Technological features of aircraft engine repair in digital production

M A Bolotov, I A Grachev, E V Kudashov, V A Pechenin and N D Pronichev
Samara National Research University, Institute of Engines and Power Plants, 443086
Samara, Russian Federation

E-mail: grachmalek2602@gmail.com

Abstract. The article analyzes the problems arising during the repair of gas turbine engines. Based on the analysis of problems, a gas turbine engines rotor repair scheme is proposed using virtual assembly technology. The proposed scheme will allow to reduce the cost and to increase the efficiency of repair work. Example of gas turbine rotor repair using virtual assembly technology is considered. The results of predicting the dimensional accuracy of assembly parameters based on the simulation of parts with real geometry are presented.

1. Introduction
Repair is an important stage of the gas turbine engines (GTE) life cycle. There are various types of repair, the main types are scheduled repair and emergency renewal repair. Scheduled repairs are carried out by the manufacturer in a certain operational period if time, which is failure or malfunction during the operation of the gas turbine engine. The main causes of emergency repairs are: wear, mechanical damage (deformation, cracks, marks and scuffing, chipping, dents, hardening, etc.), chemical and thermal damage (warping, corrosion, carbon deposits, fading), as well as vibration. Repair work is necessary to maintain the turbine engine in operating condition, its correct functioning, and in some cases to restore performance.

The cost of manufacturing of rotary parts of a gas turbine engine, including shafts, spacers, disks, is high. In case of repair works the company as a rule tries to make the most use of the used parts of the product and not to make new ones. To optimize repair works and reduce costs, after disassembling the engine parts undergo a series of technical measures. Rinsing and cleaning are carried out, parameters are checked to assess the possibility of their restoration and bringing them into compliance with the drawings and technical conditions. After the evaluation, the parts are further developed. Parts are refined, as deviations in shape and location of parts contact surfaces affect the accuracy of assembly parameters.

One of the most important and expensive steps of GTE repair is the assembly phase. The assembly process significantly impacts the quality and the final cost of the repaired product. The labor intensiveness and man-hour for modular and general assembly of aircraft engines serial production is up to 25% of the entire manufacturing process of products. The automation level of the assembly process is zero. The specified accuracy of the assembly parameters is achieved manually in conditions of incomplete interchangeability of pairwise or individual selection of parts by methods of compensation and fitting [2]. The ways to achieve the specified accuracy are determined at the design stage of the
product design [3,4,5]. The solution of this problem can be simplified due to the availability of mathematical models [6] and tools allowing to predict and determine the actual values of geometric parameters [7,8,9], characterizing the achievable accuracy.

2. Problems of GTD rotor repair
The problem of achieving the best accuracy of assembly parameters is associated with an experimental search for the optimal position of parts by assembling and disassembling the product. This takes a considerable amount of time and, accordingly, is characterized by low productivity. It should be noted that in case of numerous assemblies and disassemblies, hardening, crumbling, scoring on the contact surfaces of assembly units occur that negatively affects the final accuracy of the assembly unit.

The second problem is the impossibility to control compliance with the order and conditions of technological operations. Respecting the order and conditions of the assembly operations will result in the best possible values of the assembly parameters for current initial parts characterized by deviations in shape and location of the surfaces. After assembly operations are completed, it is not possible to determine whether the resulting assembly parameters correspond to the best achievable values. The best possible assembly parameters are achievable in case of “reference assembly”, where assembly parameters can be determined with the help of computer simulation methods.

Having analyzed the mentioned problems of existing GTE repair technology, we can note a that possible solution is the use of computer simulation of assembly parts based on the measurement results, as well as development of mathematical models [10] and methods for solving problems of dimensional accuracy. Significant and potential for improving the accuracy and productivity of assembly work consists in the use of predictive and optimization models [11] directly to control the process of forming the given accuracy of assembly work.

3. The developed scheme for GTE rotor repair
The given article presents a scheme for a GTE rotor repair using computer simulation, which is shown in fig. 1. This scheme includes three enlarged blocks: the preliminary analysis, the relative orientation of parts and the rework of parts. Let’s consider the content of each block.

The preliminary analysis block includes the following steps: measuring parts, building effective models, rotor assembly simulation at zero marks. At the first stage the engine is disassembled, the critical parts of the rotor are measured on a coordinate measuring machine.

In the second step, solid models of parts are created. Deviations of form and position of surfaces on the basis of measurement data are described. The formation of real geometric models can be represented as a complex function $F$:

$$F = f_n(...f_2(f_1(O))...)$$ (1)

where $f_1, f_2, f_n$ – functions of 1, 2 and n-th stages of processing the measured data, respectively, when creating effective geometric models.

At the last stage of processing, spline surfaces are created based on the coordinates of surface points, which replace the corresponding nominal surfaces in CAD models of parts. Actual geometric models are formed, which are 3D models of parts having real (close to real) mating and controlled surfaces. The stages of measuring and constructing real models are studied and described in [12].

The third stage includes simulation of parts assembly process taking into account the actual geometry. Simulation is performed using the ANSYS Workbench software package.

At the fourth stage, assembly parameters are predicted. Rotor assembly variant is simulated for the mutual angular position of parts by zero marks according to the design documentation. If the predicted assembly parameters satisfy the specified technical requirements, the repair rotor of the turbine engine is sent to the assembly operation. If the results do not meet the specified technical requirements, then the block of mutual orientation of parts is performed.
Figure 1. Scheme of GTE rotor repair using virtual assembly technology

Lest consider the block of relative orientation of the parts. The given block is designed to compensate for errors in assembly parameters by mutual orientation of the parts and the search for a rational position of parts in which the assembly parameters satisfy specified technical requirements. The task of this block is to compensate for systematic errors. The simulation of all structurally possible positions of parts in the repair rotor of GTE is performed. If the predicted assembly parameters do not meet the specified technical requirements, then the next block is performed, the rework of parts.

