Accuracy increase of the coordinate measurement based on the model production of geometrical parts specifications

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Abstract. There is a relationship between the service properties of component parts and their geometry; therefore, to predict and control the operational characteristics of parts and machines, it is necessary to measure their geometrical specifications. In modern production, a coordinate measuring machine is the advanced measuring instrument of the products geometrical specifications. The analysis of publications has shown that during the coordinate measurements the problems of choosing locating chart of parts and coordination have not been sufficiently studied. A special role in the coordination of the part is played by the coordinate axes informational content. Informational content is the sum of the degrees of freedom limited by the elementary item of a part. The coordinate planes of a rectangular coordinate system have different informational content (three, two, and one). The coordinate axes have informational content of four, two and zero. The higher the informational content of the coordinate plane or axis, the higher its priority for reading angular and linear coordinates is. The geometrical model production of the coordinate measurements object taking into account the information content of coordinate planes and coordinate axes allows us to clearly reveal the interrelationship of the coordinates of the deviations in location, sizes and deviations of their surfaces shape. The geometrical model helps to select the optimal locating chart of parts for bringing the machine coordinate system to the part coordinate system. The article presents an algorithm the model production of geometrical specifications using the example of the piston rod of a compressor.

Key words: geometrical specifications, coordinate system, informational content of part component, coordinate measuring machine.

1. Introduction
The widespread use of CNC machines in the production of machine parts and devices increased the accuracy of the products, which increased the requirements for the control accuracy. There is a relationship between the service properties of component parts and their geometry; therefore, to predict and control the operational characteristics of parts and machines, it is necessary to measure their geometrical specifications. At the present time, a coordinate measuring machine (CMM) is the advanced measuring instrument of the products geometrical specifications. Most of control operations of complex shape modern products in science absorbing industry and high technologies can be carried out only on the CMM because of strict requirements for the measurement accuracy and efficiency of its implementation.

2. Statement of the problem
A large number of publications of leading scientists such as A.Yu. Kasparaitis, V.G. Lysenko, V.L. Solomakho [6], R.G. Wilhelm and K.D. Summerhays [5] are devoted to the development of the process models of coordinate measurements and studies of measurement errors in measuring
geometrical specifications of component parts. The analysis of publications has shown that during coordinate measurements the problems of choosing locating chart of parts and coordination have not been sufficiently studied.

During measurements on a CMM measuring procedure can be divided into the following sub-procedures:

1) selection and production of the locating chart of parts for specifying the location of the part coordinate system in the CMM coordinate system;
2) selection of the necessary and sufficient number of measurement points;
3) identification of the coordinate system for performing auxiliary constructions, production of auxiliary systems which are necessary for the geometrical specifications of auxiliary bases sets and executive and free surfaces.

The selection of locating chart is the selection of the set of elements, mathematically representing physical surfaces which parameters are calculated based on the assumption of finite set of measured control points. The main elements are "straight line", "circle", "plane surface", "cylinder", "sphere" and "cone". Thus, the primary task is to select the most optimal locating chart that will provide the necessary positional accuracy and specify a coordinate system. However, the selection of the elements for locating is not always obvious; therefore, in order to increase the results reliability it is recommended to construct a geometrical model of the measurement object.

3. Theory
The construction of the analyzed part geometrical model allows us to visually reveal the relationship between the coordinates of the deviations in the location, size and shape of the parts surfaces and to develop an optimal measurements methodology. During the development of the coordinate measurements object geometrical specifications model the leading role is played by the generalized coordination which is materialized by a set of principal assembly bases. The accuracy of part positioning in the space is achieved by limiting the item by six degrees of freedom: three linear and three angular motions.

Depending on the surfaces type of the mating elementary items (plane, sphere, cylinder, cone, tore, multi-plane surface), sizes and number of elementary items and mating are classified into seven classes according to the number of degrees of freedom (from zero to six) which are composed of linear (l) and angular (r) constraints (c) [3]. According to [2], the sum of the degrees of freedom limited by the elementary item is called "informational content". Thus, during constructing the coordinate system of a part, it should be based on the element informational content. The informational content of each element determines the number of linear and angular coordinates that need to be normalized for its identical positioning in the part coordinate system [3]. The classification of elementary items by information content which allows determining the information content of an element more clearly depending on its mating pair is given in [3].

The development of a measurement object geometrical model is carried out using the following algorithm [1].

