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Methodology of Computer-Aided Design of Variable Guide Vanes of Aircraft Engines

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ABSTRACT

The paper presents a methodology which helps to avoid a great amount of costly experimental research. This methodology includes thermo-gas dynamic design of an engine and its mounts, the profiling of compressor flow path and cascade design of guide vanes. Employing a method elaborated by Howell, we provide a theoretical solution to the task of assessing the influence of the VGV blades' angle of rotation on the characteristic of a compressor. The finite element model of a VGV blade helps to solve some problems of strength and tune-out of resonance in the domain of a compressor's operating frequencies as well as the problem of determining the position of the pressure center and the location of a blade's pivotal point. Cinematic and dynamic analysis of the control linkage of VGVs is carried out in a MSC.ADAMS package. The investigation is based on geometric 2D and 3D models, gas-dynamic and strength analysis taking into account geometrical nonlinearity and based on the finite element method. The study is also based on the dynamic analysis according to the Euler-Lagrange equation, which describes the behavior of mechanical systems comprised of markers and the Craig-Bampton method implying the theory of superposition of vibrational modes.

KEYWORDS
Howell's method, methodology of design, turbine airfoil, strength calculation, thermo-gas dynamic analysis

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Introduction

Virtually all one- and two-shaft gas turbine engines have regulatory systems of variable guide vanes (VGVs) in their compressors. The current methodologies of VGV design are based on experimental data and include lengthy finishing work, including manual tuning (Belousov & Nazdrachev, 2014). Thus, the task of creating a methodology of design of such systems with the use of modern software is quite topical.

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Under operating conditions, the height and velocity of a flight, as well the rotor speed, vary considerably (Donus et al., 2011). The engine pressure ratio π, air consumption G_B, circumferential speeds v, and consequently Mach number M and angles of attack on the blades α, β of various stages also vary and may differ considerably from design values (Ermakov et al., 2014; Kolmakova, Baturin & Popov, 2014a). This may cause considerable changes in the power intake and efficiency of a compressor, and in some cases an increase in the instability of its work. Moreover, alterations of nominal values of the inlet angle of the airflow on the blades of a compressor trigger an increase in shock losses.

The rotation of stator blades is used widely to control the compressor and the number and location of controlled blade rings (Fig. 1) is chosen depending on the type of compressor, the general number of stages and its purpose.

Figure 1. The physical form of a VGV of three compressor stages

As far as aircraft gas-turbine engines (GTEs) are concerned, the rotation of VGV blades is used for expanding the range of stable modes of a compressor, the lowering of the level of vibration stress in the blades, starting aid and maintenance of high efficiency of a compressor in the wide range of corrected speed of the rotor, realization of required requirements of a compressor's productivity (Falaleev & Balyakin, 2014).

Controlling a VGV can be stepped ("open-closed") or stepless, when each mode of an engine's work has an optimal position of variable vanes.

Literature Review

It is reasonable to note a sharp increase of interest in this issue on part of the world and Russian scientific communities which started in 2007. Oxford University is one of the leaders investigating the issues of VGVs, along with the Rolls-Royce research center. Other leaders include such US research organizations as Virginia Polytechnic Institute and State University, NASA Glenn Research Center, Chinese scientific centers Northwestern Polytechnic University, Harbin Institute of Technology, Tsinghua University, and Jiangsu University. Among the Russian research establishments we should note the All-Russian Thermal Engineering Institute and the Central Institute of Aviation Motors.

T. Setoguchi & M. Takao (1996), for instance, focused on experimental examinations of an impulse turbine with self-adjusting blades of VGVs. His research suggests that the net efficiency of an impulse turbine can be increased with the help of VGVs connected by rods. He conducted examinations and tests aimed at improving the productivity of the Wells turbine. It was established that the turbine's general characteristics will be enhanced considerably if guide vanes are used.

Another fruitful line of research of the above-mentioned scholars was the study of the effectiveness of using 2D and 3D guide vanes (Takao & Setoguchi, 2000). As a result it was discovered that operating characteristics of a turbine with 3D guide vanes surpass those of their counterparts with 2D guide vanes.

Chinese researchers also made an important contribution to the development of this subject. Thus, were used Navier-Stokes equations and the SST turbulence model "K-ω" to design a route of the flow channel of a pump turbine with misaligned guide vanes (MGVs) in conditions of non-stationary flow (Xiao & Sun, 2012).

