Methods for determining the location parameters of GTE blade profiles based on their measurement results

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Abstract. The location parameters of the actual profile of the blades of a gas turbine engine relative to its nominal position are used to assess the quality of these parts manufacture. The complex shape of the aerodynamic surfaces of the blades, as well as the errors in their manufacture make it difficult to unambiguously determine the displacement and rotation of the actual profile. The use of various methods for calculating the parameters under consideration may result in mismatching values, which raises the question of a reasonable choice of the methods used. This paper presents two methods for determining the geometric parameters of the location of the aerodynamic profiles of the blades, taking into account the features of their manufacture and the requirements of the existing industry standard. Also, the work evaluated the effectiveness of the proposed methods in determining the processing parameters of the blades of a gas turbine engine.

1. Introduction

Errors in gas turbine engine blade manufacture cause the difference between the geometry of processed blanks of these part and its nominal value set by a designer. The complex form of aerodynamic surfaces of the GTE blades and their difference from the nominal value make it difficult to estimate the quality of these parts manufacture [1, 2]. One of the parameters used to estimate the GTE blade manufacture quality is the parameters of the actual profile location in relation to the nominal profile of the part [3].

Today there are various methods for determining the location parameters of the GTE blade profiles [4, 5]. For example, the widely used PC-DMIS application of Hexagon Manufacturing Intelligence manages the measuring process and processes obtained results by three methods for mating surfaces [6]: least square method, vector mating, and MinMax mating.

The paper of V. A. Pechenin [7] considers the mating of free form surfaces. The author proposed to use the data on the profile curvature and normal line direction in the points studied to find pairs of points.

The basic ICP algorithm and its variations have been widely used for process control of geometrical parameters of complex parts, including control of the gas turbine engine blades. The ICP algorithm places strict requirements for computing machines; therefore, a number of researchers are engaged in its optimization. So, to increase the computing rate, Bentley J. L. proposed in his papers [8, 9] to group points when mating the measurement results with their nominal values, taking into account the location in k-dimensional trees.
It should be noted that the existing methods for determining the location parameters of the GTE blade profiles are aimed at work with a wide variety of parts, thereby they do not take into account typical features of the GTE blade surfaces. The above circumstance complicates the process of the above part manufacture.

The use of different methods for computing target parameters may result in the reception of mismatched values of the parameters [10]. In connection with this fact, the urgent task is to develop new methods for determining the location parameters of the GTE blade profiles and their reasonable application.

2. Methods for determining the location parameters of GTE blade profiles
Displacement and rotation of the actual profile are determined after its mating with the nominal profile. The industry-specific standard sets the rules for mating profiles to assess the quality of the gas turbine engine blade manufacture. In accordance with the set rules, the mating shall be performed on the leading edge and the average line of the profiles. On the other hand, the similar mating procedure does not take into account process features of blade manufacture because manufacturing errors on the leading edge will cause the correction of the entire body and increase in labor intensity of the part manufacture. This necessitates the use of another mating procedure to determine the parameters of blade processing. The paper contains two methods for determining the location parameters of the GTE blade profiles which differ in the applied procedure for mating the actual profile with the nominal one. One method is intended to determine the parameters of forming operations; the other is aimed at assessing the quality of the gas turbine engine blade manufacture.

Both methods use the average line of the profile which can be obtained by different ways. Each curvature of the average line is divided into small segments so that the formed sets of points on the average lines of the actual and nominal profiles contain a large quantity of elements. The large quantity of points allows minimizing the influence of local deviations of the actual profile average line from its nominal value.

2.1. Methods for determining the processing parameters
The practice of manufacturing GTE blades demonstrates that the capacity and accuracy of their manufacture depend on the uniformity of the allowance removal from the blank [11]. To receive allowances which are the same on the back and the pan, the profiles are mated by the points on the average line by solving the optimization task:

\[
\left\{
\begin{array}{l}
\sum_{i=0}^{N} \left\| R \cdot \begin{pmatrix} x_a^i \\ y_a^i \\ \end{pmatrix} - \begin{pmatrix} x_n^i \\ y_n^i \\ \end{pmatrix} + T \right\| \rightarrow \min \\
R = \begin{pmatrix} \cos(\alpha) & -\sin(\alpha) \\ -\sin(\alpha) & \cos(\alpha) \\ \end{pmatrix}
\end{array}
\right.
\]

where \( x_a, y_a \) are the coordinates of the actual profile average line; \( x_n, y_n \) are the coordinates of the nominal profile average line; \( \alpha \) is the rotation angle of the actual profile of the blade blank; \( c, d \) are the parameters of the actual profile displacement.

