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Review Article

COORDIANATE MEASURMENT SYSTEMS CMM AND CMA – CHARACTERISTC AND METHODS OF THEIR ACCURACY EVALUATION

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ABSTRACT
The article presents the conception of coordinate measurement. The characteristic of two systems (Coordinate Measuring Machine – CMM and Coordinate Measuring Arm – CMA) which are based on this measurement is also shown. Further on their construction, working principle, application, advantages and disadvantages are described. Finally, the methods of accuracy evaluation of these devices are presented and compared.

Key words: coordinate measurements, CMM, CMA, accuracy.

INTRODUCTION

Contemporary production technologies characterised by large diversity and small tolerance of manufacturing justifies the use of coordinate measuring technology (CMT), which provides quick and precise measurement of highly complicated products.

Traditional measuring tools were based on direct measuring of one dimension. This generated difficulties in measuring complicated outlines with varied curvature, direct measuring and complicated shapes of objects, what prevented automation of quality control processes. The time of controlling with the use of high number of measuring devices appeared excessively long, in comparison to the production time, what generated additional difficulties in the integration of material circulation and its evaluation. It was only coordinate measuring technology and new computing procedures, based on point identification of the objet that faced the difficulties. From the technical point of view, such measurement is done by Coordinate Measuring Machine - CMM and its newer solution, Coordinate Measuring Arm – CMA.

Selecting the device for a specific measuring task, one should answer a fundamental question if the device is precise enough for this task. Therefore, the procedures for precision evaluation in these machines had to be developed.

THE IDEA OF COORDINATE MEASUREMENT TECHNIQUES

Coordinate measuring technique is characterised by the procedures based on measuring the values of X, Y, Z coordinates for individual points on the surface of the measured object, which are the basis for marking substitute geometric elements such as: point, straight line, circle, sphere, cylinder, cone, ellipsis and torus.

Substitute elements have nominal shapes but their sizes and locations are determined by the coordinated of the measuring points. These elements' features, i.e. circle radius, are the measurements, whereas the distances from individual measuring points from the defined reference elements are shape deviations. The calculations based on this information allow defining the measure – shape agreement of the measured element with the construction requirements [2, 12-14].

One advantage of this technique is the possibility to place the measured object on the measuring table, for which a specialist metrological programme defines a coordinate alignment from the base elements. Although the machine has its own, so called global alignment, it is possible to locate the object in any place (i.e. unambiguous mathematical definition of all six degrees of freedom) and define a new, local system on the basis of the measured or computed typical geometric elements. In this way a coordinate alignment is defined. Its initial point is located in any place and at any angle in the working area [2, 12].

SYSTEMS BASED ON COORDINATE MEASURMENTS

Coordinate Measuring Machine (CMM)

There are many systems based on the idea of coordinate measuring. Undoubtedly, the most precise measuring devises in this class of products are coordinate measuring machines, which allow measuring both simple and geometrically complicated elements, unlike in classical, single-task metrology.

According to the definition given by ISO 10360-1 norm [7]: "CMM is a device whose measuring elements relocate within defined coordinates but at least one of them realises a shift". Shifting directions are marked by X, Y and Z axes of the Cartesian system and define a spatial system of machine's coordinates.

Every typical CMM consists of: a measuring head (a probe), measuring system with an indicating system and a load bearing frame (mechanical). Supplementary systems include: measuring data processing unit, drive system and movable spatial system. Depending on a machine movable element is a table or a gantry.

Measurement is realised by a contact of the point touch probe of the head (most often spherical) with the measured surface. The probe geometry and its characteristics are described in the calibration process that is based on measuring a model element (most often a sphere) before starting the proper measurement [2, 12, 13]. More and more frequently solutions with an optical head can be encountered [3-6].

Four basic types of constructions of this type of machines are known: gantry-type, bridge-type, centliver-type and horizontal arm arm-type. The solutions differ by spatial location of the probing system, what influences such utility parameters as measuring process, durability, precision and area of usability. In case of most universal gantry-type machines the range of measurements is from 400 to 5000 per axis. Bridge type machines have significantly larger ranges reaching even 16 metres [14]. The below picture presents a gantry CMM construction with a movable table, which is situated in the Laboratory of Coordinate Metrology at Cracow University of Technology.

Fig. 1. Coordinate Measuring Machine PMM 12106 from Leitz

Coordinate measurement technique allowed automated quality control in car industry, aviation, shipbuilding and electromechanical industries, in research laboratories and measurement chambers.

Due to their size and complexity of installation process CMMs have long installation process and require special environmental conditions, thus they are very expensive and are used in large production facilities.

