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Original Article

DETERMINATION OF OPERATOR'S IMPACT ON THE MEASUREMENT DONE USING COORDINATE TECHNIQUE

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ABSTRACT
Coordinate measuring arms (CMAs) are devices which more and more often replace conventional coordinate measuring machines because of their undoubted advantages, such as mobility, the opportunity to increase the measuring volume, the opportunity to connect the optical probe, and above all, good price-quality ratio. Because these devices are handheld and redundant, what has the greatest impact on the measurement result accuracy are the operator, the machine kinematics and its ability to obtain repeatable measurement results; despite the fact that one point can be obtained from an infinite number of shoulders' positions. In this paper it was determined by using R&R method how significant are the impacts of both the operator and the measuring device on the accuracy of measurements done with CMA, both with rigid switch probe and optical probe.

Keywords: R&R method, coordinate measuring arms (CMA), operator impact, repeatability, reproducibility.

INTRODUCTION

Coordinate Metrology enables imaging objects by scanning surfaces and whole objects through the use of optical technique and computed tomography. Not long ago classical (contact) measuring machines were the main direction of development of the coordinate measuring technique. In recent years, however, growing interest in optical measuring devices of coordinate measuring technique was noted. Contactless measurement methods are characterized by: a very short measurement time, lack of necessity to program the machine, non-invasiveness and a large amount of data obtained for later analysis. The biggest disadvantage of this method is its small accuracy in comparison to contact coordinate measurements [6, 7, 9, 12].

Currently the coordinate measurements are the most advanced section in measuring technique used during quality control in the industry. Because of higher and higher requirements manufacturers of measuring instruments tend to continuously improve their devices. Coordinate Measuring Arms (CMAs)are among the most modern measuring devices. Their design makes it is possible to perform measurements of complex objects with high accuracy and in a very short time, what has a big impact on the quality of the product. CMAs cooperate with both switch probes, as well as contactless triangulation probes. Their undoubtedly biggest advantages are mobility and opportunity to increase their measuring volume up to 60 m through the use of systems, such as Gridlock or SpaceLock [5, 8, 11, 16, 19].

This paper presents the impact of the operator and of the measuring device using R&R method. The impact was determined both for CMA equipped with contact and contactless probe.

R&R METHOD

The "R&R" method (Repeatability and Reproducibility) is based on the calculation of repeatability and reproducibility of measurements, where reproducibility is, depending on the adopted set of variable conditions, a resultant of uncertainty including these conditions, while repeatability is an element of uncertainty derived from the gauge [10, 15].

In analysis by the "R&R" method, three basic concepts need to be used, such as: repeatability, reproducibility and inaccuracy. The definition of repeatability given as the standard uncertainty is determined in general as σ_g (gauge). The repeatability given as expanded uncertainty is in fact given as double expanded uncertainty (range of uncertainty) and is described as an abbreviation EV (equipment variation). A coverage factor $t = 2.575$ (level of confidence p = 99%) is most commonly used:

$$EV = 2t\,\sigma_g = 5.15\,\sigma_g \tag{1}$$

Reproducibility of measurements [17] is the degree of compliance of the measurements results performed in variable conditions. To determine the reproducibility of the "R&R" method, following the experience gained in the industry, only the operator that performs measurements under repeatability conditions needs to be changed.

The reproducibility given as the standard uncertainty is usually determined as σ_a (appraiser – carrying measurement). Reproducibility expressed in the form of the expanded uncertainty is reported as double expanded uncertainty (range of uncertainty) and described as an acronym AV (appraiser variation). A coverage factor $t = 2.575$ is most commonly used:

$$AV = 2t\,\sigma_a = 5.15\,\sigma_a \tag{2}$$

To interpret the difference between repeatability and reproducibility, definitions of the conditions of continuity need to be known, because all the cross between these concepts usually arise from the definition [10] (Figure 1).

According to [17] refractoriness is defined as a systematic error, i.e. the difference between the average of an infinite number of measurement results of the same size performed in terms of repeatability, and the true value measured quantity. Refractoriness is generally designated averaging the error of the appropriate number of repetitions of measurements.

Reproducibility conditions cause randomization of systematic error, but its expected value in a hypothetical repetition of a series of measurements is zero. Analysis of R&R applies the same mathematical apparatus, which Shewhart used to develop his control cards, especially card $X_{cer} - R$ (therefore the „R&R" methodology is often called as the analysis of medium and stretch marks). This analysis is a tool to isolate and evaluate the participation of components of variation in the total scatter of measurements carried out during the monitoring of the manufacturing process.