The works of A. Thakker & J. Jarvis (2009) investigate impulse wave turbines. The scholar identified the optimal range of the angle of incidence of upper guide vanes, which allowed him to optimize the predictive performance of impulse turbine with a VGV. The representatives of the University of Limerick researched the improvement of the design of an impulse turbine by employing a systematic method which combines two powerful design tools: the analysis of concept by the Pugh method and in 3D-CAD environment. The possibilities of the suggested approach were used in the strength calculation of elements of an impulse wave turbine with VGVs and optimization of its structure in a 3D-CAD environment.

An important issue is the cooling of guide vanes. US researchers D.G. Bogard & K.A. Thole (2006) note that in order to increase the power output of a GTE it is necessary to achieve higher temperatures at the turbine inlet. However, higher temperatures lead to thermal stress and mechanical stress, especially along leading edges. This article presents the results of a design analysis of structure as well as its experimental validation. The authors note that a computational fluid dynamics (CFD) model is in agreement with the experiment results.

It is necessary to note that the issues of VGV cooling are also of interest to British scholars - J.E Sargison & S.M. Guo (2002). One of their studies presents the first experimental data on guide vanes with a new geometry of the system of film-cooling.

Having analyzed these and many other publications, the authors of this paper found that the world scientific practice does not have a common methodology of designing and debugging the guide vanes of GTRs. The present methodologies of designing such systems are built primarily on the experimental data of prototype engines and include stages of lengthy debugging, including manual tuning. Thus, the issue of creating a design methodology for such systems is quite topical. Such a methodology should include the use of modern software tools which will help avoid costly experimental research at the stage of detail design as well as cut time and labor costs.

In view of the above said, the authors consider this investigation relevant, and the tasks being fulfilled have practical significance, both for the national and the world science in the domain of creating a new generation of gas-turbine engines and upgrading the currently used aircraft.

Aim of the Study

This paper is aimed at creating a methodology of VGV design which combines a modeling of nonstationary flow of gas through the VGVs of various kinds, which could be implemented through parametric 3D models of VGVs.

Research questions

For carrying a thermos-gas dynamic analysis need to fulfill the following tasks:

1. the choice of parameters of a projected engine and the performance of its design analysis;
2. the choice of a law and a program of engine control and ensuring a line of combined action (LCA) based on the characteristics of a compressor.

For carrying a detailed gas-dynamic analysis of a compressor which identifies the geometry of its rows and the parameters of the working medium in the given sections and points need to fulfill the following tasks:

1. Measurement of flow quantities between the stages of a compressor.
2. Calculation of cinematic parameters of a compressor at a medium radius.
3. Calculation of cinematic parameters of a compressor at various radii.
4. Calculation of geometrical parameters of a compressor's blade row.

Method

The paper presents a step-by-step methodology of designing a VGV of an aircraft GTE which takes into account all the requirements as regards construction and gas-dynamic perfection, reliability and other conditions set before such systems. The study relies on geometric 2D- and 3D-models. 3D-models were created by the method of 'moving sketches' and use parametric opportunities of the Parasolid nucleus (Melentjev & Gvozdev, 2014; Ryazanov, Urlapkin & Chempinskiy, 2013). Gas-dynamic and strength analyses were based on the application of the finite element method. CFD-calculations were made on the basis of Navier-Stokes equations (Oberkampf, Trucano & Hirsch, 2004). Geometrical non-linearity was taken into account in strength calculations. Dynamical analysis was conducted using a combination of the of the Euler-Lagrange equation, which describes the behavior of mechanical systems that consist of markers, and the Craig-Bampton method based on the theory of superposition of vibration modes (Wasfy & Noor, 2003; Makhavikou, Kasper & Vlasenko, 2014).

In order to create a virtual stand of a VGV system which offers an opportunity of various research, it is expedient to use both original programs (software implementation of Howell's method) and ASTRA, ANSYS, MSC.ADAMS, SIEMENS NX, and Star-CD packages. The use of these software tools helps to create a virtual stand of a VGV system, which solves most design problems, namely gas dynamics, strength, kinematics etc. This stand paves the way to conducting diverse research, making quick changes to the structure and carrying out its optimization. This is especially appropriate in modern GTE design.