Most recognised CMM producers include the following companies: Brown & Sharpe, DEA, Leitz (belonging to Hexagon Metrology) and Carl Zeiss, Mitutoyo

Coordinate Measuring Arms (CMA)

Recently much simpler and cheaper constructions of coordinate measuring arms appeared in the market. They are measuring devices working in coordinate measuring technology. They can be used in small and medium sized companies as well as in laboratories. They can make measurements inside large size buildings or even operate outdoors, what gives the an advantage over CMMs [11]. Unlike coordinate measuring machines, CMAs are mobile devices, what deserves particular attention. Figure 2 presents Romer CMA from Technical Institute in State Higher Vocational School in Nowy Sacz, Poland.

Fig. 2. Coordinate Measuring Arm Omega from Romera

Coordinate measuring arms CMA are systems that do not have shifting units, therefore the definition of coordinate measuring machine quoted by ISO 10360 norm does not cover them. However, considering the method of measuring and the area of use the included into coordinate systems, precisely to the group of hybrid coordinate measuring machines.

The arms usually consist of three simple tubes made of aluminium alloys or carbon fibres connected most frequently with six articulated joints with embedded angular encoders. The encoders are used to detect the angle of arm module rotation [9, 11].

After switching on the arm, the operator must follow the reference points for all the axes by turning each element by a specific angle (analogically to a scanning the reference points before measuring with a typical coordinate measuring machine). The measurement requires a touch between the probe and the measured object. The decision whether the touch was completed or not is made by the operator by pressing a button on the "wrist" of the arm. At the moment of confirming the touch by the operator angular coordinates are read by the measuring systems. The values are computed into Cartesian system values (x, y, z). Conventionally, the measurement is conducted with a rigid styli, i.e. without a converter, however, scanning probes (also optical) and Renishaw electronic touch trigger probe are also used [9, 11].

CMAs can also be equipped with probes of different length with different types of measuring sensors, which can be easily armed due to the fact that they are automatically recognised and do not require calibration each time they are used.

Typical range of measurements is from 1.2 to 4.5 m, yet with sets that enlarge the measurement range large-size objects can also be measured. The sets are composed of three internal base cones or spheres, which are used to complete the transformation procedure during the measurement. This allows enlarging the measurement range without losing the reference to the database of measurements from previous positions of the arm [3-6].

Portable measuring arms are easy to install and operate. They are characterised by good price-efficiency ratio, in comparison to other metrological devices, therefore, they are used in broadly understood measurement industry. Their basic disadvantages in comparison to CMM are lack of automation and smaller measurement accuracy.

The most recognised producers of CMAs are such companies as: CimCore, Faro, Romer, Nikonmetrology.

ACCURACY OF COORDINATE SYSTEMS – METHODS OF EVALUATION

The process of measurement requires its evaluation as the measurement is always inaccurate, what means that the measured distance is always different in comparison to the real value.

The evaluation of measurement accuracy is closely related to the task of machine accuracy evaluation. It is assumed that the error of measurement depends primarily on the accuracy of the measuring tool. Such an approach is justified provided that other causes of measurement error, i.e. measurement strategy, object impact, influence of external conditions, are minimised or corrected [13].

The producers of coordinate systems inform about the specification of their products in different manner, using different methods of accuracy evaluation for different types of measuring machines.

CMA accuracy

Accuracy of coordinate measuring arms is most frequently defined according to the tests included in American norm ASME B89.4.22 [1], and coordinate measuring machines in the guidelines included in the norm ISO 10360-2 [8], VDI/VDE 2617 guidelines [16] and CMMA [15]. The guidelines differ in terms of methods of measurement in tests, number of measurement points, the type of standards and their location in the measuring area of the machine [9, 10].

American norm ASME B89.4.22 advices using three types of accuracy tests (marking a, B, C was interoduced by Cim Core company):

- test with a sphere (so called A test),
- single-point test (so called B test),
- volumetric performance test (so called C test).

The aim of test A is to evaluate the measuring probe by measuring a sphere sized 10-50 mm with 9 recommended probing points and the method of calculating the error as the difference between the diameter of the measured sphere and the nominal diameter of the model sphere.

The arrangement of probe points on the sphere is presented in the below figure.

