the analysis, an experiment consisting of selecting ten units of Engine Console and Y – Flansch bodies from the production batch was carried out. Each of the selected bodies was measured three times by each of the three operators at different intervals.

Each time, prior to the measurement, the measured body was positioned on the measuring machine table and the head was calibrated. Subsequently, the first quality trait measurement of the perpendicular condition of the Engine Console was performed with a tolerance of 0.03 mm. The quality characteristics, i.e. the flatness with a tolerance of 0.015 mm, and the linear dimension of 220 mm with a tolerance of ± 0.2 mm were then checked on the Y – Flansch body. The measured geometric characteristics are illustrated in Figures 3 and 4.

During the study, the results of the measurements of the individual components as well as the quality characteristics measured by individual operators were recorded. In addition, the course of the measurements was observed to capture and evaluate any abnormal factors, which could lead to deviations. The obtained results are listed in Tables 1, 2, 3, consecutively.

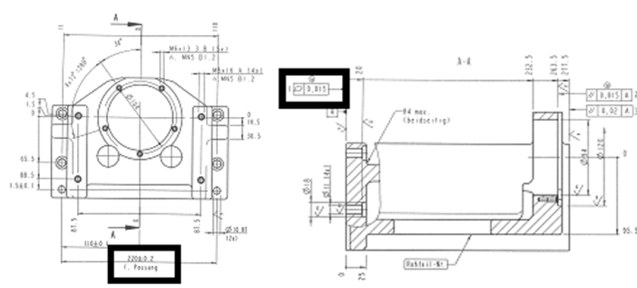


Fig. 3. Executive drawing of the Y — Flansch body with marked checked quality characteristics

1.6. Results

Table 1. Measurement results for linear dimension of 222 ± 0.2 mm

220±0,2		Measured Sample Number											
		1	2	3	4	5	6	7	8	9	10		
Operator A	**Measurement 1**	219,9839	219,9962	220,0015	219,9916	219,9988	219,9928	220,0069	220,0006	219,9822	220,0206		
	Measurement 2	219,9838	219,9955	220,0028	219,9926	219,9961	219,9928	220,0059	220,0009	219,9836	220,0212		
	Measurement 3	219,9836	219,9966	220,0011	219,9937	219,9979	219,9929	220,0046	220,0003	219,9839	220,0208		
	Average	219,9837	219,9961	220,0018	219,9926	219,9976	219,9928	220,0058	220,0006	219,9832	220,0208	$\overline{X_A}$	219,9975
	Range	0,0003	0,0011	0,0017	0,0021	0,0027	0,0001	0,0023	0,0006	0,0017	0,0006	$\overline{R_A}$	0,00132
Operator B	**Measurement 1**	219,9846	219,9971	220,0021	219,9923	219,9995	219,9945	220,0061	219,9997	219,9841	220,0216		
	Measurement 2	219,9853	219,9960	220,0029	219,9931	219,9989	219,9934	220,0053	220,0006	219,9838	220,0211		
	Measurement 3	219,9846	219,9966	220,0018	219,9928	219,9986	219,9953	220,0049	219,9995	219,9846	220,0214		
	Average	219,9846	219,9899	220,0022	219,9927	219,9990	219,9944	220,0054	219,9999	219,9841	220,0213	$\overline{X_B}$	219,9973
	Range	0,0012	0,0011	0,0011	0,0008	0,0009	0,0019	0,0012	0,0011	0,0008	0,0005	$\overline{R_B}$	0,00100
Operator C	**Measurement 1**	219,9829	219,9958	220,0010	219,9921	219,9990	219,9938	220,0056	220,0009	219,9848	220,0199		
	Measurement 2	219,9833	219,9950	220,0015	219,9925	219,9983	219,9942	220,0049	220,0006	219,9843	220,0196		
	Measurement 3	219,9838	219,9965	220,0018	219,9930	219,9986	219,9929	220,0051	220,0001	219,9836	220,0200		
	Average	219,9833	219,9957	220,0014	219,9925	219,9986	219,9936	220,0052	220,0005	219,9842	220,0198	$\overline{X_C}$	219,9974
	Range	0,0009	0,0015	0,0008	0,0009	0,0007	0,0013	0,0007	0,0008	0,0012	0,0004	$\overline{R_C}$	0,0009
	$\overline{X_P}$	219,9838	219,9939	220,0018	219,9926	219,9984	219,9936	220,0054	220,0003	219,9338	220,0206	R_P	0,0368

