Assignment of dimensional accuracy parameters of parts during assembly of aircraft repair engines

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Abstract. The article considers the existing models and methods of analysis and synthesis of geometric tolerances of products with assembly dimensional chains. There proposed a method to define the rational tolerances for the linear dimensions of parts during assembly of aircraft repair engines. The developed methodology is based on the use of computer simulation technology for assembling the assemblies with actual geometry, and a model for calculating the labor input and cost of parts manufacturing based on the assigned tolerances. The main advantages of the technique are considered by the example of assigning rational tolerances to the parts of the repair rotor of a high-pressure compressor, which have the greatest influence on the functional characteristics of the aircraft engine. The results of the relationship between the dimensional accuracy parameters of parts and assembly parameters are presented, and the dependence of the cost of refinement or manufacturing of the part on the assigned tolerance is obtained.

1. Introduction

At the stage of troubleshooting a repair aircraft engine, parts are identified that require their refinement or replacement. The designer is faced with the task of assigning geometric tolerances to the dimensionally accurate parameters of parts or assembly units, which is often performed on the basis of experience or on the basis of technical and economic calculations. In the second case, the designer is faced with the task of rationally resolving the contradictions between operational requirements and technological capabilities of production.

The geometrical parameters of the manufactured parts differ from the nominal geometry formed in computer-aided design (CAD) systems. The differences are due to the accumulation of deviations during the production (technological) process, which are unavoidable during the machining of parts [1]. In turn, the geometric deviations of the parts affect the assembly parameters and the functional characteristics of the product. The task of synthesis of tolerances is associated with the study of the influence of geometric deviations of parts on the geometric accuracy of the assembly and functional requirements [2]. Geometrical deviations of parts should be limited by tolerances to ensure a certain level of product quality. Not optimally assigned tolerances can cause assemblability problem and failure of the assembly or the entire product. Often, the assigned tolerances are not optimal in terms of the available technological capabilities of the equipment or not rational in terms of parts manufacturing cost with the defined tolerances. Tighter tolerances and tight control result in high production costs, which makes products not competitive in the global market.
Existing methods for calculating dimensional chains do not fully allow for the effect of actual linear-angular dimensions, deviations in the shape and location of surfaces, contact and volumetric deformations of parts on the closing links. There is a need for the development of models and methods allowing to take into account the influence of these factors, as well as to estimate the costs of parts manufacturing, taking into account the technical capabilities of production and the tolerances assigned by the designer.

In this regard, the urgent task is to develop models and techniques that allow to assign optimal tolerances and control the dimensional and accuracy parameters of parts, as well as provide a compromise between quality and cost of the product. The use of the above models and techniques will reduce or eliminate the risk of defects and unwanted production deviations, as well as reduce production costs.

2. Methods and models of analysis and synthesis of tolerances
To improve the functional characteristics and quality of the product, over the past decades, several methods and models for the analysis and synthesis of tolerances have been developed. The main models of tolerance analysis are Deviation Domains [3], T-Maps® [4] or Skin Models [5], GapSpace [6], their approach is based on vector chains; and they are widely used in scientific and industrial practice [7]. The main idea of this approach is that the corresponding quality characteristics are described by the so-called “functional key characteristics” (FKC) [8], which are influenced by various factors. Given the sophistication of modern aviation products, the designer must deal with several different FKCs, which are often interconnected. This means that changing one tolerance value affects more than one FKC.

In the aircraft engine industry, tolerance synthesis is a major issue in the design process or in the development of engine repair technology. A large number of studies have been devoted to the development of tolerance synthesis [9,10,11,12,13,14]. Typically, the synthesis of tolerances is determined by the specification model. Similarly, some tolerance syntheses are developed based on the tolerance zone approach by Fleming [13] and Robinson [14]. Some others are based on variational geometry [15, 16, 17]; finally, some are based on the vector tolerance [18, 19, 20].

3. Methodology for assign of rational tolerances
The paper proposes a methodology for assigning rational tolerances on dimensional accuracy parameters of parts when assembling repair aircraft engines. The proposed methodology uses an assembly computer model for assemblies (rotors) and costs estimation models for parts improvement or manufacturing with assigned tolerances. The technique is presented as a flow chart in figure 1.

Repair of a gas turbine engine is carried out in accordance with the repair technology. The engine undergoes a series of events related to input control. After that, the product received in the assembly shop must be disassembled according to the repair technology, washing and fault detection. After troubleshooting, an act of conformity of the parts with the technical requirements (or conditions) is concluded.

The developed technique includes two enlarged blocks: simulation of unit assembly and cost estimation. Let’s consider the content of each block.

