Influence of geometric deviations of the fan blade airfoil on aerodynamic and mechanical integrity

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Abstract. A technology for robust multi-criteria optimization of the fan blades with real deviations of airfoil geometry is proposed which includes simultaneously solving aerodynamic and mechanical integrity problems as well as balancing and arranging the blades in the row. In accordance with this technology, automated measurements of blades airfoil geometry (more than 1200 points) are used to automatically create a blade “cold” 3D model, meshing, and static and dynamic analysis of mechanical integrity. Then the model and mesh are automatically transformed in a “hot” condition and an aerodynamic analysis is carried out to estimate the measured geometry influence on fan parameters. Finally, arrangement of blades in the row is carried out based on static moments and aerodynamics analysis. The final stages of this technology are presented in this paper more detail.

1. Introduction

The optimization of the fan blade used in the design of an aviation engine often does not take into account a possible influence of technology, however even allowable airfoil geometry deviations after production could affect engine efficiency, life and reliability. Robust multi-criteria optimization [1, 2] of the fan blade design and arrangement of the blades in the row taking into account the actual geometric parameters will solve this problem and achieve a consistently high level of aerodynamic and strength characteristics.

Due to the high complexity, the geometry of the fan blade airfoil must be measured using automated coordinate measuring machines, and subsequent gas dynamic and strength calculations must be performed using numerical methods of gas dynamics and finite elements in a three-dimensional (3D) setting [3, 4].

Vinogradov et al [5] considered geometrical uncertainties from the fan blade manufacture tolerances and deviations and measured approximately 2500 fan blades by means of CMM process to reconstruct the probability density function for more than 40 geometrical uncertainties. CFD and FEM calculations were carried out, correspondingly, and robust optimal solutions (the Pareto set) were found for aerodynamics and mechanical integrity criteria. The robust optimization results were compared with the deterministic optimization results.

Several problems have become relevant, among them the problem of automatically creating 3D models for fan blades with geometric profile deviations from the nominal profile measured after they are manufactured, as well as significant reduction the preparation and time for aerodynamic and
mechanical integrity calculations and analysis. This paper is the final in a series of papers dedicated to finding a solution to this issue.

A technique for constructing a 3D model in a CAD-system based on coordinate measurement, considering real manufacturing deviations of an airfoil was presented in papers [6, 7]. The geometrical parameters necessary for creating a parametric model of a fan blade were chosen, and a parametric 3D model of the fan blade was developed in paper [8]. The obtained models significantly reduced the time for preparing and carrying out mechanical integrity and aerodynamic calculations.

A method for automatically creating a model of finished blades with real production deviations of the airfoil according to the data of measurement in the CAD system was presented in paper [9]. A program was developed, specifically a macro written in the programming language PHYTON, working together with the selected CAD-system Siemens NX, which significantly reduced the time to prepare models for aerodynamic and MI calculations.

The results of aerodynamic characteristic calculations for the fan blades with different geometric airfoil deviations were presented in paper [10].

The results of the mechanical strength characteristics calculation for the fan blades considering manufacturing deviations were also studied. The analysed models of blades with different geometric deviations on the airfoil, the design model of the fan assembly, the estimated mechanical strength characteristics, and the design scheme for a set of blades were described in paper [11].

Presently the main method of blade arrangement in row is balancing. There are a lot of projects and patents related to this problem. For example, Choi W. and Storer R.H [12] proposed heuristic methods for balancing blades based on the number partitioning algorithm. The proposed methods outperformed existing methods remarkably in terms of accuracy with a negligible increase in the running time.

V.M. Ryzhenkov and V.V. Tikhomirov [13] considered the possible causes of the main balancing errors in the manufacture of rotary systems of gas turbine engines. The recommendations developed as a result of their research demonstrate the dominant balancing errors, identify and eliminate their causes, which, without significant costs, can provide a noticeable improvement in the quality of the engines produced.

Methods of arrangement of turbomachine rotor blades based on measuring the radial static moment of a great number of blades to be fitted on rotor have been patented [14, 15] and are used at present.

Summarising, carried out studies allowed us to develop a technology for robust optimization of the fan blade with real deviations of airfoil geometry, which includes simultaneously solving gas-dynamic and strength problems and optimum arrangement of the blades in the row, the final stages of which are presented in this paper.

2. General approaches
Figure 1 shows the flow-chart of optimization technology for the fan blade with real deviations of airfoil geometry.

