Artículo de investigación

Analysis of the geometric deviation influence on the aerodynamic characteristics of the fan blades

Анализ влияния геометрических отклонений рабочих лопаток вентилятора на аэродинамические характеристики ступени

Análise da influência do desvio geométrico nas características aerodinâmicas de pás de ventilador

Análisis de la influencia de la desviación geométrica en las características aerodinámicas de las palas del ventilador

Recibido: 05 de julio del 2019 Aceptado: 14 de agosto del 2019

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Abstract

In this article there are the results of the aerodynamic characteristic calculations for the fan blades of the gas turbine engine for the regional aircraft, considering production deviations. The analyzed models of blades with different geometric airfoil deviations, the calculated model of the fan stage, the estimated aerodynamic characteristics are described. Here you can find the example of the calculation results.

Keywords: Aerodynamic characteristics, fan, gas turbine engine, geometric deviations, low-pressure compressor, NUMECA, robust optimization, Siemens NX.

Аннотация

Представлены результаты расчета аэродинамических характеристик лопаток вентилятора газотурбинного двигателя для регионального самолета с учетом производственных отклонений. Описаны анализируемые модели лопаток с различными геометрическими отклонениями на пере, расчетная модель ступени вентилятора, оцениваемые аэродинамические характеристики, приведен пример результатов расчета.

Ключевые слова: NUMECA, Siemens NX; аэродинамические характеристики; вентилятор; газотурбинный двигатель; допуски; лопатка; робастная оптимизация.

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Resumo

Neste artigo são apresentados os resultados dos cálculos das características aerodinâmicas das pás do ventilador do motor de turbina de gás para um avião regional, tendo em conta os desvios de produção. Além disso, são descritos os modelos analisados de lâminas com diferentes desvios geométricas de perfil aerodinâmico, o modelo calculado da fase do ventilador e as características aerodinâmicas estimadas. Por sua vez, os resultados do cálculo são ilustrados com um exemplo.

Palavras-chave: Características aerodinâmicas, compressor de baixa pressão, desvios geométricas, motor de turbina a gás, NUMECA, otimização robusta, Siemens NX, ventilador de teto.

Resumen

En este artículo se presentan los resultados de los cálculos de las características aerodinámicas para las aspas del ventilador del motor de turbina de gas para un avión regional, teniendo en cuenta las desviaciones de producción. Asimismo, se describen los modelos analizados de aspas con diferentes desviaciones geométricas de perfil aerodinámico, el modelo calculado de la etapa del ventilador y las características aerodinámicas estimadas. A su vez, los resultados del cálculo se ilustran con un ejemplo.

Palabras clave: Características aerodinámicas, compresor de baja presión, desviaciones geométricas, motor de turbina de gas, NUMECA, optimización robusta, Siemens NX, ventilador.

Introduction

A multidisciplinary robust optimization of complex-profile fan blades is implemented in order to ensure the competitive advantages of the dual-circuit gas turbine engine for the Russian regional-main aircraft. Today's widespread deterministic optimization without taking into account production deviations makes the fan blade insufficiently resistant to geometric deviations of the profile shape when changing the operating modes of the engine relative to the nominal. A robust multidisciplinary optimization of the fan blade design and a complete set of blades taking into account the actual geometric parameters will solve this problem and achieve a consistently high level of aerodynamic characteristics of the engine.

Aerodynamic calculations of the fan blade in this work are an important stage for preparation for robust multidisciplinary optimization and development of a program for modeling the fan stage with increased gas-dynamics and mechanical integrity considering the data of coordinate measuring machines (CMM) on local geometric deviations of the airfoil. The nominal model of the blade is used as the initial model for aerodynamic calculations.