1. Identification of the measurement object coordinate system.

As a measurement object, consider the piston rod of the compressor. The piston rod transmits the force from the crankshaft to the piston and serves as the main link for converting the rotational motion of the crankshaft into reciprocating motion of the piston. The piston rod small end is connected to the piston via the piston pin; the piston rod big end serves to connect it to the crankshaft crank (figure 1).
The set of principal assembly bases forms a rectangular coordinate system 0XYZ and determines the position of the piston rod in the compressor:

A) the base symmetry axis of the inner tubular element A4 in the piston rod end with informational content of 4 limits the piston rod in two linear movements, perpendicular directions to the axis and two angular rotations which are mutually perpendicular to the axis A4 and forms the coordinate axis Z4 with the informational content of 4 of the rectangular coordinate system;

B) the base plane of symmetry B1 of the piston rod end prismatic element with informational content of 1 limits the piston rod in one linear motion along the axis Z4. The point of the base B1 symmetry plane intersection with the coordinate axis Z4 forms the origin 0 of the rectangular coordinate system;

C) the base axis of the inner tubular element C1 in the piston rod end has informational content of 1, deprives the piston rod of rotation around the axis Z4 and determines the direction of the axis X2 with the informational content of 2 of the rectangular coordinate system;

D) the axis Yθ has zero informational content, because its direction does not need an additional base which is the perpendicular reconstructed from the origin θ to the coordinate plane Z4X2, in which the axes Z4 and X2 are located with a general informational content of 6.

2. Determination of the geometrical specifications of the measurement object

The rectangular coordinate system finally takes the form 0X2YθZ4 taking into account the informational content of the axes. The geometric model of the piston rod is constructed in three projections on the contours of the nominal piston rod for their comparability. The constructed image of the generalized coordinate system 0X2YθZ4 is similar to the construction on the nominal sketch of the piston rod. Let us define the geometrical specifications of the principal assembly base, starting with the base A4, which has the greatest informational content. The base A4 does not have unused degrees of freedom because the maximum informational content of a tubular element is four (2t + 2r = 4c).

All four degrees of freedom are spent on materializing the coordinate axis Z4, providing informational content of 4 for the axes. The distance between the generators of the superimposed cylinder determines the first geometrical adjective of the element diameter D1+ED1, which will have a primary sizing error. Representing from the element body the real shape of the element surfaces with a wavy line, we can find the second geometrical adjective of the elementary item A4 these are the primary form errors EF1. The form deviations of the base hole are included in the diameter deviations ED1 and increase the diameter due to the positive sign of the deviation.

Let us now continue with plain base B1. Since the base limits the piston rod of one translational motion 1t along the axis Z4, two angular motions (1t + 2r-1t = 2r) are unused, having maximum informational content (1t + 2r = 3c). Therefore, the base determines the position of the rectangular
coordinate system 0, origin remaining two angular degrees of freedom in the form of primary angular distortions around the axes X2 and Yθ relative to the nominal angle of 90° with the base axis Z4: 90°±AEX2 и 90°±AEY2. The prismatic element has its own width size w2-Ew2, and the primary form errors EF2 of two planes that reduce the width size.

Then, continue with cylindrical base Ci. The base has informational content l1r and limits the piston rod from one angular rotation around the axis Z4 due to losing of own linear degree of freedom l1t on the axis Yθ. The maximum informational content of a cylindrical element is four (2t+2r=4c), therefore, three degrees of freedom remain unused: 1 linear and 2 angular (2t+2r-l1t=l1t+2r). This leads to the formation of the linear coordinate X3±EX3 of the center C3 and two angular distortions 0°±AEX3 and 0°±AEY3 of axis C1 relative to the coordinate axis Z4 with the maximum informational content of 4. The diameter of the element will have a primary size error D3+ED3 and the primary form errors EF3. The length of the element base axis of symmetry Ci is limited by the width size w4-Ew4 of the piston rod end. The action of the base axis extends to the protruding length lP, which is equal to the length of the piston pin. This length determines the maximum X3M and minimum X3L values of the coordinate X3±EX3.

Primary errors of free surfaces can not be found. On the piston rod model, these surfaces are shown in nominal position and of nominal shape relative to the appropriate coordinate system, in which module of elements they work.

The base hole C performs the functions of the main C1 and the auxiliary C4 assembly base, which limits the four degrees of freedom of the connected piston pin. They form an auxiliary coordinate system 0’X’2Y’θZ’4 together with the prismatic element D1 of the piston rod end w2-Ew2.

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**Figure 2.** a) geometrical model of the compressor piston rod; b) indicator of the bases
3. Compiling the matrix of measurement object geometrical specifications.