2.1. Main input data
The following input data is entered for calculation start:

- The nominal model of the engine Sam-146 fan blade is used as the base model for the development of 3D optimization technology [6-9]
- The model for mechanical integrity calculations is a sector of the fan wheel and includes the blade itself (with replaceable measured airfoils), sectors of disk, platform, part of the rotor and a locking device [11].
Figure 1. Technology optimization flow-chart
The model for aerodynamic calculations is a simplified version of a real low-pressure compressor sector (with replaceable measured airfoils) and is used to assess the sensitivity of aerodynamic parameters to the influence of individual geometric parameters of the blade model [10]. In addition to the single-channel sector, a two-channel fan sector model was also created (figure 2)

- Set of geometry data for every measured blade [6-9]
- Measured static moments of blades

![Figure 2](image)

Figure 2. Geometry (a) and mesh (b, c) of two-channels aero model

Criteria and constraints of optimization [10, 11]:
- Outlet mass flow, $G_B$, [kg/s];
- Pressure ratio, $\pi k$ *;
- Efficiency, $\eta k$ *;
- Axial thrust, $P$, [N];
- Allowable limit values of static stresses [$\sigma$, [MPa] taking into account the specified life for low-cycle fatigue
- Restrictions on the frequencies of the blades vibrations [f], [Hz]

2.2. Creating models for strength and aerodynamic calculations

The first step is the construction of parametric models of the blade for strength and aerodynamic calculations. This is solved in several stages [6-9]:

- Parameterized models of the sector geometry
- Static strength calculations (equations)
- Aerodynamic calculations (CFD simulations)
- Optimization of the blade geometry based on the results of the strength and aerodynamic calculations

Input domain
Output domain
First fan blade
Second fan blade

Figure 2 (a-c) shows the geometry of the two-channel sector and the mesh for the CFD simulation.
- Measuring the position of base surfaces and points for every blade on the portal coordinate-measuring machine Coord3 Hera NT
- Profile coordinates measurement on the Coord3 Hera NT
- Primary processing of the measurement results using software of the Coord3 Hera NT
- Creating a measured model of a fan blade using special custom macros BladeTool written in the programming language PHYTON, working in conjunction with the selected Siemens NX CAD system
- Creating a measured parametric model of a fan blade for mechanical integrity analysis using BladeTool
- Converting the blade model to the TurboGrid format
- Rebuilding the “cold” airfoil model into a “hot” model for aerodynamic analysis (with due account for the deformation at operating rotation speed) and calculation in the FineTurbo (Numeca) program using macros GeomTurbo (created in ODK-Saturn PJSC)

2.3. Preparation, calculation, and analysis of the measured blade mechanical integrity
Preparation, calculation, and analysis of the measured blade mechanical integrity was presented in [11].

Creation of FE meshes of the measured airfoils, application of boundary conditions, calculations and post-proceeding are carried out in ANSYS Mechanical automatically.

2.4. Preparation, calculation, and analysis of the measured blade aerodynamics
Preparation, calculation, and analysis of the measured blade aerodynamic calculations was presented in [10].

Creation of FE meshes of the measured airfoils, application of boundary conditions, calculations and post-proceeding are carried out in FineTurbo (Numeca) using custom macros BladeTool, GeomTurbo automatically.

In addition to the single-channel sector, a two-channel fan sector model including two different airfoils was also created (figure 2) and analysed.

2.5. Analysis of fan blades balancing
Analysis of fan blades balancing is considered in more detail in Chapter 3.

2.6. Evaluation of the effect of balancing on aerodynamics
Evaluation of the effect of balancing on aerodynamics is described in more detail in Chapter 4.

3. Analysis of fan blades balancing

3.1. Procedure of static moments measurements
Measurement of static moments is carried out for every ready blade after geometry measurements using special torque scales MERA-ISM-0,4 (figure 3).

These 3D static moment scales allow measuring radial and axial static moments. To do this, the blade is installed in the radial direction on the receiving disk, which is rotated. A counterweight connected to the control ring allows balancing the rotation. The static moment is equal to the product of the lever arm D (it is determined relative to the reference point P of the balance) by the mass M applied to the centre G of gravity of the blade. This is a device that also measures the tangential static moment by rotating the receiving disk 90°.
The main parameters necessary for further balancing are calculated using the following formulas: weight of blade (1), coordinate of the centre gravity (2), static moment relative to the base surface of the blade (3), static moment of the blade relative to any base axis (4).

\[
P_l = \frac{b}{\Delta} (R_2 - R_1 - \Delta R_0)
\]

(1)

\[
a = b \frac{R_1}{P_u} - c
\]

(2)

\[
M_c = bR_1 - cP_1
\]

(3)

\[
M_{cr} = P_l(a + r_l)
\]