The above optimization task solving lies in actual profile displacement and rotation parameters of interest.

2.2. Methods for assessing the quality of the GTE blade manufacture
In accordance with the industry-specific standard, the mating is performed on the leading edge and the average line of the profiles [12]. The rotation angle of the actual blade body is determined by solving the optimization task:
\[
\sum_{i=0}^{N} \left\| R \cdot \left( x^i_a - a_a \right) - \left( y^i_n - b_n \right) \right\| \rightarrow \min
\]

where \( \left( a_a \right) \) and \( \left( a_n \right) \) are the coordinates of the points of the average line intersection with the leading edge profile, and the actual and nominal profiles, respectively.

The actual profile displacement vector is determined by formula:

\[
T = \left( a_n \right) - R \cdot \left( a_a \right)
\]

The calculated displacement and rotation parameters allow mating the actual and nominal blade profiles to estimate the deviations of the manufactured blade form.

3. **Approving the proposed methods**

3.1. **Procedure for approving the proposed methods**

The procedure for mating the actual and nominal profiles has a direct impact on the determination of the improvement parameters of the gas turbine engine blades. The form deviation calculated after mating the profiles defines the volume and location of the material removed from the blank. Reaching of the uniform allowance allows optimizing the parameters of forming operations, which in turn makes it possible to increase the capacity and accuracy of the GTE compressor blade manufacture.

To assess the expediency of using the proposed methods for determining the location parameters of the GTE blade profiles, their influence on the allowance distribution was studied. The function of determining the allowance value for the profile point depends on the form deviation in this point:

\[
a(p) = \begin{cases} 
\Delta F(p): & 0 \leq \Delta F(p) \\
0: & \Delta F(p) < 0 
\end{cases}
\]

where \( \Delta F(p) \) is the form deviation in the profile point \( p \).

The following function was considered as the function of allowance non-uniformity:

\[
\Delta a(l) = |a(p_s) - a(p_p)|
\]

where \( p_s \) and \( p_p \) are the points on the suction and pressure side of the profile, which are located at the intersection of the corresponding areas with the straight line perpendicular to the average line in the point \( p_i \); \( p_i \) is the point on the average line of the profile located at a distance \( l \) on the curvature.

The graphic explanation of this function is shown in Figure 1.

![Figure 1. Graphic explanation of the allowance non-uniformity function.](image-url)

To assess the allowance non-uniformity in the entire profile, the generalized non-uniformity of the allowance was used:

\[
D = \int_0^l \Delta a(t) \, dt
\]

The generalized non-uniformity of the allowance for the profiles mated in accordance with the following procedures was calculated in the course of the research:

1) Mating on the leading edge and the average line. It is used in the developed methods for assessing the quality of the GTE compressor blade manufacture (P1).

2) Mating on the average line. It is used in the developed methods for determining the correction parameters for sizing the profiles of the GTE blade blank body (P2).
3) Mating in accordance with the ICP algorithm. ICP (Iterative Closest Point) is a standard algorithm of point mating used in most metrology software.

To estimate the expediency of using the developed methods for determining the correction parameters for sizing the profiles of the GTE blade blank body, the generalized non-uniformity of the allowance received with the help of the procedures P1 and P2 was compared with the value received during the procedure P3. The profiles below were used as the initial data for mating.