Many works (Bestle, Flassig, 2010; Bestle, Flassig, Dutta, 2011; Ma, Gao, Cai, Li, 2017; Li, Liu, Agarwal, 2018) are devoted to influence of possible deviations of the sizes on aerodynamic characteristics of gas turbine engines. In the context of fan blades, one should emphasize an article (Vinogradov, Kretinin, Leshenko, Otriakhina, Fedechkin, Vinogradova, Bushmanov, Khramin, 2018), analyzing the impact of possible deviations from actual and theoretical airfoils on the efficiency factor.

However, it is necessary to consider effect of geometric deviations not only on the efficiency, but also on other parameters estimated in aerodynamic calculations, for example, on the mass air flow, the degree of pressure increase, etc.

In this case, for fan blades with a complex airfoil geometry, it is necessary to consider not only airfoil thickness deviation, but also the displacement of the centers of gravity and the angles of the cross sections. An approach to the choice of the blade model and boundary conditions should be very careful.

This article describes a methodology to assess aerodynamic characteristics of a fan blade sensitive to airfoil geometry deviations.

Models of airfoils

The main question in the aerodynamic calculations is the creation of airfoil 3D finite element model. This task solution was based on CMM methods that enable to create a 3D model of a fan blade following measurement results, and on the methods of automated 3D modeling of fan blades following CMM data in the CADsystem Siemens NX (Arkhipov, Ravikovich, Fedorov, Kholobtsev, 2017; Arkhipov, Bugryashova, Ravikovich, Savin, Terentjev, Shevyakov, 2018).

The following geometry parameters have been used to analyze the influence of the geometry of the blade airfoil on the aerodynamic characteristics of the fan stage:

- Deviations from the center of gravity of Tx and Ty;
- Deviations from the angle of installation Δθ (Rz);
- Maximum thickness of the profile ΔE;
- Blade thickness at the inlet and outlet edges Δe1 and Δe2;
- Measured in the 21 cross-sections (04-95) along the height of
- The blade (Figure 1).

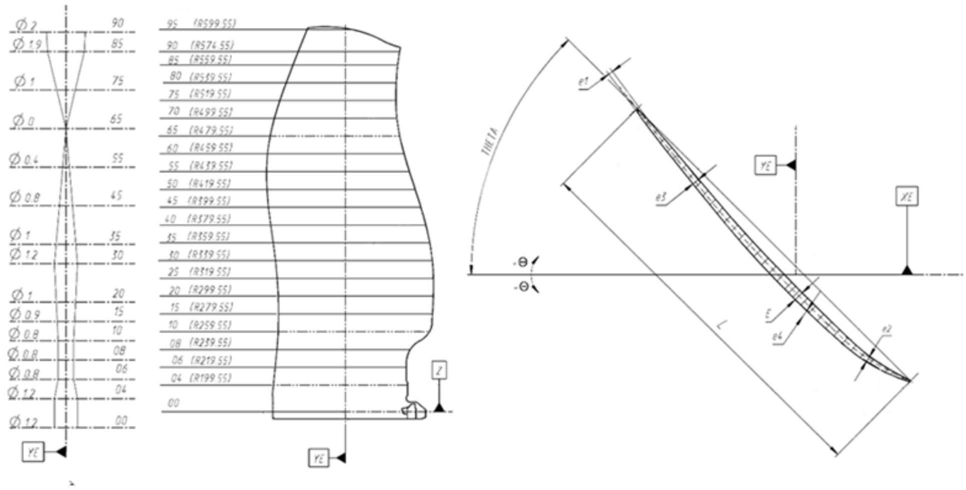


Figure 1. Geometric deviations of the blade airfoil for assessment of their influences on the aerodynamic characteristics of the fan stage

18 models of blades with single limit deviations (according to one of the studied geometric parameters, six parameters in three sections 45, 75 and 90) have been built in the CAD-system Siemens NX with the help of a modified macro, created on the basis of subroutine "BladeTool" (Arkhipov, Ravikovich, Matushkin, Kholobtsev, Shevjakov, 2018).