(4)

where: 
- \( R_1 \) and \( R_2 \) are the values of the force sensor responses, respectively, in the first carriage position corresponding to one distance of the blade’s centre of gravity from the fixing support, and in the second position corresponding to another distance of the blade’s centre of gravity from the fixing support, \([\text{N}]\);
- \( \Delta R_0 \) – the difference in the force sensor responses when moving the carriage without a blade attached to it from the first position to the second, \([\text{N}]\);
- \( b \) – distance between supports, \([\text{mm}]\);
- \( c \) – the distance of the base surface of the blade from the fixing support at the first position of the carriage, \([\text{mm}]\);
- \( \Delta \) – the distance between the locations of the base surface of the blade, formed when moving the carriage from the first position to the second, \([\text{mm}]\);
- \( r_l \) – distance from the base surface of the body to any base axis \([\text{mm}]\).

3.2. Procedure of blade arrangement in the row using static moments measurements

To balance the fan blades, the concept of a four-petalled scheme is introduced. This is a scheme in which the heaviest blades with the greatest static moments (figure 4a) are concentrated in four petals (figure 4b). To get this distribution, it is necessary to arrange the blades along the grooves in descending order of their static moment according to the scheme in figure 4b. The diagram shows the order of arrangement of the descending series to obtain a 4-petal scheme (4PS).
The variation of the Number of blades

The algorithms of the method for arranging the blade are shown in figure 5 and consist of 4 stages:

1) Calculating the matrix of acceptable pairs by the criterion of the difference of statistical moments for opposite blades
2) Defining an array of blade location boundaries in rows for each blade for a given coefficient of deviation from the 4PS
3) Creating two permutation arrays taking into account the allowed pair and the permutation boundary in the row for two blocks
4) Calculating searching for the minimum disk unbalance function (by \( R, RT, A \)) for combinations of arrays \( E1(12 \times N1) \) and \( E2(12 \times N2) \) in total \( N1 \times N2 \) variants

Figure 4. The distribution of blades by the total static moment (a) and arrangement of the blades according to the 4-petal scheme (b)
Figure 5. Flow-chart of blade arrangement based on static moments measurements

Calculation of static moments differences for the opposite blades and checking of requirements of the assembly technology (allowable differences of radial R, radial-tangential RT and axial A moments) is carried out in Process 1. The blades are rearranged in the row by permutation in a certain sequence to reduce unbalance. The blade should not be much removed from the original layout of the row Ro to maintain the shape of the 4PS. The specified limits determine the number of permutation combinations that can be made in the original row D(24x24), where 24 is the number of blades in the row.

Process 2 defines an array of blade location boundaries. Restrictions are imposed for the first four blades that have the highest static moments. The heaviest blade P1 cannot be moved from position P1 further than position P4, for example, for a given coefficient of deviation from the 4PS that can be varied from 1 to 4. A similar restriction is imposed for blades P2-P4 from the heaviest four blades. The boundaries of the location of the blades of the second four depend on the boundaries of the location of the first four, there is a possibility of getting a blade from the first four to the place previously occupied by a blade from the second four; similarly for the following fours.

Two permutation arrays E1(12xN1) and E2(12xN2) are created in process 3 taking into account the allowed pair D and the permutation boundary in the row START END for two blocks E1(12xN1) and E2(12xN2).

Process 4 captures calculation and search for the minimum disk unbalance function (by R, RT, A) for combinations of arrays E1(12 x N1) and E2 (12xN2) in total N1 x N2 variants. As usual there are a
few options of blade arrangements that satisfy unbalance requirements. The best ten options are used for further optimization considering aerodynamic requirements.

4. Evaluating the effect of balancing on aerodynamics

4.1. Input for procedure of balancing evaluation
After balancing, three excel files are generated. One file contains an array of data with the arrangement of blades in the row grooves (ten the best variants). The second file should contain data on the geometric deviations of 24 blades of the same set. The third file should contain unbalance data for each arrangement option.

These files are used to create matrix of deviations for every option of blade arrangement taking into account relative blade positions.

4.2. Balancing estimation based on the summary effect of geometry deviations on fan thrust
In accordance with the results of the aerodynamic calculations showed in figure 1 and described more detail in [10] a series of linear equations is obtained $Y_i(x) = x \frac{\Delta y_j}{\Delta x_i}$, where $\Delta y_j$ is the coefficient of influence of parameter $x_i$ on the criterion $y_j$, determined by the results of a series of calculations of blades with different geometry deviations, $Y_j$ – the value of the criterion for the nominal blade, $i = 1...n$ (n=18 – the number of geometry parameters), $j = 1...m$ (m=24 – the number of blades in the row).