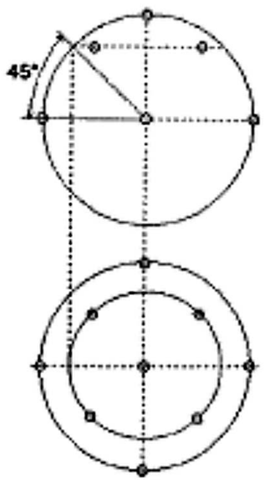

Fig. 3. The measurement points arrangement on the sphere standard according to ASME

Test B (single point test) is performed in order to check if a given measuring arm is capable of obtaining similar coordinates of measured points while measuring theoretically the same point in the measuring area from multiple approach directions of the arm. In other words, the tests defined the repeatability of measuring the location of a point in the measuring area of the arm.

B test is conducted on a point standard in a form of an inside cone, which if fixed to the measuring table. The measurement is performed for three points in the measurement space: first – in the distance of 20% of the arm's length; second – in the distance between 20% and 80% of arm's length, third - in the distance over 80% of arm's length. In each of these locations 10 measurements must be performed. For each of the positions maximum deviation is selected from averages coordinates of the point.

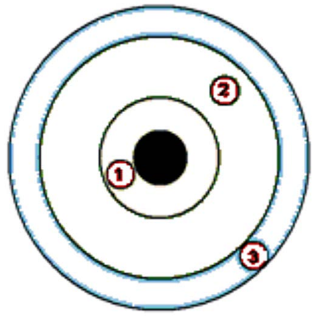

Fig. 4. The position of standard in measurement space of the measuring arm: 1 – 0÷20% , 2 – 20÷80%, 3 – 80÷100% measuring arm lengths [10]

C test (spatial length test) is aimed at defining precise linear length of the arm in its measurement space. Recommended model is a straight edge with three conical holes or spheres at its ends which define two certified lengths: shorter – 50-75% of arm's length and longer – 120-150% of arm's length.

The test is performed for 20 locations of the standard in the measurement space of the arm. 4 vertical and 6 horizontal positions and 10 at 45^o angle. The measurement error is calculated with the difference between the measured and nominal value. Undoubtedly, the advantage of this test is that the result of the measurement is traceable to the unit of length – meter – and allows predicting device performance during similar measurements.

Producers present the arm accuracy in a form of a table with a given range and accuracy according to the above tests. The below table presents technical specifications of Romer arms [5].

CMM accuracy

ISO 10360-2 norm recommends performing two types of accuracy tests for CMMs

- Volumetric probing uncertainty test (P test),
- Volumetric Length Measuring Uncertainty (E test).

Table 1. The accuracy of Measuring Absolute Arm from Romer

	Model	Measurement range	Point repeatability	Probic volumetric accuracy	Arm's weight
Series 73	7315	1.5 m	+/- 0.025 mm	+/- 0.037 mm	7.1 kg
	7320	2.0 m	+/- 0.030 mm	+/- 0.042 mm	7.4 kg
	7325	2.5 m	+/- 0.038 mm	+/- 0.051 mm	7.7 kg

P test corresponds to A test for arms. The difference lies in the number of probing points on the surface of a sphere or a model ring (25 in ISO 10360-2) and the method calculating the error.

A sphere with the nominal size between 10 mm and 50 mm must be measured in 25 points equally distributed on the surface of at least half of the sphere. The distribution presented in fig. 5 is recommended. With the data from 25 measurements one must calculate an associated item, a sphere with the smallest squares method, according to Gauss. Then probe error is computed. It is equal to the range of deviation of 25 lengths of radiuses, calculated according to Gauss's method $R_{max} - R_{min}$ [4].

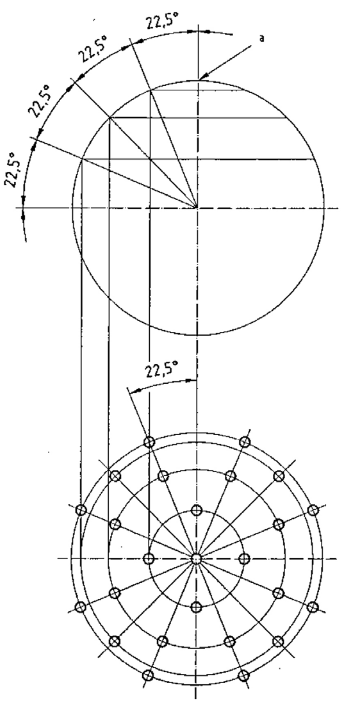

Fig. 5. The measurement points arrangement on the sphere standard according to ISO 10360-2

E test (Volumetric Length Measuring Uncertainty) corresponds to C test (length spatial test). Both tests show linear accuracy of a machine in its measuring space, on the basis of measuring a given length. The difference lies in the recommended model (according to ISO10360-2 they must be calibrated length models or a set of 5gouge blocks) and a method of placing the models in the machine's measuring space in and number of length measurements [9].