3.2. Generated profiles
Mathematical modelling allows creating a set of parts with known dimensional parameters [13]. The nominal form of the profile and imposed form deviation allow creating an actual model of the gas turbine engine blade blank. The nominal model of the blade is set in design documents. The deviation of the profile form of the blade blank body can be represented as the sum of three components

$$\delta_t = \delta_h + \delta_m + \delta_r,$$  \( (7) \)

The harmonic deviation of the form can be approximated using the composition of the sinus and cosine functions by the following formula:

$$\delta_h = A_h \cdot \sin(w_x \cdot x + w_y \cdot y + \varphi_{\sin}) + B_h \cdot \cos(w_x \cdot x + w_y \cdot y + \varphi_{\cos}), \quad (8)$$

where \( A_h \) and \( B_h \) are the amplitudes of the components; \( w_x \) is set as \( \omega_x \cdot 2\pi/L_x \), \( w_y \) is set as \( \omega_y \cdot 2\pi/L_y \), here \( \omega_x, \omega_y \) are the frequencies of the harmonic components along the axes \( x \) and \( y \), respectively; \( L_x \) and \( L_y \) are the reference lengths along the axes \( x \) and \( y \), respectively; \( \varphi_{\sin} \) and \( \varphi_{\cos} \) are the phases of the sinus and cosine angles.

The form deviation component \( \delta_m \) results from the part contact with a processing tool. This error distribution can be calculated using values of the mean profile curvature:

$$\delta_m = A_m \cdot (i_s - 0.5), \quad (9)$$

where \( A_m \) is the maximum error of processing; \( i_s \) is the index calculated by formula (10).

$$i_s = (H - H_{\text{min}})/(H_{\text{max}} - H_{\text{min}}), \quad (10)$$

where \( H \), \( H_{\text{min}} \), \( H_{\text{max}} \) is the mean curvature value in the point of the surface, and the maximum and minimum values of the mean curvature over the entire surface, respectively.

Random errors have different sources which total action has minor influence. The random error distribution usually follows the normal Gaussian law.

To study the uncertainty of measuring dimensional parameters, three cross-sections of the nominal CAD model of the compressor blade were obtained and the received profiles were defined analytically with NURBS splines. The parameters of the actual profile form deviation from its nominal value were determined based on the statistic data.

The maximum value of the amplitudes \( A_h \) and \( B_h \) amounted to 0.02 mm. The phases and frequencies of the harmonic component changed by the law of equal probability. The phase value varied within a range of 0° to 360° and the frequencies had the values 1, 2, 3, and 4. The profile displacement components changed by the normal law within the following range: displacement along the axis \( OX \pm 0.02 \) mm; displacement along the axis \( OY \pm 0.02 \) mm; displacement along the axis \( OZ \pm 0.15 \) mm. The surface rotation angles changed by the normal law within the following limits: about the axis \( OX \pm 9° \); about the axis \( OY \pm 3° \); about the axis \( OZ \pm 6° \). The value of the accidental deviation component \( \delta_e \) was calculated in a random manner, with the maximum value 0.002 mm.

100 profiles of the blade blank body were modelled for each cross-section under consideration. The created profiles were used to estimate the efficiency of using the methods proposed in the paper.

3.3. Measured profiles
Along with the created profiles, the profiles received based on the results of measuring the set of the GTE compressor rotor blade blanks were used. Each blank was measured on the coordinate measuring machine DEA Global Advantage 09.12.08 using a swivel head TESA and a scanning sensor SP25M of Renishaw (Figure 2). The measuring parameters are given in Table 1.
Figure 2. Measuring the blade blank body.

Table 1. Parameters of conducting experimental researches

| Parameter          | Value                        |
|--------------------|------------------------------|
| Measuring probe length | 60 mm                       |
| Probe tip diameter  | 2 mm                        |
| Ambient temperature | 20 °C                       |
| Relative humidity   | 82 %                        |
| CMM error           | $1.7 + L/333$ micron         |
| Probe tip error     | 1.7 micron                  |

Prior to start measurements of each blank on the tapered shank surfaces, the coordinate system of the blade was set. Each blank was measured in 4 cross-sections. The measurement results were exported in text files for further processing in the MATLAB system [14].

3.4. Approval results

The comparison results for the allowance non-uniformity calculated after mating on the leading edge and the average line (P1) are shown in Figure 3.

Figure 3. Comparison of the allowance non-uniformity when mating P1: a) generated profiles; b) measured profiles.

The comparison results for the allowance non-uniformity calculated after mating on the average line (P2) are shown in Figure 4.
Figure 4. Comparison of the allowance non-uniformity when mating P2: a) generated profiles; b) measured profiles.

