Problems and ways to reduce measurement uncertainties in evaluating the geometric assembly parameters of gas turbine engine assemblies

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Abstract. The measurement results of the geometric parameters of the parts play an important role in the assembly process of gas turbine engine assemblies. The article provides an analysis of the problems of reducing the measurement uncertainties of gas turbine engine parts. Significant uncertainties in the measurement of the geometric parameters of gas turbine engine low-rigid parts are caused by uncertainties in the processing algorithms for measured data. The ways of improving the processing algorithms for measured data are proposed, they are based on taking into account the contact of the surfaces during assembly and the rigidity of the measured parts. Theoretical and experimental studies of the uncertainties in the processing algorithm for measured data are carried out, using the example of measuring the geometric parameters of a low-rigid part of the "spacer" type. Comparison of three variants of the processing algorithms for measurement results are presented.

1. Introduction
Coordinate measuring machines (CMMs) are widely used to control the geometric parameters of parts in aircraft engines. The uncertainties of coordinate measurements depend on many factors, their classification is given in [1,2]. In coordinate measurements, along with instrumental uncertainties, there are uncertainties that are caused by algorithms for processing the measured data [3]. The noted uncertainties can be called methodological or depending on the algorithms for processing the measurement results. Often, the values of methodological uncertainties can be impotent in case of measuring critical parts of a gas turbine engine, since they are characterized by relatively high accuracy and low rigidity.

The current work is devoted to the study of uncertainties that arise due to the use of measurement data processing algorithms. A large number of measurement data processing algorithms are based on the use of the least squares method (LSM) [4,5]. Determining the parameters of the replacement elements (planes, cylinders, etc.) using the least squares method involves averaging the geometric deviations. Another possible method is "minimum-maximum".

The mating of parts surfaces is carried out based on their contact by a set of points, during which a certain contact spot is created and the relative position in the assembly unit is determined. In its turn, the relative position of the parts affects greatly the assembly parameters of the product. The procedure and methods for assessing the geometric parameters of parts and assembly units are provided for in standards [6,7]. These standards take into account the mating surfaces of parts or assembly units with
nominal surfaces. When normalizing the accuracy of the shape and location of surfaces, the so-called adjoining surface is used. For rotor and stator parts of a gas turbine engine, an adjoining surface for the end faces and an adjoining cylinder for cylindrical surfaces are used.

Algorithms used in most cases based on the use of the least squares method (LSM), they determine the sizes and positions of middle, but not adjoining surfaces. If the deviations of the shape of the measured surfaces are significant in comparison with the tolerance on the measured parameters, then the discrepancies between adjoining and middle elements are significant. For this reason, a discrepancy arises between the measured and actual values of the measured geometric parameters. The use of algorithms based on the LSM is relevant when measuring rigid parts for which the shape deviation is not significant.

A significant number of GTE parts are represented as a variety of hollow shells with low rigidity, due to the strict requirements for their mass. The tolerance for deviations in shape and location of the surfaces of low-rigid parts of a gas turbine engine is in the range from 0.005 to 0.05 mm.

In this regard, the urgent task is to study the measurement uncertainties of geometric parameters when using various algorithms for processing the measured data. Another important task is to identify ways to improve the algorithms for processing measurement results to increase their reliability.

Studies of measurement uncertainties at the CMM are carried out using an approach called the “virtual coordinate measuring machine”. To implement the above approach, it is necessary to have a mathematical model and software algorithms for coordinate measurement process that can realize this model. A set of mathematical models and software algorithms form the so-called VCMM [8]. Many works have been published on “virtual coordinate measuring machine”, where simulation is used including the Monte Carlo method [9-11].

One of the areas for improving data processing algorithms is the development of models that allow to determine the parameters of contact interaction of surfaces and their interfaces and can also take into account the rigidity of the assembled parts. For assembly simulations of rigid parts, models based on the solid body hypothesis, that is, the T-Map model [12-14], are used. The estimation of the parameters of low-rigid parts mating during assembly is carried out using a model based on the surface representation of Scin objects [15,16], in which the deviation region is not limited to a solid body.

2. Theoretical and experimental studies of error of measured data processing algorithm

Figure 1 shows a block diagram of the implementation of theoretical and experimental studies of uncertainties in the algorithms for processing the measured data using the example of measuring a low-rigidity part of the "spacer" type. The given block diagram includes three enlarged blocks corresponding to the considered options for processing measurement results. The first block includes the processing of the measured data using the least-squares method. The second block provides for considering the nature of parts mating, using a finite element model of assembly of the measured part and a simulator of the mating part. The third block contains the processing of the measured data by the method of the maximum inscribed circle and implements the method of adjoining surfaces. Let’s consider the content of each of the blocks.

Measurement of base (datum) and control surfaces on a CMM. Part surfaces were measured on a DEA Global coordinate measuring machine (CMM) with PC-DMIS software. The part was fixed between two prisms and one small rectangular prism, to ensure the accessibility of the probe system. The length of the stylus was 40 mm and the diameter of the stylus was 4 mm.