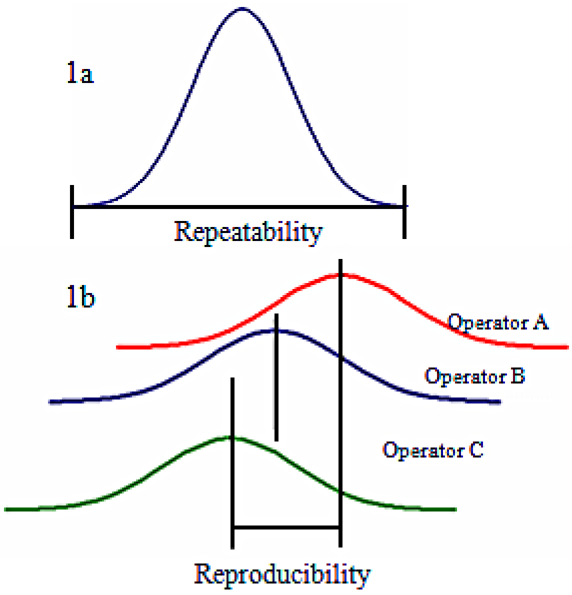

Fig. 1. Graphical interpretation of a) repeatability b) reproducibility of measurements

Currently, the "R&R" analysis is a proven, recognized and required by many customers method (particularly the automotive industry). Till now, accepted procedures of "R&R" analysis have been introduced by the so-called "big three" (Ford, Chrysler, General Motors) in collaboration with Automotive of the American Society for Quality Control (ASQC) and the Automotive Industry Action Group (AIAG) under the requirements of the quality system QS-9000 [3, 10].

R&R METHOD (FORD-TYPE-2 FULL VERSION)

This method allows to determine the error of repeatability and reproducibility of the measuring gauge in a separated form (separately). The measurements were made by three operators, who measured ten parts (distance on step gauge ball-bar) in three trials. Measurement conditions were similar to the conditions of repeatability [1, 2, 3, 4, 13, 14, 17].

At the beginning the measurement was performed using CMA with rigid switch probe, where information of the contact was induced by an operator. The results were then processed in PC-Dmis metrological software (Figure 2).

Then the measurement was performed using CMA with a mounted R-Scan triangulation probe. As a result a cloud of points in 3DReashaper collaborative software was obtained, and then it was imported into Gom Inspect software provided by GOM, where data were processed and calculated (Figure 2).

Sequence of performed operations in R&R method for Coordinate Portable – Arm with switch probe

a) Each of the operators carried out the measurement of 10 different length of artefact (Figure 3).

Fig. 2. The window of the GOM company software

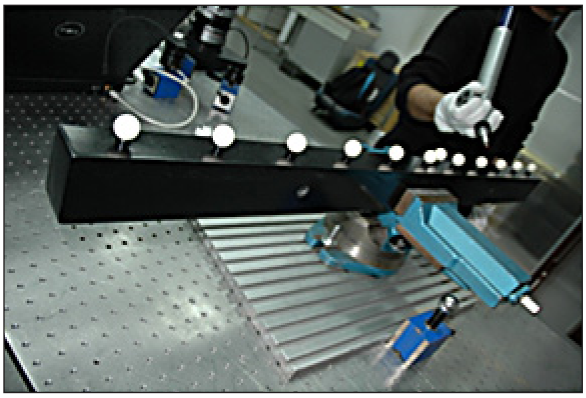

Fig. 3. Measuring station with Ball-Bar artefact

Fig. 4. Measuring CPA with optical probe [6]

b) Heave value (R) for each operator was calculated, as an absolute value of the difference between the value of maximum and minimum length of the measurement results:

$$R_J = \left| P_g - P_d \right| \tag{3}$$

c) The sums of individual heave values were calculated (ΣR_A, ΣR_B, ΣR_C).

d) Average values of the heave sum of the individual operators were calculated:

$$R_{Acer} = \frac{\sum R_A}{L} = 0.0140 \tag{4}$$

$$R_{Bcer} = \frac{\sum R_B}{L} = 0.0220 \tag{5}$$

$$R_{Ccer} = \frac{\sum R_C}{L} = 0.0190 \tag{6}$$

where: L – quantity of measured parts.

e) Average values from measurements of all trials for the individual operator were calculated:

$$X_{Acer} = \frac{\sum X_A}{I} = 549.7200 \tag{7}$$

$$X_{Bcer} = \frac{\sum X_B}{I} = 549.7150 \tag{8}$$

$$X_{Ccer} = \frac{\sum X_C}{I} = 549.7040 \tag{9}$$

f) From average values (X_{Acer}, X_{Bcer}, X_{Ccer}) extreme values were chosen (Max_{Xcer}, Min_{Xcer}) and their differences were calculated (R_{Xcer}):

$$R_{X\,cer} = Max_{X\,cer} - Min_{X\,cer} = 0.0160 \tag{10}$$

g) The values of coefficients were determined D_4 and K_1 on the basis of Table 1, depending on the number of attempts.