4 models with combined limit deviations of all investigated geometrical parameters influencing aerodynamic characteristics have been also created:

- Negative deviations of all geometric parameters;
- Positive deviations of all geometric parameters;
- Positive maximum deviations of all parameters at the bottom of the airfoil (section 04-25), negative maximum deviations of the thicknesses, centers of gravity and positive maximum deviation from the angle of installation at the top of the airfoil (section 30-95);
- Positive limit deviations of all parameters at the bottom of the airfoil, negative limit deviations from the angle of installation and positive limit deviations of thicknesses and centers of gravity at the top of the airfoil.

"Cold" models have been transformed in a "hot" model of the blades using the macros "blade_heat" based on the transferring of the existing "cold" geometry in "hot" state when the application to the model of displacements and gas loads for the calculation mode (reduced rotation speed n=0.95 in the regime with maximum efficiency).

As a result, a family of parameterized "hot" 3D models of the fan blades, that are different from each other in geometry parameters, has been created for the design aerodynamic study.

3D aerodynamic fan model

The basic element for the study of the airflow in turbomachines of any type is the calculated domain or the space around the streamlined fan blade, filled with an air and limited by the elements of the inter-blade channels, inlet and outlet domains.

The fan rotor consists of the radially mounted 24 blades. Fan blades are wide-chord, designed to convert the mechanical energy of rotation of low-pressure rotor into kinetic energy of air.
Computational model contains one blade airfoil and inlet and outlet sectors (1/24 part of fan) (Figure 2).

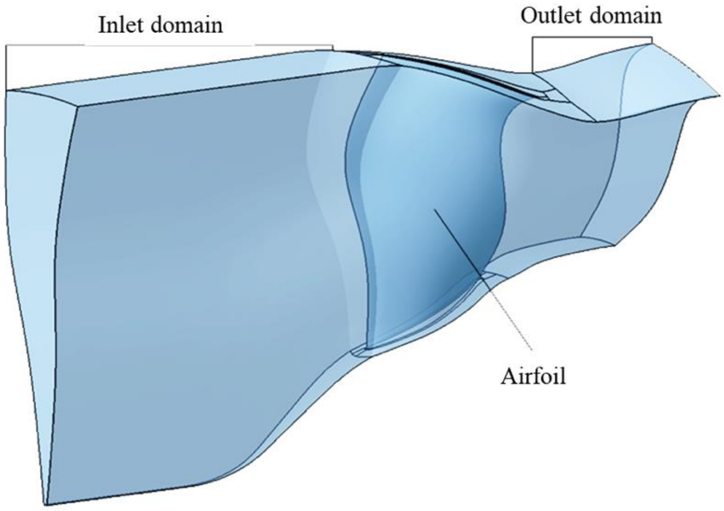


Figure 2. Calculation domain scheme

The following assumptions have been used when creating a numerical model of the airflow in the fan blade:

- Flow in the fan has the property of cyclic symmetry. Consequently, all models contain only one inter-blade channel with periodic boundary conditions on the side surfaces;
- Radial boundaries of the computational domain are set on the cylindrical surfaces of the hub (platform) and peripheral (top) contours.

The calculating model takes into account the presence of radial gaps above the fan blades.

The creation of a finite element (FE) mesh has been implemented in the module "AutoGrid V. 5" of the program complex "NUMECA", which involves the construction of a multi-block O-grid near the surface of the blades and a multi-block H-grid in the inter-blade channels. The generated computational meshes have been block-structured and consisted of hexahedral elements. Thickening of the FE mesh has been done near walls for the calculation of the boundary layer. The quality of the mesh has been achieved due to the use of universal

templates (schemes of dividing the inter-blade channel into blocks), as well as the use of tools for smoothing the grid, including the possibility of structural blocks deformation (Baturin, Goryachkin, Kolmakova, Popov, Ledenev, 2013).

Mesh model of nominal blade contains 1.08 million finite elements (Figures 3, 4). The calculated meshes with such parameters allow obtaining a flow field acceptable for determining the integral characteristics of the fan stage.