The unit assembly simulation includes the measurement of contact and control surfaces of parts on coordinate measuring machines or on universal measuring instruments. It is necessary to take into account the factors affecting the accuracy of measurements in the measurement process [21]. Inaccurate measurement of mating and reference surfaces of parts can lead to errors in building of the real models, that is not acceptable when assessing the accuracy of assembly parameters.

The data obtained are necessary for building valid models of parts. The building of real models is described in detail in [22]. The next step is the determination of the parts or parts that have the greatest impact on the monitored assembly parameters and on the functional characteristics of the repair product. The identification of these parts is carried out on the basis of the analysis of the results of prediction of the assembly parameters of units (or products). Assembly simulation is performed with
nominal models. The stages of forecasting and determining the actual values of geometric parameters are presented in [23,24].

Figure 1. The flowchart of the method for assigning rational tolerances to the linear dimensions of parts.
After analyzing the estimated assembly parameters, the parts or the part with the greatest impact are identified. The next step is the creation of valid models of parts with various options for sizes and technical requirements. Sizes and specifications are assigned from the tolerance limits for dimensional accuracy parameters. The limit boundaries of the assigned tolerance are formed from the technical requirements of the product or technical and economic calculations.

The cost calculation consists of several stages. At the first stage, data are generated on the production capabilities of the enterprise, including information on the technological equipment of machine shops. At the second stage, the calculation of the labor input for parts manufacturing with the assigned tolerances is performed. The labor input of machining is characterized by computer numerical control (CNC) machining time:

$$T_{mt} = T_0 + T_{n.m.t} + T_{i.m.s} + T_{r.a.p}$$

where $T_0 = \sum T_{0j}$ – principal time for machining operation, min; $T_{0j}$ – principal time transition $j$ processing elementary surface;

$$T_{0j} = \frac{(L + l)i}{ns} = \frac{(L + l)}{S_m}$$

$T_{n.m.t}$ – nonproductive machine time, min; $T_{i.m.s}$ – time for machine servicing, min; $T_{r.a.p}$ – relaxation allowance and personal needs, min; $L$– length of the processed surface, mm; $l$ – cutting and overrun length of the tool, mm; $i$ – number of working strokes; $S_m$ – minute feed mm/min; $n$ – rotational speed of the workpiece or tool, rpm; $s$– feed per revolution, mm/rev.

Important values in determining the principal machining time are the values $l$, $i$, $s$. When designing a machining process, allowances must be assigned that ensure the accuracy of the machined surface. Most often, existing methods for calculating allowance do not provide the specified accuracy. Basically, allowances are prescribed from production experience.

In aircraft engine manufacturing, tolerances on the geometric parameters of parts are comparatively less than in conventional engineering. The decrease in the number of units of tolerances of parts leads to an increase in allowance for technological operations, which causes an increased consumption of materials and energy, the introduction of additional technological transitions. All these increases the labor input, cost increase for parts manufacturing, and therefore reduces the competitiveness of the entire product as a whole. The cost of machining is determined by the following formula:

$$C_{sm} = C_{ch} + C_{h.m.r} + I_{sm},$$

where $C_{sm}$ – the cost of machining, rub.; $C_{ch}$ – hourly machine rate, rubles/hour; $C_{h.m.r}$ – estimated time for machining of the workpiece, hour; $I_{sm}$ – tooling investment, rub.

After calculating the cost of manufacturing the part or parts, the assembly parameters are estimated using valid models that are generated from the measurement results, or from the arrays of geometric deviation parameters of the options considered. From the obtained results of the assembly parameters and cost, a rational option is selected that satisfies the given requirements.

At the next stage, after determining the cost and assembly parameters, research for the rational position of the parts in the product is performed to compensate for the influence of deviations in the shape and location of the surfaces of the parts on the assembly parameters of the assembly that arose during manufacturing. In addition to the nominal positions, various angular positions of the parts in the assembly relative to each other are considered in order to determine the rational angular position of the parts in the product.
At the final stage of the developed methodology, rational tolerances on the linear dimensions of parts or a part are determined that satisfy the specified functional characteristics of the product and are optimal in terms of production costs.

4. An example of the application of the methodology on the assembly unit of the GTE rotor

Let’s consider the application of the proposed methodology as an example of an assembly unit included in the rotor of a high-pressure compressor (HPC), which consists of a shaft, a disk of the 11th stage, a spacer, an intermediate ring, a path ring, a disk of the 12th stage. The main assembly parameters that determine the functional characteristics of the product are the end and radial runout of the control surfaces of the disk of the 12th stage. The maximum boundaries of the assigned tolerances for dimensional accuracy parameters of parts are obtained from the design documentation for the product. In accordance with the developed methodology, parts were measured on a coordinate measuring machine and their actual models were created based on the measurement results.