Table 1. Values of coefficients D_4 and K_1

Number of attempts	D_4	K_1
2	3.27	4.56
3	2.58	3.05

h) Reproducibility of the measuring gauge was calculated ($E.V.$) as:

$$E.V. = R_{cer} \cdot K_1 = 0.000042 \tag{11}$$

i) Percentage repeatability of the measuring gauge was calculated (E.V.%):

$$E.V\% = 100 \cdot \frac{E.V.}{Tolerance} = 0.0310\% \tag{12}$$

j) The value of coefficient K_2 on the basis of Table 2 was determined:

Table 2. Values of coefficient K_2

Number of operators	K_2	Number of operators
2	3.65	2
3	2.70	3

k) Reproducibility of the measuring gauge was calculated (*A.V.*):

$$A.V. = \sqrt{(R_{Xcer} + K_2)^2 - \frac{E.V.^2}{(n \cdot r)}} = 0.0190 \quad (13)$$

where: n – number of parts,
r – number of attempts.

l) Percentage reproducibility of the measuring gauge was calculated (A.V.%):

$$A.V\% = 100 \cdot \frac{A.V.}{Tolerance} = 13.9950\% \quad (14)$$

m) Repeatability and reproducibility resultants of CMA (R&R):

$$R\&R = \sqrt{(A.V.)^2 + (E.V.)^2} = 0.0190 \quad (15)$$

n) Percentage (*R&R%*):

$$R\&R\% = \sqrt{(A.V.\%)^2 + (E.V.\%)^2} = 13.9951\% \quad (16)$$

Sequence of performed operations in R&R method, for Coordinate Portable – Arm with an optical probe

a) Each of the operators carried out the measurement of 10 different length of artefact (Figure 3).
b) Heave value (R) for each operator was calculated, as an absolute value of the difference between the value of maximum and minimum length of the measurement results:

$$R_J = \left| P_g - P_d \right| \quad (17)$$

c) The sums of individual heave values were calculated (ΣR_A, ΣR_B, ΣR_C).
d) Average values of the heave sum of the individual operators were calculated:

$$R_{Acer} = \frac{\sum R_A}{L} = 0.0710 \quad (18)$$

$$R_{Bcer} = \frac{\sum R_B}{L} = 0.0980 \quad (19)$$

$$R_{Ccer} = \frac{\sum R_C}{L} = 0.0930 \quad (20)$$

where: L – quantity of measured parts.

e) From average values (X_{Acer}, X_{Bcer}, X_{Ccer}) extreme values were chosen (Max_{Xcer}, Min_{Xcer}) and their differences were calculated (R_{Xcer}):

$$R_{X\,cer} = Max_{X\,cer} - Min_{X\,cer} = 0.0270 \quad (21)$$

f) Reproducibility of the measuring gauge was calculated (*E.V.*) as:

$$E.V. = R_{cer} \cdot K_1 = 0.00026535 \quad (22)$$

g) Percentage repeatability of the measuring gauge was calculated (*E.V.%*):

$$E.V\% = 100 \cdot \frac{E.V.}{Tolerance} = 0.2110\% \quad (23)$$

h) Reproducibility of the measuring gauge was calculated (*A.V.*):

$$A.V. = \sqrt{(R_{Xcer} + K_2)^2 - \frac{E.V.^2}{(n \cdot r)}} = 0.0297 \quad (24)$$

where: n – number of parts;
r – number of attempts.

i) Percentage reproducibility of the measuring gauge was calculated (*A.V.%*):

$$A.V\% = 100 \cdot \frac{A.V.}{Tolerance} = 22.5700\% \quad (25)$$

j) Repeatability and reproducibility resultants of CMA (*R&R*):

$$R\&R = \sqrt{(A.V.)^2 + (E.V.)^2} = 0.0297 \quad (26)$$

k) Percentage (*R&R%*):

$$R\&R\% = \sqrt{(A.V.\%)^2 + (E.V.\%)^2} = 22.5701\% \quad (27)$$

INTERPRETATION OF RESULTS

The percentages obtained from the calculation of specific indicators of concern:

- E.V.% – gauge (repeatability),
- A.V.% – operator (reproducibility),
- R&R% – gauge and operator together (repeatability and reproducibility).
- below 10% – resultant error of repeatability and reproducibility (gauge and operator) is acceptable,
- 10–30% – resultant error of repeatability and reproducibility can be acceptable depending on the required accuracy of measurement,
- above 30% – resultant error of repeatability and reproducibility is too high, the system should not be allowed to use.

R&R method concerns the assessment of the measurement system through the analysis of repeatability, reproducibility and dispersion in a situation where measurements were carried out by different operators [15]. In both cases the operators have the biggest impact. This is not surprising because CPAs are manual machines, but the percentage of operator participation suggests that during calibration of given device it should be taken into account as a part of the system. Looking at Table 3 it can be seen, that after connection of the optical probe to CMA the error significantly increased, almost twice. This is related to the fact that probe errors propagate the device error. The device equipped both with contact and contactless probe can be used conditionally depending on what measurement we want to do.

Table 3. Summary of results

Parameter	CPA with switch probe (%)	CPA with optical probe (%)
E.V.%	0.0310	0.2110
A.V.%	13.9950	22.5700
R&R%	13.9951	22.5701

CONCLUSION

Taking into account PN-EN ISO 14253-1 standard (Figure 5) [18], it can be seen that with the increase of measurement uncertainty the field of compliance decreases, which may lead to go beyond the scope of the MPE of measuring device. For comparison the same measurements were carried out with the operators who use the CMA for the first time. AV% reproducibility error was over 18% [10].

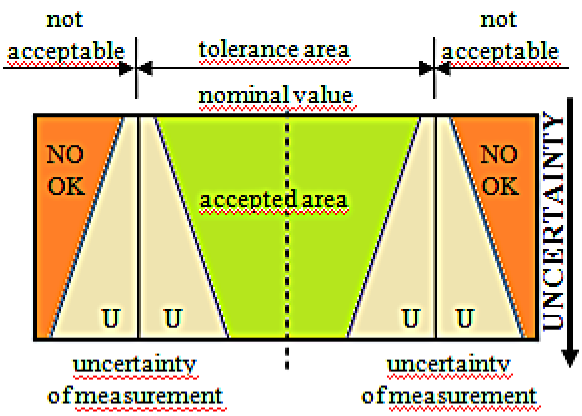

Fig. 5. Measurement uncertainty: the range of uncertainty reduces the fields of compliance and non-compliance [15]

Figure 6 shows how many factors affect the accuracy of measurement on CMA. These devices are largely dependent on the operator, its experience, software experience, manual efficiency, or ways of object attachment. Designated error of reproducibility of the measurement originating from the operator increases the range of maximum permissible error MPE of a measuring device, especially in hand-held devices for measurement, where the influence is dominant [10, 15].

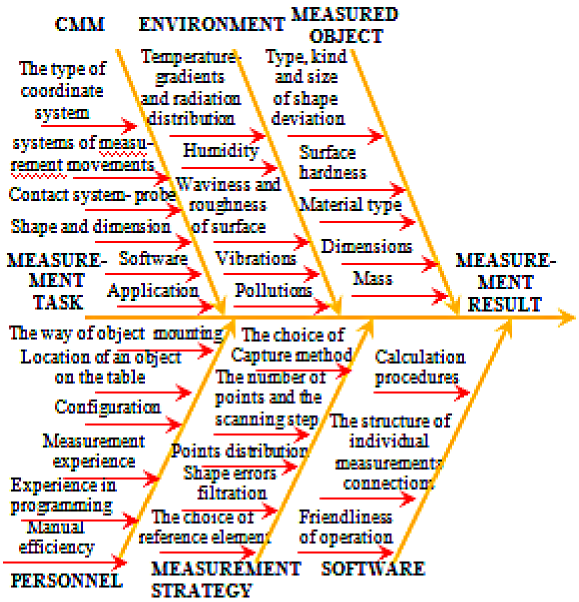

Fig. 6. Ishikawa diagram developed for the process of assessment of measurement error [15]

Effect of operator can be reduced if we assume the measurement strategy that includes access to the measuring object on the same side, without changing significantly the characteristics of the distribution of encoders.

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