Table 2. Measurement results for perpendicular b *of 0.03 mm*

b		Measured Sample Number											
		1	2	3	4	5	6	7	8	9	10		
Operator A	**Measurement 1**	0,0115	0,0114	0,0118	0,0109	0,0087	0,0104	0,0376	0,0088	0,0119	0,0125		
	Measurement 2	0,0119	0,0128	0,0106	0,0114	0,0096	0,0112	0,0368	0,0096	0,0116	0,0115		
	Measurement 3	0,0117	0,0127	0,0108	0,0116	0,0096	0,0110	0,0373	0,0097	0,0126	0,0111		
	Average	0,0117	0,0123	0,0110	0,0113	0,0093	0,0108	0,0372	0,0093	0,0120	0,0117	X_A	0,0136
	Range	0,0004	0,0014	0,0012	0,0007	0,0009	0,0008	0,0008	0,0009	0,0010	0,0014	$\overline{R}_A$	0,00095
Operator B	**Measurement 1**	0,0117	0,0115	0,0116	0,0131	0,0094	0,00096	0,0380	0,0101	0,0155	0,0119		
	Measurement 2	0,0118	0,0110	0,0112	0,0127	0,0097	0,0110	0,0340	0,0084	0,0123	0,0106		
	Measurement 3	0,0106	0,0113	0,0117	0,0109	0,0098	0,0109	0,0334	0,0102	0,0114	0,0113		
	Average	0,0113	0,0112	0,0115	0,0122	0,0096	0,0097	0,0344	0,0095	0,0130	0,0112	$\overline{X}_B$	0,01336
	Range	0,0012	0,0005	0,0005	0,0022	0,0004	0,0014	0,0024	0,0018	0,0009	0,0013	$\overline{R}_B$	0,00126
Operator C	**Measurement 1**	0,0105	0,0117	0,0112	0,0115	0,0104	0,0093	0,0287	0,0090	0,0109	0,0112		
	Measurement 2	0,0104	0,0115	0,0111	0,0113	0,0098	0,0094	0,0280	0,0090	0,0106	0,0112		
	Measurement 3	0,0108	0,0118	0,0115	0,0114	0,0097	0,0094	0,0276	0,0092	0,0104	0,0111		
	Average	0,0105	0,0116	0,0112	0,0114	0,0099	0,0093	0,0281	0,0090	0,0106	0,0111	$\overline{X}_C$	0,01227
	Range	0,0004	0,0003	0,0004	0,0002	0,0007	0,0001	0,0011	0,0002	0,0003	0,0001	$\overline{R}_C$	0,00038
	$\overline{X}_P$	0,0111	0,0117	0,0112	0,0116	0,0096	0,0099	0,0332	0,0092	0,0118	0,0113	$\overline{R}_P$	0,024

Table 2. Measurement results for flatness c *of 0.015 mm*

c		Measured Sample Number											
		1	2	3	4	5	6	7	8	9	10		
Operator A	**Measurement 1**	0,0064	0,0056	0,0043	0,0053	0,0051	0,0157	0,0061	0,0046	0,0052	0,0049		
	Measurement 2	0,0062	0,0063	0,0049	0,0054	0,0054	0,0156	0,0058	0,0051	0,0059	0,0058		
	Measurement 3	0,0069	0,0066	0,0045	0,0055	0,0055	0,0154	0,0050	0,0059	0,0051	0,0055		
	Average	0,0065	0,0061	0,0045	0,0054	0,0053	0,0155	0,0056	0,0052	0,0054	0,0054	$\overline{X}_A$	0,0064
	Range	0,0007	0,0010	0,0006	0,0002	0,0006	0,0003	0,0011	0,0013	0,0008	0,0014	$\overline{R}_A$	0,0008
Operator B	**Measurement 1**	0,0058	0,0062	0,0051	0,0058	0,0056	0,0106	0,0057	0,0051	0,0056	0,0053		
	Measurement 2	0,0061	0,0058	0,0056	0,0052	0,0064	0,0159	0,0064	0,0056	0,0064	0,0060		
	Measurement 3	0,0058	0,0063	0,0049	0,0050	0,0058	0,0156	0,0059	0,0053	0,0050	0,0060		
	Average	0,0058	0,0061	0,0052	0,0053	0,0059	0,0157	0,0060	0,0053	0,0058	0,0057	$\overline{X}_B$	0,0066
	Range	0,0004	0,0007	0,0011	0,0008	0,0008	0,0004	0,0007	0,0005	0,0009	0,0007	$\overline{R}_B$	0,0006
Operator C	**Measurement 1**	0,0061	0,0059	0,0049	0,0057	0,0055	0,0152	0,0064	0,0053	0,0063	0,0058		
	Measurement 2	0,0065	0,0068	0,0051	0,0059	0,0061	0,0155	0,0053	0,0049	0,0069	0,0057		
	Measurement 3	0,0060	0,0053	0,0044	0,0052	0,0059	0,0150	0,0058	0,0054	0,0059	0,0059		
	Average	0,0062	0,0060	0,0048	0,0056	0,0058	0,0152	0,0058	0,0052	0,0063	0,0058	$\overline{X}_C$	0,0066
	Range	0,0005	0,0015	0,0007	0,0007	0,0006	0,0005	0,0011	0,0005	0,0010	0,0002	$\overline{R}_C$	0,0007
	$\overline{X}_P$	0,0061	0,0060	0,0048	0,0054	0,0057	0,0154	0,0058	0,0052	0,0058	0,0056	R_P	0,0106

2. Calculations

After performing a series of measurements for the selected bodies, the repeatability, reproducibility, process variability, and standard deviations were calculated, and % R&R indicators were determined for selected quality features: perpendicularity, flatness, and linear dimension.