Data, Analysis, and Results

The investigation resulted in the establishment of a systematic approach to designing VGVs and creation of an original methodology for analytical assessment of characteristics of an engine's compressors, which consists of several stages, each of which fulfills its own tasks.

At the first stage a thermos-gas dynamic analysis is carried out. The following tasks are fulfilled:

- the choice of parameters of a projected engine and the performance of its design analysis;

- the choice of a law and a program of engine control and ensuring a line of combined action (LCA) based on the characteristics of a compressor.

The specified tasks are fulfilled with the help of ASTRA software package, which was developed at the Department of the Theory of Aircraft Engines of Samara State Aerospace University (Kuz'michev et al., 2014a). However, these tasks can be performed by means of other well-known programs of thermo-gas dynamic analysis, for instance, GasTurb. A realistic mathematical model of an engine is created during a thermo-gas dynamic analysis which takes into account its various characteristics, including the working medium's admission to and diversion from the engine mounts. The engine's parameters are optimized with a view to identifying minimum specific consumption in a cruising mode and the required takeoff thrust. The authors take into consideration the gas-dynamic analysis of the GTEs, the compressor and blade channels (Kolmakova, Baturin & Popov, 2014b; Kolmakova et al., 2014; Kuz'michev et al., 2014b; Matveev et al., 2014). A flow channel of an engine is constructed based on this analysis.

The next step is a detailed gas-dynamic analysis of a compressor which identifies the geometry of its rows and the parameters of the working medium in the given sections and points. The following tasks are fulfilled at this stage:

K-1. Measurement of flow quantities between the stages of a compressor. In the process of this task's fulfillment, the compression ratios of each stage π_{st} are identified, as well as total pressure heads P* and temperature T* at the inlet to every stage are calculated.

K-2. Calculation of cinematic parameters of a compressor at a medium radius. The fulfillment of this task establishes the values and directions of stream velocity per stages given the mean diameter and the open flow areas of the compressor flow path.

K-3. Calculation of cinematic parameters of a compressor at various radii. The values of speed and the directions of the flow are established which ensure the obtainment of ideal values of expended work and the compression ratio π_{st} under a particular law of the distribution of the swirl according to the height of a blade.

With regard to this study it is necessary to calculate the values of the flow on the sleeve, medium and peripheral radiuses of a VGV's first blade. In order to measure these values it is necessary to measure the values of the wheels in front and behind the analyzed VGV. The values at the outlet of the first wheel are the values at the inlet to the VGV. The values at the inlet to the second wheel are those at the outlet from the VGV.

К-4. Calculation of geometrical parameters of a compressor's blade row. In the process of the fulfillment of this task, geometrical parameters of a VGV blade are identified in three sections. These parameters include constructive angles, airfoil chords, airfoil coordinates etc.) (Fig. 2).

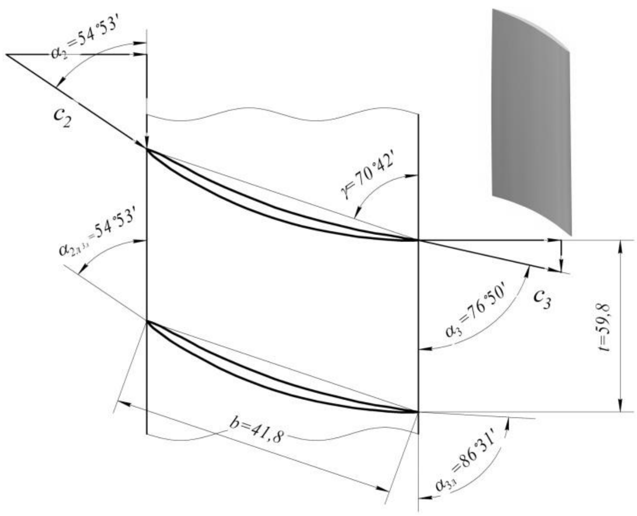


Figure 2. Cascaded airfoils of a VGV's first blade in medium section, 3D model of a blade

The tasks specified are fulfilled with the help of Kompressor Install software package, which was elaborated by Samara State Aerospace University. If needed, the results of calculations, which were obtained exclusively by analysis, can be collated with numerical analytical calculations of compressors made with the help of commercial software, for instance Concepts NREC.