The statistical analysis of modelling results allows making a reasonable conclusion on the nature of the processes studied [15, 16]. The obtained results show that the actual profile displacement and rotation depend on the procedure for its mating with the nominal profile. These parameters have a direct impact on the calculated deviation of the actual profile form which is the key parameter determining further processing of the gas turbine engine blade blank.

4. Conclusions

The complex shape of the aerodynamic surfaces of the gas turbine engine blades and errors in their manufacture make it difficult to unambiguously determine the location parameters of the actual profile of the blade in relation to its nominal position. The paper contains two methods for finding the above parameters: the first method is intended to determine the part processing parameters and the second method is intended to assess the quality of the GTE blade manufacture.

The results of the conducted researches showed that the allowance non-uniformity determined after mating the actual and nominal profiles of the GTE compressor blade blank mostly depends on its processing error. After mating the profiles in accordance with the industry-specific standards, the allowance can be more and less uniform as compared to the mating in accordance with the widely used ICP algorithm. The use of the procedure for mating on the average line allows reaching a more uniform allowance in 16–60 % of cases, which will have a positive effect on the capacity and accuracy of processing the gas turbine engine blade blanks.

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6. References

[1] Rezhikov A, Kochetkov A and Zakharov O 2017 Mathematical models for estimating the degree of influence of major factors on performance and accuracy of coordinate measuring machines MATEC Web of Conf. 129 01054.
[2] Shi Z, Li X, Li Y and Lin J 2019 A High-Precision Form-Free Metrological Method of Aeroengine Blades Int. J. of Precision Engineering and Manufacturing 20(12) 2061-2076.
[3] Gao L, Ma C and Cai Y 2019 A Robust Blade Design Method based on Non-Intrusive Polynomial Chaos Considering Profile Error J. of Thermal Science 28(5) 875-885.
[4] El-Hayek N, Nouira H, Anwer N, Gibaru O and Damak M 2014 A new method for aspherical surface fitting with large-volume datasets Precision Engineering 38(4) 935-947.
[5] Craig M 1998 Least-Squares Fitting Algorithms of the NIST Algorithm Testing System J. of Research of the National Institute of Standards and Technology 103(6) 633-641.
[6] PC DMIS User Manual v4.2.
[7] Pechenin V, Bolotov M and Ruzanov N 2016 Technique of decomposition of form deviation for freeform surfaces Key Engineering Materials 685 334-339.
[8] Bentley J 1975 Multidimensional binary search trees used for associative searching Communications of the ACM 18(9) 509-515.
[9] Friedman J, Bentley J and Finkel R 1977 An algorithm for finding best matches in logarithmic expected time *ACM Transactions on Mathematical Software* **3**(3) 209-226.
[10] Zakharov O and Kochetkov A 2016 Minimization of the systematic error in centerless measurement of the roundness of parts *Measurement Techniques* **58** 1317-1321.
[11] Volkov D and Poluglazkova N 2019 Control of the Deep Grinding of Gas-Turbine Components *Russian Engineering Research* **39**(7) 605-608.
[12] OST (State Standards) 1 02571-86: 1986 *Blades of compressors and turbines. Limit deviations of the size, shape and location of the blade airfoil* (Moscow: Standartinform).
[13] Kazanskiy N, Stepanenko I, Khaimovich A, Kravchenko S, Byzov E and Moiseev M 2016 Injectional multilens molding parameters optimization *Computer Optics* **40**(2) 203-214 DOI: 10.18287/2412-6179-2016-40-2-203-214.
[14] Morunov N and Golovashkin D 2019 Design features of block algorithms of FDTD-method implemented on a GPU using MATLAB *Computer Optics* **43**(4) 671-676 DOI: 10.18287/2412-6179-2019-43-4-671-676.
[15] Orlov E and Sizova I 2016 Analytical representation of the statistical properties of random processes with arbitrary spectra *Computer Optics* **40**(4) 560-571 DOI: 10.18287/2412-6179-2016-40-4-560-571.
[16] Zakharov O, Bobrovskij I and Kochetkov A 2016 Analysis of Methods for Estimation of Machine Workpiece Roundness *Procedia Engineering* **150** 963-968.