The calculation of geometric parameters in the PC-DMIS software package uses the LSM. At step 1.1, the geometric parameters of the replacement elements are calculated. The algorithm for finding the parameters of the replacement plane can be represented by the following system of equations:

\[
\begin{align*}
A_p \cdot x_p + B_p \cdot y_p + C_p \cdot z_p + D_p &= 0 \\
\sum_{i=1}^{n} (z_i - z_p)^2 &\rightarrow \text{min}
\end{align*}
\]  

(1)
where \( A_p, B_p, C_p \) - coefficients that specify the angular position of the plane; \( x_p, y_p, z_p \) - actual coordinates of points. The algorithm for finding the parameters of the replacement cylinder can be represented by the following equation [17]:

\[
\sum_{i=1}^{m} \left[ (X_i - C)^2 \left( I - WW^T \right) (X_i - C) - r^2 \right]^2 \rightarrow \min, \tag{2}
\]

where \( x_i \) - is the coordinate of the cylinder point \( (x_i, y_i, z_i) \); \( C \) - coordinates of the point on the axis of the cylinder; \( W \) - is the directing vector of the cylinder; \( I \) - is the identity matrix; \( r \) - is the radius of the cylinder.

At step 1.1, the PC-DMIS software generates the part coordinate system based on the calculated geometric parameters of the replacement elements and mathematically correlates it with the machine coordinate system.

At step 1.2, the PC-DMIS software mathematically aligns the parts by forming a coordinate system based on the geometric parameters of the replacement elements.

Step 1.3 forms the calculated geometric parameters of the part measured surfaces. The results of the calculation of geometric parameters are presented in table 1.

The stage of preliminary processing of the measured data. The measured points of the parts can have “outlying” values due to the presence of contaminants on the surface, incorrect operation of the sensor, etc., the value can be on average from 5 to 30 microns and higher. To filter such values on cylindrical and flat surfaces, you must first enter the replacement elements in the array of measured points: respectively, “cylinder” and “plane”, using the least squares method. Deviations from replacement elements are filtered using the moving average method [18]. Points with deviations above 15 microns are removed from the array.

Block 2 Data measurement taking into account the nature of parts mating. At step 2.1, using the developed application [19] and the processed measured data, a model of the part with real surfaces is created using a technique that includes three stages.

At the first stage, a nominal solid body model is built. At the second stage real surfaces are built automatically by a finite set of measured points. The third stage carries out the restructuring of the nominal surfaces in such a way that they limit the contour of the part and form a single closed body.
The part from the NX CAD package is saved in the *.x_t format and the geometry is imported into the CAE system. A detailed description of building of parts real surfaces based on measurements in [19]. Figures 2a and 2b respectively show the deviations in the shape of cylindrical and end surfaces.

![Figure 2. Cylindrical surface deviations - (a); b End surface deviations - (b).](image)

At step 2.2, in the NX software package a simulator of the mating part is created; its mating cylindrical surface is formed taking into account the provision of an interference fit with the base surface A of 0.04 mm. The diameter of the mating nominal cylindrical surface of the simulator is determined as the sum of the interference and the average diameter of the surface A spacers.

![Figure 3. Assembly scheme with a simulator of the mating part - (a); basing spacers on metrological parallelepipeds - (b).](image)

At step 2.3, the CAE Ansys package was used to simulate the assembly process of the “spacer” with the response part. The assembly diagram of the “spacer” with a simulator of the mating part is shown in figure 2a. The simulation technique is presented in [20].

Stage 2.4. Prediction of geometric parameters is carried out as described in detail in articles [20]. The results of the predicted geometric parameters are presented in table 1.

Block 3. Processing of measured data by the method of the maximum inscribed circle. At step 3.2, the coordinates of the center point of the inscribed circle of the base surface A are defined. This is necessary to move the coordinate system of the part into the center of the inscribed circle.

At step 3.3, the simulation of part location on the turntable is performed. The base end surface C is mounted on three metrological parallelepipeds fixed on the surface of the turntable. Then, the axes of the base cylindrical surface A and the axis of the table are aligned. The alignment of the part and the
axis of the turntable is carried out base on measurements of the base surface A runouts. The installation diagram and the plot of the interface between the spacer and the surfaces of the parallelepipeds are presented in figure 2b.

At step 3.4, the calculation of the measured geometric parameters is performed, the results are shown in table 1. In order to study the convergence of the results, the geometric parameters of the “spacer” are measured on a universal measuring instrument, including a turn table 1, metrological parallelepipeds and dial indicators.

3. Results
The results obtained for the three versions of the algorithms for processing the measured data details "spacer" are presented in table 1.

Table 1. Theoretical and experimental measurement data of geometric parameters of the spacer part.

| №  | Option for processing measurement results / used measuring instrument | Parameter, mm. | The distance between the ends of C and D |
|----|---------------------------------------------------------------------|-----------------|----------------------------------------|
|    | Processing measured data                                           | Radial runout, B | End runout, D                          |
| 1  | Least square method                                                 | 0.069           | 0.086                                  | 90.957 |
| 2  | Forecasted geometric parameters                                     | 0.064           | 0.091                                  | 90.965 |
| 3  | Modeling measurements on a universal measuring tool                 | 0.071           | 0.102                                  | 90.946 |
| 4  | Universal measuring tool                                            | –              | 0.09                                   | 90.55  |

Tolerances for radial and end beats with controlled surfaces B and D in accordance with the drawing details are 0.03 mm. It can be seen from the results that the differences between the methods obtained by LSM and using the proposed method for processing the measured data is 5 μm., In relation to the tolerance of the controlled parameter is 17%.

4. Conclusions
Alternative algorithms for processing of measurement results were developed based on the best compliance with the generated dimensional ties during assembly of units. The discrepancies between the measurement results obtained using the proposed and traditional LSM algorithms are significant. This suggests that when measuring parts having significant shape deviations, it is necessary to take into account the nature of the generated dimensional ties in the assembly unit.

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