A required storage of stability ΔK_y plays a decisive role in defining the angle of rotation $\Delta\gamma$ of a VGV. A less than a required amount of gad-dynamic stability ($\Delta K_y = 15$ percent is accepted for design calculations) is identified. We decided to apply VGV rotation at angle $\Delta\gamma$ in this mode. In order to determine the minimal $\Delta\gamma$, an analysis was carried out of a compressor in the selected mode of engine performance at some angle $\Delta\gamma$. The iteration method was used to select a minimal angle $\Delta\gamma$, at which $\Delta K_y \geq 15\%$.

These calculations resulted in the specification of the geometry of the stage (angles α_1, α_2, α_3, β_1, β_2, β_3), of the flow parameters in all the three sections (both total and static), and, most interestingly, of the characteristic of the stage as a whole. This implies that the calculation of a VGV rotation angle comes down to the calculation of the compressor's new characteristic.

In order to fulfill all the above tasks on the basis of the created arial module, we developed a program based on Howell's method, which offers an opportunity to build a compressor's characteristics automatically.

The interdependence proposed by Howell for low-speeds is widely used by designers of axial compressors and is built on the conditions of typical operations: the flow turning angle ε^* is 80 percent of the turning angle at the stall break ε_m. The choice of $\varepsilon^* = 0.8$, ε_m as a design condition is an engineering compromise. Howell established that the nominal angle of rotation in different compressor cascades depend primarily on the pitch-chord ratio b/t, nominal nozzle-stream angle β_2^* (rated nozzle stream angle for compressor rotor wheel) for flow rate factor (α_3^* is rated nozzle stream angle for the guide vanes) and the Reynolds number *Re*:

$$\varepsilon_{PK}^* = f\left(b/t, \beta_2^*, \mathrm{Re}\right) \quad (1)$$

$$\varepsilon_{GV(VGV)}^* = f\left(b/t, \alpha_3^*, \mathrm{Re}\right) \quad (2)$$

It is quite obvious that Howell's method is a simple and quite straightforward one for assessing the characteristic of a given stage in case of change of the lead angle of the flow. These data can be used also for solving a more complex inverse problem, namely the choice of an appropriate geometry of the cascade at a given angle of deflection. In this case, when the previous method of calculations of nominal ratings is used by rote, it is possible to obtain unacceptable values of the cascade pitch-chord ratio. However, a cascade pitch-chord ratio can be determined to a certain extent by the configuration of the compressor, when the critical angle of attack will coincide with the nominal one only by chance. Therefore the critical angle should be chosen arbitrarily.

Thus, the following computation algorithm was obtained:

A new characteristic of a compressor at zero degree angle of VGV rotation is calculated and entered into the ASTRA system in order to obtain a corrected line of joint action;

A stall margin ΔK_y is established:

$$\Delta K_Y = \left(K_Y - 1\right) \cdot 100\% \quad (3)$$

where $K_Y = \dfrac{\left[\pi_\kappa^* / q\left(\lambda_B\right)\right]_{BD}}{\left[\pi_\kappa^* / q\left(\lambda_B\right)\right]_{LSO}}$, where the values π_κ^*, $q\left(\lambda_B\right)$ are taken from the graph: $\pi_{\kappa гр}^*$ and $q\left(\lambda_B\right)_{BD}$ – from the surge limit line; $\pi_{\kappa LSO}^*$ and $q\left(\lambda_B\right)_{LSO}$ – from the local cost estimate.

We accept that $\Delta K_{y\min} = 15\%$. The modes are checked from the nominal mode to the cutoff with a 5 percent interval.

1. Inlet VGV is calculated. We assume from the outset that only the inlet guide vane will be controlled. In this mode of operations the VGV rotation angles are set at $\Delta\gamma VGVi$ ($\Delta\gamma 1VGV$). In the first calculation we recommend an angle

of $\Delta\gamma 1VGV = 5^{\circ}$ and subsequently to select it in the range between 0° and 40° with an interval of 5°. This will result in angle α_1, which will be necessary for subsequent calculation of a compressor's first stage, pressure p_1^* and temperature T_1^*.