According to ISO 10360-2 norm the length model should consist of 5 lengths; the longest one should not be smaller than 66% of the space diagonal of the cuboid in the measuring volume of the machine. Each of 5 blocks must be measured three times in 7 positions, what makes length 105 measurements in the machine measuring volume. For each of the measurements length measuring uncertainty is calculated by subtracting the calculated value and the proper length of the model. Then the values of all errors are presented on a graph. The error value should not exceed the threshold defined as *maximum permissible error* MPE of the machine during length measurement. In most measuring devices the error has a linear form. Defining permissible values for threshold errors is one of the basic tasks in the process of machine calibration.

Maximum permissible error is most frequently expressed as

$$MPE = A + L/K$$

where: A – a constant describing the share of random errors in micrometers,
K – dimensionless constant describing the character of changes in systematic errors,
L – length of the part being measured.

The diagram presents an example of Volumetric Length Measuring Uncertainty for CMM PMM 121060 (Fig. 6).

B test (single point test) does not have its counterpart in European ISO norm.

The procedures implemented by ISO 10360 norm refer primarily to the evaluation of length measurement and the probing head error. Broader approach for evaluating CMMs is recommended by VDI/VDE and CMMA. These methods are called analytic ones,; they allow detecting all geometric component errors in CMMs, such as positioning, rotation, straight-line and perpendicularity errors, most often with the use of laser

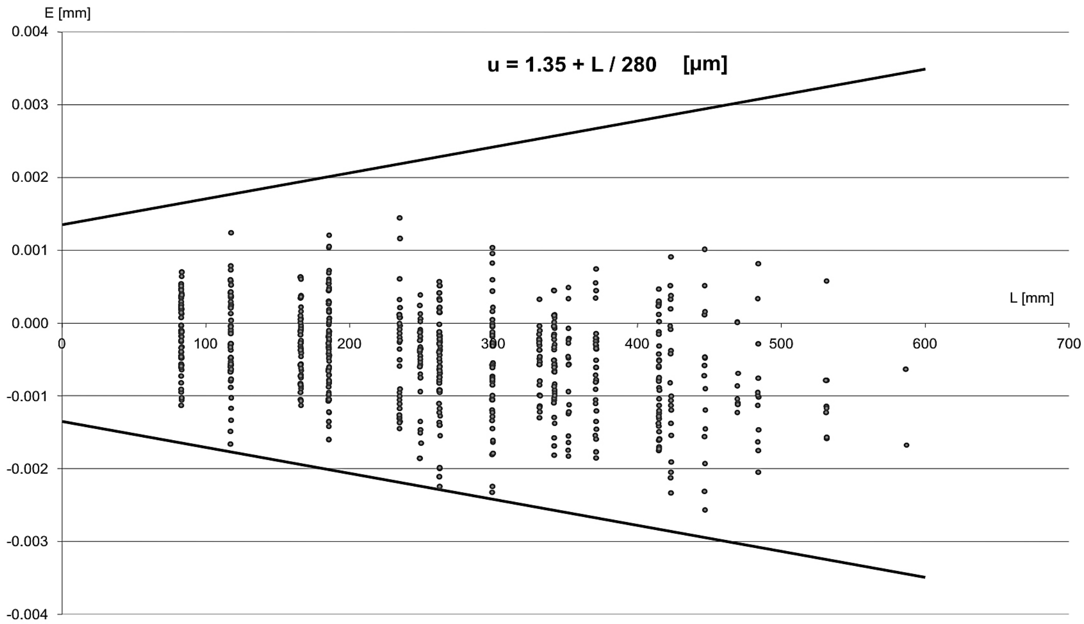

Fig. 6. The maximum permissible error of length measurement for CMM PMM 121060

interferometer [14]. CMM's geometric errors defined in selected points should not exceed maximum permissible error. These methods are very complex and rarely used, therefore, they are not presented in this article.

CONCLUSION

The above paper presents the idea of coordinate measurements. Two coordinate systems were analysed (CMM and CMA) for their construction, measuring techniques and area of interest. The procedures of their accuracy evaluation were also presented. The defined device accuracy can be significantly different from the accuracy of the measurement task to be performed if the measurement errors, i.e. measurement strategy, object surface and geometry, the influence of external conditions, are not minimised or corrected. As the measuring services are required to provide complete information concerning inaccuracy level of individual measurements, further considerations should include a broad discussion of measurement accuracy evaluation in these systems.

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