To determine the parts that have the greatest impact on the assembly parameters of the assembly, a simulation of three scripts was performed. The first script is the assembly of the following parts: 11th stage disc, spacers, intermediate ring. Part modeling was performed in such a way as to ensure maximum interference \( n_{\max} \) – or minimum interference \( n_{\min} \) – between the spacer and the intermediate ring. The second script: a shaft, a disk of the 11th stage, spacers, a path ring, a disk of 12 stages. Parts simulation was performed in such a way as to ensure maximum tightness \( S_{\max} \) – or minimum tightness \( S_{\min} \) – between the spacer and the disk of the 12th stage. The third script: a shaft, a disk of the 11th stage, spacers, an intermediate ring, a path ring, a disk of the 12th stage. Parts were modeled to provide maximum \( n_{\max} \) – interference or minimum interference \( n_{\min} \) – between the spacer and the intermediate ring. The control of assembly parameters was carried out on the radial surface \( C \) and the end surface \( B \) of the disk No. 11, as well as on the radial surface \( E \) and the end surface \( D \) of the disk No. 12. In the scenarios under consideration, the surfaces of the parts had a nominal shape. The research results are presented in table 1.

| № | Modeling script | Parameter, surface, mm |
|---|----------------|------------------------|
|   |                | End runout, \( B \)  | Radial runout, \( C \) | End runout, \( D \) | Radial runout, \( E \) |
| 1 | 4 parts \( n_{\max} \) | 0.0010 | 0.0092 | – | – |
| 2 | 4 parts \( n_{\min} \) | 0.0008 | 0.0085 | – | – |
| 3 | 5 parts \( S_{\max} \) | 0.0022 | 0.0134 | 0.0023 | 0.0129 |
| 4 | 5 parts \( S_{\min} \) | 0.0001 | 0.0062 | 0.0001 | 0.0042 |
| 5 | 6 parts \( n_{\max} \) | 0.0016 | 0.0113 | 0.0010 | 0.0070 |
| 6 | 6 parts \( n_{\min} \) | 0.0019 | 0.0123 | 0.0034 | 0.0175 |

From the obtained results it was determined that the path ring has the greatest influence on the assembly parameters of the assembly. The main geometric parameters of the part that have the greatest effect on the radial runout of surface \( C \) is the linear dimension, which is 30.2 mm.

At the stage of troubleshooting parts of the rotor assembly, it was determined that the path ring has a linear dimension that goes beyond the tolerance field, so a decision was made to improve it. To
refine the part, one can use both the deposition of an allowance layer by the method of chromium plating and the modern methods of laser surfacing of alloys presented in [25, 26]. After applying the allowance, machining of the surfaces of the parts is performed. The main operation that determines the cost of refinement of parts is the trimming of the end, which forms a linear dimension. Based on the tolerance limits for linear dimensions, we consider four options for linear dimensions that can be expected after machining. The values of the linear size and the corresponding tolerance after trimming the end face are presented in table 2.

| Linear size (mm) | Tolerance (mm) | End runout, B (mm) | The cost of completion, rub |
|------------------|----------------|-------------------|-----------------------------|
| 30,05            | 0,01           | 0,0332            | 0,015                       | 1980,64                     |
|                  | 0,05           | 0,0327            | 0,029                       | 1874,30                     |
|                  | 0,1            | 0,027             | 0,016                       | 1540,41                     |
|                  | 0,15           | 0,0309            | 0,011                       | 1520,34                     |

The cost of path ring modification for each variant of the linear size was calculated, the results are presented in table 2.

At the next stage, the unit assembly was simulated at four angular positions of the parts. The research results will determine the rational angular position of the parts at which the minimum errors of the assembly parameters of the assembly unit are achieved. The results of the estimated assembly parameters are presented in table 2 and in figure 2.

![Figure 2. The dependence of the assembly parameters of the node on the angular positions of the parts.](image)

From the results obtained, it can be concluded that the rational option is the tolerance for the linear dimension of the path ring is 0.1 mm and the angular position in the assembly is 270 degrees.
5. Conclusion
As a result of the use of the proposed methodology, the rational value of the tolerance on the linear dimensions of the path ring was determined, which satisfies the given assembly parameters and is optimal in terms of modification costs. The task is set for further research, which is to develop a mathematical cost calculation model for products manufacturing, taking into account organizational and technical conditions.

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