2. The first stage of the compressor is calculated taking into consideration the selected $\Delta\gamma 1VGV$ and $\Delta\gamma VGVi$, where the vane ring of this stage serves as a VGV;

3. The next stage is calculated taking into consideration the fact that its input parameters are the output parameters of a previous stage. If a guide vane of some stage is a VGV, then this stage's $\Delta\gamma VGVi$ is taken into consideration. This point is repeated until the entire compressor is analyzed.

4. Thus we obtain the point of a compressor's new characteristic. In order to get the entire characteristic, the airflow G is changed and Points 3-8 are repeated. The result is a new characteristic of a compressor.

5. Using the ASTRA 2 system, a line of joint action is specified and the reserves of gas-dynamic stability are identified again. If $\Delta K_y < 15\%$, then the entire calculation of Points 3-6 must be repeated, after correcting $\Delta\gamma VGVi$ and introducing extra VGVs.

6. After the necessary reserves of gas-dynamic stability in a set mode are obtained, it is necessary to transit to the next mode, where small ΔK_y values are observed and analysis of Points 3-7 is repeated.

7. After this, a graph of variance of an individual ΔγVGV is created according to rotation frequency *n*.

Let us consider a compressor with three VGVs as an example. Fig. 3 shows the outcome of detuning a surge line as a result of a VGV blades' rotation (the continuous line represents the initial position at zero angles of a rotation, the dashed line shows the result of blades' rotation at set angles).

Based on the analysis of VGV functions, the following requirements with regard to its design are formulated: regularity of blade rotation, identical position of all the blades after rotation, impossibility of delay (jamming) in cinematic connections at the turn of the drive ring, ensuring reliability (of resource), including a system of control, taking into consideration the tandem arrangement of a large number of details. A use of elastic inserts and vibration dampers may prove useful for reducing the dynamic load in the system (Falaleev & Balyakin, 2014).

The technological requirements as regards the kinematic node clearly specify the time parameters of work, e.g. the time of relaying VGV blades when transiting from one mode of engine operation to another. Moreover, the operating conditions of a VGV's kinematic nodes, including temperature, acceleration in the process of aircraft evolution, may change in the process of operation. The kinematic mode must operate without scuffing under any flight conditions.

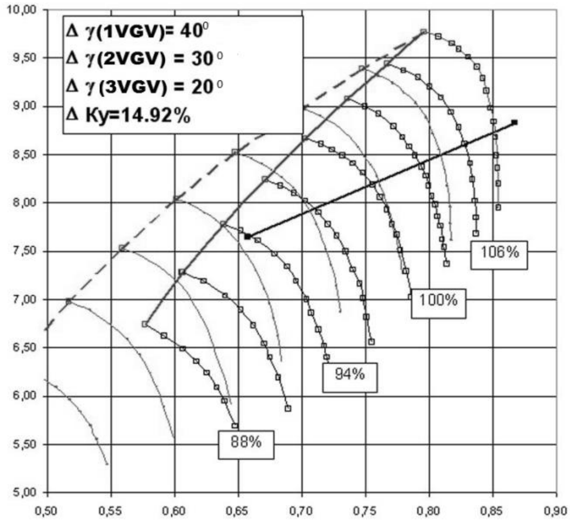


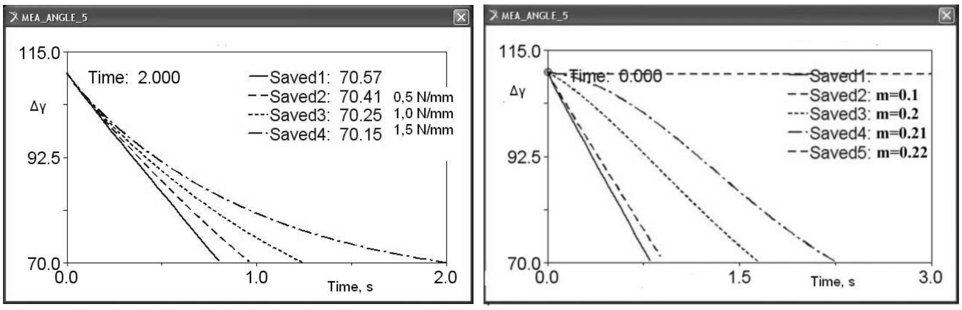
Figure 3. The characteristics of a compressor: obtainment of a required amount of gas-dynamic stability of a compressor

In the processes of design and construction of kinematic nodes it is necessary to 1) ensure efficiency of the kinematic chain; 2) rate for strength the elements of a kinematic node, 3) calculate the wear-and-tear of pivot pin bearings, 4) calculate the pressure demand and the geometry variables of the hydraulic drive, 5) ensure the implementation of set time parameters in the designed kinematic mode, 6) predict any emergency situations and off-design behavior of kinematic nodes. The fulfillment of the said tasks is complicated by the strains of a VGV kinematic node as well as complex operating conditions.