2.1. For the b feature

- **Repeatability** – is represented in the Table by spreads Ra, Rb, Rc; hence, the repeatability is calculated from the entire experiment and is expressed as a medium spread.

$$R_e = \frac{0.00095+0.00126+0.00038}{3} = \mathbf{0.00086\,mm} \quad (1)$$

- **Reproducibility** – is represented by the maximal average spread of the operator $\bar{X}_A$,$\bar{X}_B$, $\bar{X}_C$

$$R_O = 0.01366 - 0.01227 = \mathbf{0.00139\ mm} \quad (2)$$

- **Process variability** – spread of the $\bar{X}_p$value

$$RP = 0.0332 - 0.0092 \mathbf{= 0.024\ mm} \quad (3)$$

- **Standard deviation** – of variability caused by the measuring instrument (repeatability)

$$\boldsymbol{\sigma_e} = \frac{\boldsymbol{R_o}}{\boldsymbol{d_{n-3,p30}}} = \frac{0.00086}{1.693} = \mathbf{0.000507} \quad (4)$$

- **Standard deviation** – of variability caused by the operators (reproducibility)

$$\boldsymbol{\sigma_o} = \frac{\boldsymbol{R_o}}{\boldsymbol{d_{n-3,p-1}}} = \frac{0.00139}{1.91} = \mathbf{0.00072} \quad (5)$$

- **Standard deviation** of variability caused by the whole measuring system (R&R indicator)

$$\sigma_m = \sqrt{\sigma_e^2 + \sigma_0^2} + = \mathbf{0.00088} \quad (6)$$

- **Standard deviation** of variability caused by the process

$$\sigma_p = \frac{R_e}{d_{n=10,p=1}} = \frac{\mathbf{0.024}}{\mathbf{3.18}} = \mathbf{0.0075} \quad (7)$$

- **Total standard deviation** of variability caused by the process and the measuring system

$$\boldsymbol{\sigma_t} = \sqrt{\boldsymbol{\sigma_p^2} + \boldsymbol{\sigma_m^2}} + = \mathbf{0.00755} \quad (8)$$

- **Determination of the %R&R** indicator

$$\%R\&R = \frac{\sigma_m}{\sigma_t}.\ 100\% = \mathbf{11.35\%} \quad (8)$$

2.2. For the c feature

- **Repeatability** – is represented in the table by spreads R_A, R_B, R_C; hence, the repeatability is calculated from the entire experiment and is expressed as a medium spread.

$$R_e = \frac{0.0008+0.006+0.0007}{3} = \mathbf{0.0007\,mm} \quad (9)$$

- **Reproducibility** – is represented by the maximal average spread of the operator $\bar{X}_A$,$\bar{X}_B$, $\bar{X}_C$

$$R_O = 0.0066 - 0.0064 = \mathbf{0.0002\ mm} \quad (10)$$

- **Process variability** – spread of the $\bar{X}_p$value

$$RP = 00.0154 - 0.0048 \mathbf{= 0.0106\ mm} \quad (11)$$

- **Standard deviation** – of variability caused by the measuring instrument (repeatability)

$$\boldsymbol{\sigma_e} = \frac{\boldsymbol{R_o}}{\boldsymbol{d_{n-3,p30}}} = \frac{\mathbf{0.0007}}{\mathbf{1.693}} = 0.000413 \quad (12)$$

- **Standard deviation** – of variability caused by the operators (reproducibility)

$$\boldsymbol{\sigma_o} = \frac{\boldsymbol{R_o}}{\boldsymbol{d_{n-3,p-1}}} = \frac{\mathbf{0.002}}{\mathbf{1.91}} \mathbf{0.000104} \quad (13)$$

- **Standard deviation** of variability caused by the whole measuring system (R&R indicator)

$$\sigma_m = \sqrt{\sigma_e^2 + \sigma_0^2} + = \mathbf{0.000425} \qquad (14)$$

- **Standard deviation** of variability caused by the process

$$\sigma_p = \frac{R_e}{d_{n=10,p=1}} = \frac{0.0106}{3.18} = \mathbf{0,00333} \qquad (15)$$