Based on the obtained linear equations, functions for each geometric deviation (the angle of installation $\Delta \theta$, the centre of gravity coordinates $T_x$ and $T_y$, maximum thickness of the profile $\Delta E$, blade thicknesses at the leading and trailing edges $\Delta e_1$ and $\Delta e_2$) in three sections 45, 75 and 90 of blade height are entered.

Comparing the values of deviations of parameter $x_i$ in the equation for $y_j$ with the corresponding values of the coefficients of influence of parameters $\frac{\Delta y_j}{\Delta x_i}$, the values of the influence of these deviations on the thrust are determined. As a result, for each selected balancing option $k = 1...10$, the matrix $M(i,j,k)$ is determined (where $k$ is equal to the number of arrangement options from 1 to 10, $i = 1...18$, $j = 1...24$).

To determine the maximum effect of geometric deviations on the thrust, the influence of the proximity of identical deviations is estimated. For this purpose, the total effect of production deviations is checked for four sectors $S_b$, $b=1...4$, each sector includes 6 blades.

The results are saved to an separate Excel file.

The sector with the maximum modulo negative value is determined for each of the arrangement options. It is determined which arrangement option has the minimum modulo negative effect on the thrust. If the indicators match, the option with the smallest radial unbalance is selected. The unbalance criterion (either radial unbalance, or radial-tangential unbalance, or axial unbalance, or total unbalance) can be changed in the program text. If there are options in sectors that do not have negative values, the main criterion for selecting such options is the smallest radial unbalance.

4.3. Balancing estimation based on the smoothness of changes in deviations of adjacent blades
An indicator of "smoothness" of changes in individual geometric parameters of neighboring blades (5) is proposed by G.V.Kretinin

$$d\Theta = \max \left( \frac{1}{i=1,24} \left( \Theta_i^{15} - \Theta_{i-1}^{15} \right)^2 + \left( \Theta_i^{45} - \Theta_{i-1}^{45} \right)^2 + \left( \Theta_i^{90} - \Theta_{i-1}^{90} \right)^2 \right) / 3$$

$$i = 1, \ i - 1 = 24.$$
After analysing the conducted aerodynamic calculations on the influence of deviations on the gas characteristics of the engine, three geometric parameters are selected with calculated coefficients (installation angles of 45, 65, 90 cross-sections), which maximally affect the characteristics of the engine [10]. A matrix Θ is formed for each arrangement option and the maximum difference of the geometric parameter in the pair is selected.

Then a matrix of maximum deviations is formed for each arrangement option, and the option with the smallest deviation difference is selected from it. If the results match, the option with the smallest radial unbalance is selected.

4.4. Choice of the optimum option of blades arrangements in the row

According to criterion 4.2, in order to determine the optimal arrangement of the blades, a set is defined in which there is a sector with the least negative impact on the thrust. If there are sets with all sectors with a positive impact on the thrust, then the set with the minimum radial unbalance is selected from these sets.

According to criterion 4.3, the smoothness of the geometry change is evaluated, and if the best results match, the set with the smallest radial unbalance is selected.

5. Conclusion

A technology for robust multi-criteria optimization of the fan blades with real deviations of airfoil geometry is proposed which includes simultaneously solving aerodynamic and mechanical integrity problems, as well as balancing and arranging the blades in the row.

In accordance with this technology, automated measurements of blades airfoil geometry (more than 1200 points) are used for automatically creating a blade “cold” 3D model, meshing, and static and dynamic analysis of mechanical integrity. Then the model and mesh are automatically transformed in a “hot” condition and aerodynamic analysis is carried out to estimate the measured geometry influence on fan parameters. Finally, arrangement of blades in the row is carried out based on static moments and aerodynamics analysis.

The final stages of this technology are presented in this paper in more detail. Blades arrangement in the row is carried out using the known criterion of the difference of statistical moments for opposite blades and definition of an array of blade location boundaries for each blade for a given coefficient of deviation from the 4PS. Then, as per the new approach, two permutation arrays are created taking into account the allowed pair and the permutation boundary in the row for two blocks and the minimum disk unbalance function is calculated for combination of two permutation arrays for the chosen number of options.

The best ten options are used for further optimization taking into account aerodynamic requirements. Two criteria of balancing estimation are proposed:

- Based on the summary effect of geometry deviations on fan thrust
- Based on the smoothness of changes in deviations of adjacent blades.

The set with the minimum radial unbalance that better satisfies both criteria is selected from these options of arrangement.
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