Table 1. Matrix of piston rod geometrical specifications

| Number and element designation, the center of the element, the reference system | The type, functionality, informational content and maximum informational content of element | Sizes and primary errors in the basic coordinate system | Bases, sizes, permissible error from the detail drawing |
|---|---|---|---|
| 1 | A4 0X2Y0Z4 | Cylindrical main base  
N_{inf} = 2t+2r  
N_{max} = 2t+2r | N_{crd} = 2t+2r \cdot 2t - 2r = 0  
D1 + ED1  
EF1  
RZ1 | A4  
Ø19H7 \{+0.021\}  
\{0.006\} = \{0.006\}  
RZ 3.2 |
| 2 | B1 0X2Y0Z4 | Flat, prismatic main base  
N_{inf} = 1t+θr  
N_{max} = 1t+2r | N_{crd} = 1t+2r \cdot 1t = 2r  
90°±AEY2  
90°±AEX2  
EF2  
w2 - EW2  
RZ2 | B1  
37±0.013  
\{0.006\} = \{0.006\}  
Ø10H6  
RZ 1.6 |
| 3 | C1 0X2Y0Z4 | Cylindrical main base  
N_{inf} = 1r \Rightarrow 1t  
N_{max} = 1t+2r | N_{crd} = 2t+2r \cdot 1t = 1t+2r  
X3±EX3  
0°±AEY3  
0°±AEX3  
D3 + ED3  
EF3  
RZ3 | C1  
0±EZ4 = 0.043 mm  
9±0.011  
RZ 3.2 |
| 4 | C4 0X2Y0Z4 0°X’2Y’0Z’4 | Flat, prismatic auxiliary base  
N_{inf} = 0  
N_{max} = 1t+2r | N_{crd} = 1t+2r \cdot 0k-\theta r = 1t+2r  
w4 - EW4  
0°±EZ4  
90°±AEX4  
90°±AEY4  
RZ4 | C4  
0° | 4. Experimental results

The geometrical model of the compressor piston rod constructed in accordance with the recommendations is shown in figure 1. The hole with diameter D1 + ED1 deprives the greatest number of degrees of freedom – 4 (2 linear and 2 angular displacements) as it can be seen on the geometrical model. Thus, it is advisable to place the origin of the coordinate system in the center of this hole; therefore, to create a reference of a part to the CMM coordinate system, it is necessary to use the plane-cylinder-cylinder scheme. It is recommended to draw the table with a complete account of all bases, sizes and primary errors of the geometrical model (see table 2). This will allow developing the most effective measurement design. Thus, for example, it is more obvious to see that the difference between the values of X3L and X3M will be a deviation from parallelism.

Based on the constructed geometrical model at the KIM-1000 LLC “Lapik”, the following studies were carried out and the following results were obtained:
- angle of axes misalignment is 0°±AEX3 = 0°+0′47″;
- angle of axes misalignment is 90°±AEY3 = 90°+0′3′19″;
- deviation of the hole C4 real center relative to the nominal center C4 0±EZ4 = 0.043 mm;
- angle of axes misalignment is 90°±AEX4 = 89°56′08″=90°-3′52″;
- angle of axes misalignment is 0°±AEY4 = 0°+0′48″;
- angle of axes misalignment is 90°±AEY4 = 89°52′00″=90°-8″.

These primary errors can significantly affect the accuracy of the measurement result. However, without the model production of the geometrical specifications of the part, in most cases, the primary
errors are not taken into account which leads to a decrease in the measurement accuracy. In support of this theory, studies were carried out to measure the coordinate $X_3$ of the axis of the piston rod base hole $B_1$ with a permissible error of ±0.013 mm (see table 2).

| The origin of the coordinate system at the center of the axis of the inner tubular element $B_1$ (detail drawing) | The results, mm | The origin of the coordinate system at the center of the axis of the inner tubular element $A_4$ (geometrical model) | The results, mm |
|-------------------------------------------------|---------------|-------------------------------------------------|---------------|
| $X_{3M}$ | 37.319 | $X_{3M}$ | 37.299 |
| $X_{3L}$ | 37.317 | $X_{3L}$ | 37.294 |

Thus, the difference between the results was 0.020 mm for the maximum value $X_{3M}$ and 0.023 mm for the minimum value $X_{3L}$. It is more than 75% of the permissible error for the coordinate size $TX=0.026$ mm.

5. Discussion of the results
The following statements are suggested for discussion:
- during coordinate measurement it is necessary to take into account the informational content of the elementary items and coordinate axes that allow us to identify coordinate systems without redundancy of the basing and helps identically specify the position of the connected part using three linear and three angular coordinates;
- the geometrical model construction of the coordinate measurements object taking into account the informational content of coordinate planes and coordinate axes increases the accuracy of the measurement results, since it allows to develop an optimal scheme of coordinate measurements.

6. Conclusions
The proposed approach for constructing geometrical models of parts based on the informational content of coordinate planes and coordinate axes for coordinate measurements makes it possible to scientifically and reasonably increase the reliability of measurement results and develop the most effective measurement scheme.

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