Mesh models for the other blades with the different geometry deviations have been created with parameters similar to nominal blade.

Numerical values of the boundary conditions, solver setting and calculation have been performed in the module "Fine/Turbo" of the software complex "NUMECA" (NUMECA Int., 2014). During the study, the following boundary conditions have been applied: at the inlet the total pressure and the flow temperature have been set, and at the outlet the static pressure have been set also.

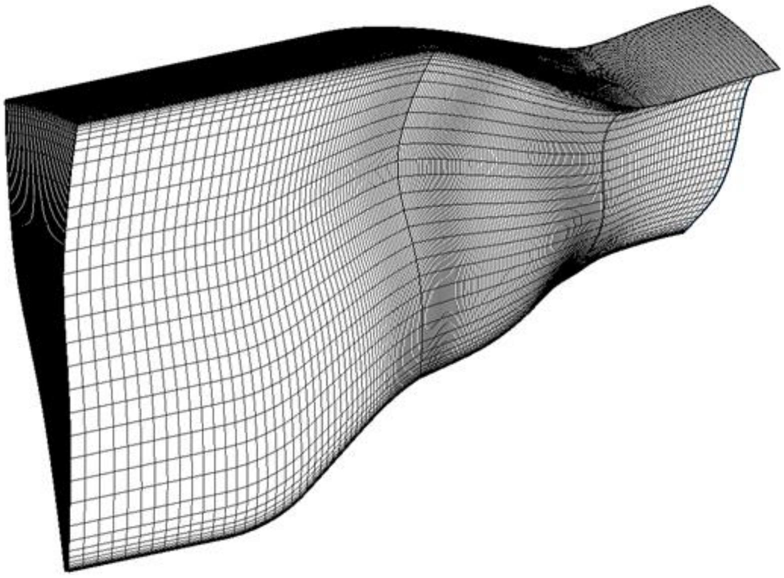
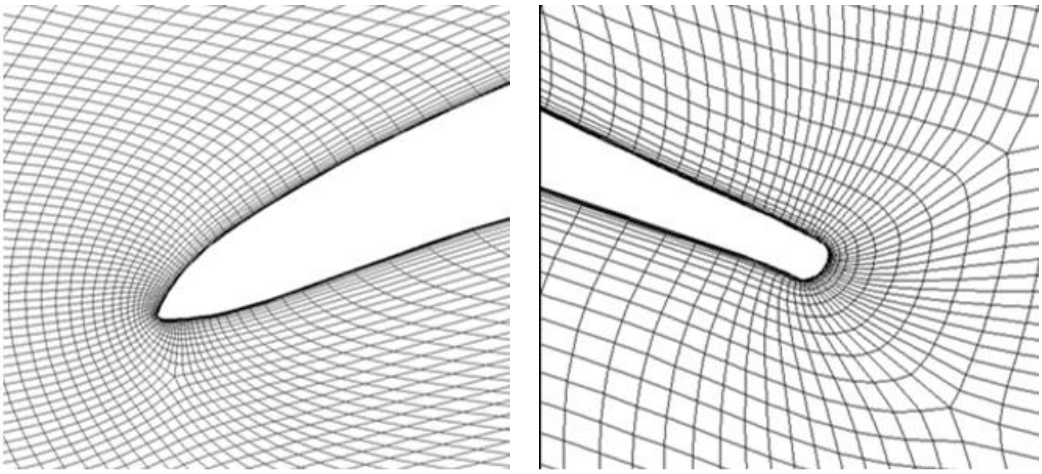


Figure 3. Finite element mesh of aerodynamic fan model



a) **b)**

Figure 4. Finite element mesh around leading (a) and trailing (b) edges of fan blade airfoil

Aerodynamic calculations have been performed at the mode: reduced rotation speed n=0.95 (maximum efficiency), which determines the main aerodynamic parameters of the fan stage.