Let’s consider the block of rework of parts. Parts are determined that are economically viable or advisable to be reworked. Repair and dimensional accuracy parameters of parts are also determined. The search of parts for rework is carried out on the basis of the minimum cost of their rework. After the rework of the part, all stages of the virtual technology of the rotor repair are repeated from the measurement stage to build effective model.

Let’s consider an example of GTE rotor repair. Rotor repair was carried out using the developed technological scheme. The rotor assembly diagram is shown in figure 2.
4. Results of predicted assembly parameters before and after repair

In the course of the preliminary analysis and mutual orientation of the parts, it was revealed that the assembly of the rotor with the existing deviations of the parts will be unsatisfactory, since the radial runout of the control surface G in the considered mutual angular positions will exceed the specified tolerance by 0.04 mm. The simulation results are presented in Table 1.

During the implementation of the third block, it was determined that it is economically viable to refine the parts of ring № 1 and ring № 2. After analyzing the measurement results of these parts, it was revealed that the surface T of the ring № 1 had a high deviation in location relative to the base surface. To repair the part modern methods of laser processing, laser cladding of heat-resistant nickel and titanium alloys can be used as presented in [13, 14]. The deviation of the surface T before machining is shown in fig. 3a.

After laser cladding of the material, it is possible to perform machining of the radial surface T, to reduce the deviation of the location relative to the base surface. After performing all steps of the third block, positive results for assembly parameters prediction were reserved.

Figure 2. Scheme of GTE rotor assembly: 1 – Shaft; 2 – Disk 1; 3 – Ring 1; 4 – Disk 2; 5 – Ring 2.

Figure 3. Deviation and location of the surface B of the ring 1: a) Initial measurement; b) After surface repair.
The results of the predicted assembly parameters with the modified part are presented in table 1. The assembly of the real engine was carried out in accordance with the developed technology for the repair of GTE rotors. The resulting assembly parameters are presented in table 1.

| The mutual angular position of the ring 2, deg | Assembly parameter, surface | Modeling | Experiment | Deviation |
|-----------------------------------------------|------------------------------|----------|------------|-----------|
|                                               | Preliminary (mm) | After completion (mm) | (mm) | (mm) | Absolute. (mm) | Relative (%) |
| 0 Radial runout of the ring 2, G              | 0.081            | 0.026       | 0.031 | -0.005 | -17.57 |
| End runout of ring 2, B                       | 0.020            | 0.015       | 0.016 | -0.001 | -7.82 |
| Radial runout of disk 2, D                    | 0.089            | 0.050       | 0.040 | 0.010  | 25.31 |
| End runout of disk 2, E                       | 0.076            | 0.053       | 0.045 | 0.008  | 18.75 |
| Distance from end A to B                       | 470.422          | 470.429     | 470.347 | 0.082  | 0.02 |
| The parallelism of the end face B relative to A| 0.020            | 0.008       | 0.006 | 0.002  | 25.26 |
| 90 Radial runout of the ring 2, G              | 0.085            | 0.068       | -    | -     | -      |
| End runout of ring 2, B                       | 0.019            | 0.028       | -    | -     | -      |
| Radial runout of disk 2, D                    | 0.089            | 0.051       | -    | -     | -      |
| End runout of disk 2, E                       | 0.076            | 0.060       | -    | -     | -      |
| Distance from end A to B                       | 470.352          | 470.434     | -    | -     | -      |
| The parallelism of the end face B relative to A| 0.021            | 0.015       | -    | -     | -      |
| 180 Radial runout of the ring 2, G              | 0.074            | 0.041       | -    | -     | -      |
| End runout of ring 2, B                       | 0.019            | 0.025       | -    | -     | -      |
| Radial runout of disk 2, D                    | 0.088            | 0.041       | -    | -     | -      |
| End runout of disk 2, E                       | 0.073            | 0.079       | -    | -     | -      |
| Distance from end A to B                       | 470.422          | 470.427     | -    | -     | -      |
| The parallelism of the end face B relative to A| 0.026            | 0.009       | -    | -     | -      |
| 270 Radial runout of the ring 2, G              | 0.067            | 0.021       | -    | -     | -      |
| End runout of ring 2, B                       | 0.019            | 0.023       | -    | -     | -      |
| Radial runout of disk 2, D                    | 0.088            | 0.036       | -    | -     | -      |
| End runout of disk 2, E                       | 0.072            | 0.075       | -    | -     | -      |
| Distance from end A to B                       | 470.426          | 470.434     | -    | -     | -      |
| The parallelism of the end face B relative to A| 0.013            | 0.008       | -    | -     | -      |

The maximum observed discrepancy between theoretical and experimental data was no more than 25%. A significant effect on the assembly parameters is exerted by the deviation of the shape and location of the mating surfaces. A significant effect on the value of the assembly parameters is exerted by the mutual angular position, its change is observed within 62%.

5. Conclusion
Based on the analysis of the problems, GTE rotor repair scheme using virtual assembly technology was proposed. The results of theoretical and experimental assembly data for the repair rotor of a gas turbine engine show the possibility to use the developed repair scheme in real production.

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