In order to calculate a VGV's engineering kinematics and stress loads in coupling, we applied MSC.ADAMS, a widely used software tool for virtual reality modeling of machines and mechanisms.

Figure 4. Solid model of a VGV

A cinematic model of a VGV mechanism was built and a number of experiments were conducted (Figures 4 and 5). The computer-aided design (CAD) model was created and parameterized using the materials (Ermakov et al., 2014; Kolmakova, Baturin & Popov, 2014a; Melentjev & Gvozdev, 2014).



a) b)

Figure 5. Dependence of the angle of VGV rotation (in degrees) on time at different values of a feedback transmitter's characteristic (a) and coefficient of friction in articulated joints (b)

Within the framework of this study, the stress load of a VGV blade is calculated using the ANSYS package (Fig. 6). Moreover, we suggested a methodology of establishing the pressure center of a set gas load and measuring the torque around the axis of a blade rotation, which is significant for calculating the kinematics of a VGV system.

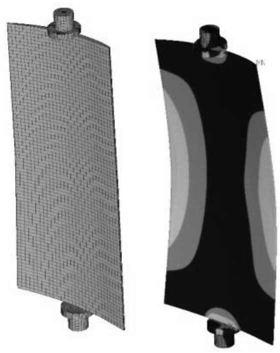


Figure 6. FEM-model of a VGV blade and distribution of tensions: maximal tensions 238 MPa, and 106 MPa on the airfoil

An finite element method (FEM) model is created using the three sections obtained as a result of a gas dynamic design of a GTE. Nine circular curves are evenly spread along the entire length of every obtained cross-section. Subsequently, coordinates are taken of the points of contact between the curve and the cross section. Entering and trailing edges are modeled by drawing lines that are tangent to inlet and outlet curves.

The lines on the opposite sides of the point of contact feature contain half of the length of radius of each curve. Thus, the extremities of the pressure side and the back of each section airfoil are obtained. The points are located in such a way that the segment connecting them is perpendicular to the center line of the airfoil. Such arrangement of points gives an opportunity to vary the thickness of the airfoil without dislocating the center of gravity of the section and the form of the center line. The coordinates of points are entered in the ANSYS tool as an array where they are used to create the model of a blade.

Axis Z coincides with the axis of the blade and directed from the sleeve section to the peripheral section.

An 8-node design finite element Solid45 was used for creating the grid. This mode presupposes an application of a gas load at every node on the surface of the pressure side. An opportunity exists of varying the number of elements in the generated grid, which is accompanied by automatic redistribution of nodal loads.

Discussion and Conclusion

The methodology has never been applied before. However, some of its stages, especially the ones dealing with the strength calculations and a preliminary design analysis of a gas-turbine engine's passageway, have already been applied in Russian and international design bureaus. The comprehensive approach suggested by the authors paves the way to a more efficient VGV design using multidisciplinary models. It includes an analysis of impulse wave turbine VGVs which was developed by A. Thakker & J. Jarvis (2009), joint actions among systems of VGVs and seals and vibration dampers of aircraft gas-turbine engines (Kuz'michev et al., 2014a; Matveev et al., 2014; Falaleev & Balyakin, 2014).

Calculation of film cooling in VGV turbines according to K.A. Thole's method (Bogard & Thole, 2006), using VGVs in Wells and Francis turbines (Xiao & Sun, 2012), as well as other important tasks.

Thus, as an outcome, we have a virtual stand of a VGV system, in which most problems of design (gas dynamics, strength, kinematics etc.) have been solved. This stand offers an opportunity to conduct various research, make prompt changes to the structure and optimize it, which is especially important in the present conditions of GTE design.

The final layout is built on the basis of this stand which will be embodied in metal and debugged. However, the virtual stand helps to considerably reduce the time of final finishing of a product as well as material and labor costs.