Table 1 shows the numerical values of the boundary conditions and the parameters of the solver set to determine the aerodynamic characteristics.

Table 1. Theil coefficients

Setting field	Input value / setting
Working environment	Air (Perfect) (air with ideal gas parameters)
Task type	Steady (stationary calculation)
Mathematical method	Turbulent Navier - Stokes
Turbulence model	k-ε (Extende Wall Function)
Rotation speed	6164.52 [rev/min]
Inlet total pressure	101325 [Pa]
Inlet total temperature	288.15 [K]
Free-stream turbulence parameters	Epsilon=30000 $[\frac{m^2}{s^3}]$ k=5 $[\frac{m^2}{s}]$
Outlet static pressure	124500 [Pa]
Current grid level	0 0 0
Convergence criterion	10^{-6}

Mathematical model based on Navier-Stokes partial differential equations (1-4) (Skibin, Solonin, Sosunov, Temis, 2010) is used in the calculation of airflow:

$$\frac{\partial}{\partial t}\cdot\rho+\frac{\partial}{\partial x_j}\cdot\rho\cdot u_j=0. \quad (1)$$

$$\frac{\partial}{\partial x_j}\cdot\rho\cdot u_j+\frac{\partial}{\partial x_j}\cdot\left(\rho\cdot u_i\cdot u_j+p\cdot\delta_{ij}\right)+\frac{\partial}{\partial x_j}\cdot\tau_{ij}-\rho\cdot\varepsilon_{ijk}\cdot\left(\omega_j\cdot(\varepsilon_{klm}\cdot\omega_l\cdot r_m+ +2\cdot u_k)\right)=0. \quad (2)$$

$$\frac{\partial}{\partial t}\cdot e+\frac{\partial}{\partial x_j}\cdot(e+p)\cdot u_j+\frac{\partial}{\partial x_j}\cdot\left(k\cdot\frac{\partial}{\partial t}\cdot T+\tau_{jk}\cdot u_k\right)-Q=0. \quad (3)$$

$$\tau_{ij}=\mu\cdot\left(\frac{\partial}{\partial x_j}\cdot u_j+\frac{\partial}{\partial x_j}\cdot u_i\right)+\lambda\cdot\delta_{ij}\cdot\frac{\partial}{\partial x_k}\cdot u_k. \quad (4)$$

where ρ is a density; u_i are the components of the velocity vector; e is a total specific energy; T is an absolute temperature; p is a pressure; τ_{ij} are the components of viscous stress tensor; μ and λ are the viscosity coefficients; k is a thermal conductivity; ω_i is an angular velocity vector of a rotating coordinate system; Q is a heat dissipation.

The convergence criterion is the reduction of the mean square discrepancy to the level of 10^{-6} or lower in aggregate with the stabilization of the airflow parameters, which is achieved in approximately 250-750 steps.

Estimated aerodynamic parameters

Preliminary calculations of the fan sector with the nominal blade airfoil have shown that the following aerodynamic characteristics are the most important for robust optimization:

- Outlet mass flow, *Gв*, [kg/s];
- Pressure ratio, π_k^*;
- Efficiency, η_k^*;
- Axial thrust, *P*, [N].

Distributions of the Mach numbers, static pressures and temperatures in the average cross section in height have been shown to evaluate the results obtained in the aerodynamic calculations of the "hot" models of the fan blades (Figures 5-7).