- **Total standard deviation** of variability caused by the process and the measuring system

$$\boldsymbol{\sigma_t} = \sqrt{\boldsymbol{\sigma_p^2 + \sigma_m^2}} + = \mathbf{0.00335} \qquad (16)$$

- **Determination of the %R&R** indicator

$$\%R\&R = \frac{\sigma_m}{\sigma_t} . 100\% = \mathbf{12.68\%} \qquad (17)$$

2.3. For the linear dimension feature of 220 ± 0.2 mm

- **Repeatability** – is represented in the table by spreads R_A,R_B, R_C; hence, the repeatability is calculated from the entire experiment and is expressed as a medium spread.

$$R_e = \frac{0.00132+0.0010+0.0009}{3} = \mathbf{0.00107\ mm} \ (18)$$

- **Reproducibility** – is represented by the maximal average spread of the operator $\bar{X}_A$,$\bar{X}_B$, $\bar{X}_C$

$$R_O = 219.9975 - 219.9973 = \mathbf{0.0002\ mm} \qquad (19)$$

- **Process variability** – spread of the $\bar{X}_p$value

$$R_P = 220.0206 - 219.9838 = \mathbf{0.000368\ mm} (20)$$

- **Standard deviation** – of variability caused by the measuring instrument (repeatability)

$$\boldsymbol{\sigma_e} = \frac{\boldsymbol{R_o}}{\boldsymbol{d_{n-3,p30}}} = \frac{\mathbf{0.00107}}{\mathbf{1.693}} = \mathbf{0.000632} (21)$$

- **Standard deviation** – of variability caused by the operators (reproducibility)

$$\boldsymbol{\sigma_o} = \frac{\boldsymbol{R_o}}{\boldsymbol{d_{n-3,p-1}}} = \frac{\mathbf{0.002}}{\mathbf{1.91}} \mathbf{0.0001047} \qquad (22)$$

- **Standard deviation** of variability caused by the whole measuring system (R&R indicator)

$$\sigma_m = \sqrt{\sigma_e^2 + \sigma_0^2} + = \mathbf{0.0006406} \qquad (23)$$

- **Standard deviation** of variability caused by the process

$$\sigma_p = \frac{R_e}{d_{n=10,p=1}} = \frac{0.0368}{3.18} = \mathbf{0,01157} \qquad (24)$$

- **Total standard deviation** of variability caused by the process and the measuring system

$$\boldsymbol{\sigma_t} = \sqrt{\boldsymbol{\sigma_p^2 + \sigma_m^2}} + = \mathbf{0.011587} \qquad (25)$$

- **Determination of the %R&R** indicator

$$\%R\&R = \frac{\sigma_m}{\sigma_t} . 100\% = \mathbf{5,52\%} \qquad (26)$$

3. Summary and Conclusion

The assessment of the measuring system is based on the variability of the production process. The purpose of the analysis of the measuring system in the case of the coordinate-measuring machine was to obtain information on the acceptance of the measuring system. Table 4 [8] shows guidelines for the capability of the measuring system depending on the R&R parameter, which the authors used to evaluate the tested system.

Table 4. Capability of the measuring system depending on the R&R parameter [8]

Assessment of the measuring system capability	Total spread of the measuring system	
	Used measuring system	New measuring system
Capable	%R&R< 20%	%R&R< 10%
Conditionally capable	20%≤%R&R≤30%	10%≤%R&R≤30%
Incapable	%R&R > 30%	%R&R > 30%

The coordinate-measuring machine subjected to the research has been in operation at FAMOT for several years; therefore, the acceptance thresholds for a used measurement system were adopted for the evaluation.
The conducted study of the individual geometric characteristics reveals that in the case of all assessed characteristics, i.e. perpendicularity (11.35% was obtained), flatness (12.68% was obtained), and linear dimension (5.52% was obtained), the variability share of the coordinate-measuring machine in tolerance is capable, acceptable without any reservations.

Although the system has been classified as capable, from the analysis it can also be concluded that the share of the CMM variability is associated with the inaccuracies of the machine itself, and in addition, the factor affecting its deterioration is the rudimentary section of the checked characteristics and the one handling them.

The share of variability is also largely dependent on the tolerance field width established by the constructor. The greater the tolerance field, the more favorable the variability result, and vice versa.

The use of the quantitative method of expression of the qualitative parameters in the present study allows for an objective and reliable assessment of the tested product, in this case CMM.

The numerical equivalents of the strictly assigned values of the tested characteristic receive various aspects of quality in the analysis, and thus can be easily compared and processed by calculations. Using graphical data records facilitates fast realization, particularly with a large number of studied features.

In conclusion, it should be assumed that the role of statistical methods, such as the analysis of measurement systems in modern manufacturing companies, will continue to increase, as the quality requirements for manufactured products are constantly increasing [4, 6].

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