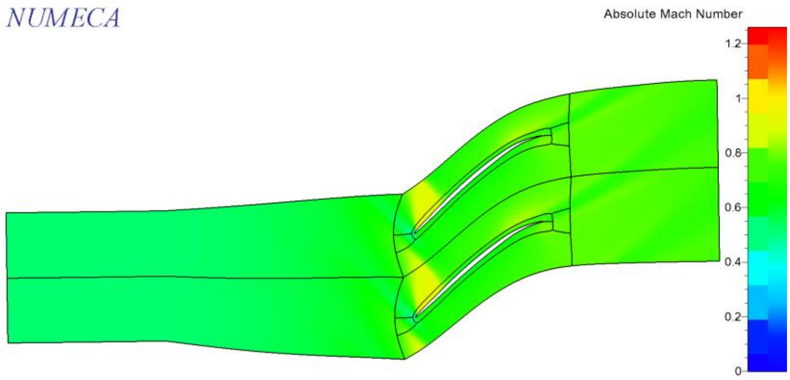


Figure 5. Distribution of the Mach numbers, relative height 0.5

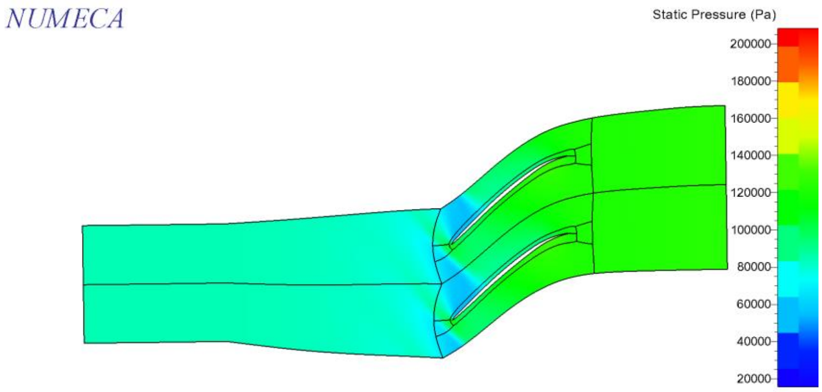


Figure 6. Distribution of the static pressures, relative height 0.5

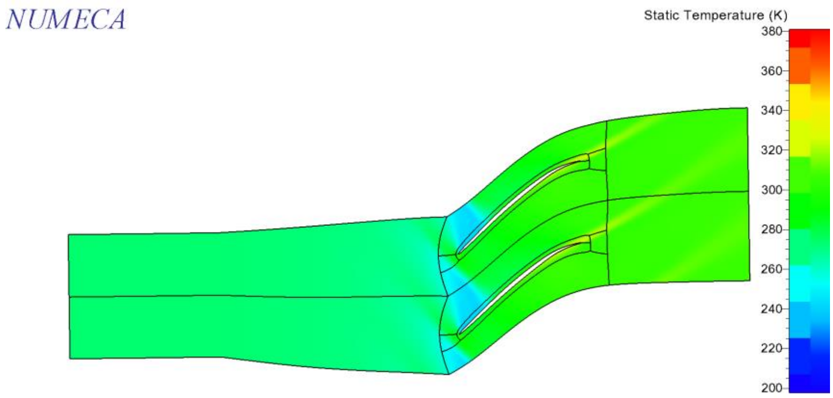


Figure 7. Distribution of the temperatures, relative height 0.5

3D calculations allow obtaining reliable qualitative and quantitative data on the parameters of the fan. Their optimization come down to the solution of airflow at the variation of the coordinates of the blade airfoils and the flow contour (Inozemtsev, Nikhamkin, Sandratskii, 2008).

Calculation results

The results of calculations show the difference of the main aerodynamic parameters of the blades with single and combined geometry deviations from the parameters of the nominal blade in percent (Tables 2, 3). The green color shows the maximum deviation in plus, the blue one shows the maximum deviation in the minus.

Table 2. Model with single geometry deviations, the difference of main aerodynamic parameters from nominal model, %

Model No.	Geometry parameter	Cross-section	Coefficient of influence, %			
			Outlet mass flow, *Gв*, [kg/s]	Pressure ratio, π_k^*	Efficiency, η_k^*	Thrust, P[N]
0	Nominal		0.00	0.00	0.00	0.00
1	Tx+0.40 mm	45	-0.5	0.3	-0.01	-0.16
2	Tx+0.50 mm	75	-0.40	0.35	0.05	0.25
3	Tx+1.00 mm	90	-0.45	0.36	-0.01	0.11
4	Ty+0.40 mm	45	-0.50	0.30	0.00	0.10
5	Ty+0.50 mm	75	-0.40	0.34	0.02	0.13
6	Ty+1.00 mm	90	-0.45	0.37	-0.03	0.18
7	Θ (Rz) +0.55°	45	-0.97	0.44	-0.27	-0.91
8	Θ (Rz) +0.55°	75	-0.29	0.71	-0.22	1.52
9	Θ (Rz) +0.55°	90	-0.23	0.63	-0.11	1.53
10	d_E+0.25 mm	45	-0.51	0.28	0.02	-0.16
11	d_E+0.25 mm	75	-0.49	0.30	0.02	-0.09
12	d_E+0.25 mm	90	-0.53	0.30	0.00	-0.18
13	d_e1+0.10 mm	45	-0.45	0.31	0.00	-0.08
14	d_e1+0.10 mm	75	-0.46	0.30	0.00	-0.05
15	d_e1+0.10 mm	90	-0.47	0.33	-0.02	0.001
16	d_e2+0.30 mm	45	-0.49	0.31	-0.01	-0.09
17	d_e2+0.30 mm	75	-0.51	0.33	-0.02	-0.005
18	d_e2+0.30 mm	90	-0.53	0.32	-0.03	-0.07

Maximum deviation from the angle of installation Θ (Rz) in 45, 75 and 90 sections give the most significant influence on the aerodynamics of the fan stage. The mass air flow, increase of the pressure, efficiency, and thrust showed the greatest difference in values, both in plus and in minus (Table 2).

The analysis of the results shows that the lowest sensitivity to changes in single geometric deviations has an efficiency parameter from -0.27% to +0.05% compared to the nominal, and the highest sensitivity has a thrust parameter from -0.91% to +1.53%.

In its turn, the sensitivity of mass air flow and pressure increase rate parameters was from -0.23% to -0.97% and from 0.28% to 0.71%, respectively.

Table 3. Model with combined geometry deviations, the difference of main aerodynamic parameters from nominal model, %

Model No.	Coefficient of influence, %			
	Outlet mass flow, *Gв*, [kg/s]	Pressure ratio, π_k^*	Efficiency, η_k^*	Thrust, P[N]
1	0.58	1.05	-0.10	3.24
2	-0.49	0.81	-0.47	0.67
3	0.46	0.87	-0.02	2.53
4	0.69	1.02	0.03	3.13

Geometry deviations related to the models 1 and 2 reveal the most significant influence on the aerodynamics of the fan stage (Table 3). The mass air flow, pressure increase, efficiency, and thrust show the highest values, both in plus and in minus.

The analysis of the results shows that the lowest sensitivity to changes in geometry has an efficiency from -0.47% to +0.03%, and the highest sensitivity has a thrust from +0.67% to +3.24%.

In its turn, the sensitivity of mass air flow and pressure increase rate parameters was from -0.49% to +0.69% and from +0.81% to +1.05% respectively.

The following conclusion have been made based on the results of the sensitivity analysis: the thrust parameter should be considered as a target function for robust optimization due to the high sensitivity to changes in geometric deviations. Whereas such a parameter as the efficiency, which showed low sensitivity, should be considered as a functional limitation in a certain range of values.

Conclusions

The calculation of 18 models with single deviations of the airfoil geometry (within tolerances) and 4 models of blades with combined deviations and comparison of the results with the nominal model allows to conclude that the relative deviation of the thrust parameter from the nominal can reach to 3.24%. This deviation of the thrust parameter can be significant and should be taken into account when completing the blades taking into account the actual geometric parameters.

Changes in the blade airfoil geometry within tolerances also significantly affect the aerodynamic parameters of the fan stage, such as the mass flow rate (from -0.97% to +0.69%), the pressure increase in the fan stage (up to +1.05%), the efficiency factor (from -0.47% to +0.05%). Deviations of these integral characteristics can affect the aerodynamic parameters of the engine at the proximity of the considered geometric deviations to the permissible values.

The proposed method of the aerodynamic characteristics assessing for the fan blade, taking into account their sensitivity to the geometric deviations of the airfoil in combination with similar strength calculations, can be used for multidisciplinary robust optimization of complex-shaped fan blades for the arrangement of the blades in fan stage taking into account the actual geometric parameters. This approach allows achieving a consistently high level of aerodynamic characteristics of the blades, to make the fan more stable to geometric deviations of the airfoil shape.

The results presented in this article were achieved during the implementation of the comprehensive project at the financial support of the Government of the Russian Federation under a contract with the Ministry of Education and Science (Russia) code 2017-218-09-172.

References

Arkhipov A.N., Ravikovich Yu.A., Fedorov I.M., Kholobtsev D.P. (2017). Constructing 3D fan blade models in cadsystem on the basis of coordinate measuring techniques. Vestnik of Samara University. Aerospace and Mechanical Engineering, 16(3), 7-16.

Arkhipov A.N., Bugryashova E.V., Ravikovich Yu.A., Savin R.A., Terentjev V.V., Shevyakov A.O. (2018). Automated construction of a fan blade model according to data of CAD profile measurements. Vestnik of Samara University. Aerospace and Mechanical Engineering, 17(4), 7-17.

Arkhipov A.N., Ravikovich Yu.A., Matushkin A.A., Kholobtsev D.P. Shevjakov A.O. (2018). Automation program for the construction of a fan blade using NX CAD systems according to KIM. Certificate of state registration of a computer program №2018665345. 04 December 2018.

Baturin O.V., Goryachkin E.S., Kolmakova D.A., Popov G.M., Ledenev A.I. (2013). Numerical simulation of the working process of a free turbine together with low-pressure turbines, a transition channel and an output device. Electronic textbook. Samara: Samara state aerospace university.

Bestle D., Flassig P.M. (2010). Optimal Aerodynamic Compressor Blade Design Considering Manufacturing Noise. Conference: Association for Structural and Multidisciplinary Optimization in the UK.

Bestle D., Flassig P.M., Dutta A.K. (2011). Robust Design of Compressor Blades in the Presence of Manufacturing Noise. Conference: 9th European Conference on Turbomachinery.

Inozemtsev, A.A., Nikhamkin, M.A., Sandratskii, V.L. (2008). Fundamentals of the Design of Aircraft Engines and Power Plants. Moscow: Mashinostroenie.

Ma C., Gao L., Cai Y., Li R. (2017). Robust Optimization Design of Compressor Blade Considering Machining Error. Turbomachinery Technical Conference and Exposition. ASME Turbo Expo.

NUMECA Int., «Flow Integrated Enviroment», User Manual, Numeca Int., Brussels, Belgium, 2014.

Li Z., Liu Y., Agarwal R.K. (2018). Robust Optimization Design of Single-Stage Transonic Axial Compressor Considering the Manufacturing Uncertainties. Turbomachinery Technical Conference and Exposition. ASME Turbo Expo.

Skibin, V.A., Solonin, V.I., Sosunov, V.A., Temis, Yu.M. (2010). Machine Building. Encyclopedia. Moscow: Mashinostroenie, 2010

Vinogradov K.A., Kretinin G.V., Leshenko I.A., Otriakhina K.V., Fedechkin K.S., Vinogradova O.V., Bushmanov V.V., Khramin R.V. (2018). Robust Multiphysics Optimization for Fan Blade Aerodynamic Efficiency, Structural Properties and Flutter Sensitivity. Turbomachinery Technical Conference and Exposition. ASME Turbo Expo.