The authenticity of the proposed methodology of VGV design is based on the internationally accepted methods of the theories of strength, elasticity and plasticity of materials, fundamental research in the area of gas dynamics of airflow, mathematical analysis and statistics, as well as classical methods of theoretical mechanics and dynamic analysis of mechanical systems (Belousov & Nazdrachev, 2014; Oberkampf, Trucano & Hirsch, 2004; Wasfy & Noor, 2003; Makhavikou, Kasper & Vlasenko, 2014). The obtained data agree in qualitative terms with the results of experiments conducted by various authors. The verification of results of computational modeling, which consists in a sum-total of research assessing the adequacy of the models developed to the real objects of research and the workflows in them, is based on collating the results of the study with experimental and analytical data. The simulation-related research of the workflows in the objects of research, for instance, in CFD-analysis, is noted for its complex 3D geometry and characterized by a large number of physical phenomena. Therefore we have broken this process up into simpler stages.

The validity of methodology employed by this approach is verified using sequential modeling of individual physical phenomena, as well as using simple geometry, which are then gradually complicated and are transferred onto a more complex geometrical plane. This process is described at length in a number of works (Kuz'michev et al., 2014a; Kuz'michev et al., 2014b; Oberkampf, Trucano & Hirsch, 2004; Ryazanov, Urlapkin & Chempinskiy, 2013). The most difficult aspect of the verification process is obtainment of experimental data which are the basis for assessing the validity of the results of simulation. The principal bases of experimental data for the objects of the study are presented in (Xiao & Sun, 2012).

At present the issue of a cut-through transfer of information along the chain of virtual modeling remains unresolved. Although the resulting data of one module are the input data for another module, it is necessary to export and import them by hand, simultaneously reformatting them, which entails extra labor costs.

This is also an obstacle to the obtainment of results in ways that would provide for their accuracy after comparison and analysis.

Implications and Recommendations

The subject of this paper is relevant in view of the fact that the universal scientific discourse does not have a common methodology of designing and finishing work of regulatory systems of VGVs of gas-turbine engines, and the task of creating a methodology for the design of such systems is topical. Such a methodology would help to avoid costly experimental research at the stage of detail design and to cut time, labor costs and spending on design. The tasks that it helps to fulfill are of practical importance for creating a new generation of gas-turbine engines and upgrading the current models of aircraft.

Thus, the process of VGV design can be presented as follows:

1. Thermo-gas dynamic design:

- a thermo-gas dynamic calculation of a compressor is carried out in rated conditions and the modes are identified in which the values of coefficients of gas-dynamic stability are insufficient;
- the angles of VGV rotation as well as their number and locations are identified according to Howell's method.

2. Cinematic design of VGVs:

- a law of controlling a VGV is chosen;
- a system of controlling a VGV is chosen;
- a structure of elements of a VGV is chosen;
- a preliminary layout of a VGV is chosen;
- preliminary measurements (gas load, pressure in the hydraulic actuator etc.) are made.

3. Parametric 3D modeling of a VGV:

- Parameterization of details (analysis and planning of a detail taking into consideration the specifics of mock-up work pieces for the system of strength analysis and cinematic modeling);
- Construction of parameterized assemblies;
- Conversion of an obtained model into packages of cinematic analysis and strength calculations.

4. Conducting cinematic and strength calculations:

- simulation of work of all VGVs in all modes in an MSC.ADAMS package;
- modeling of emergency situations on a virtual stand in MSC.ADAMS;
- measuring the structural components for strength in ANSYS package.

5. Final layout of a VGV.

The methodology of design presented in the paper, which includes thermo-gas design of an engine and its mounts, profiling of the compressor flow path, analysis of design of the cascades of guide-vanes allows one to avoid a great amount of costly experimental research in the process of creating a gas-turbine engine. The data obtained in the study according to Howell's method help to resolve the theoretical problem of assessing the influence of VGV blades' angles of rotation on the characteristic of a compressor. As a result of this, a required VGV number for ensuring gas-dynamic stability of a compressor is established. The finite element model of a VGV blade helps to fulfill the tasks of strength and tune-out of the resonance in the field of operating frequencies of a compressor as well as establish the pressure center and the location of the pivotal point of the blade. The cinematic and dynamic analyses help to examine the most rational patterns of implementation of a VGV system of an axial-flow machine.

Disclosure statement

No potential conflict of interest was reported by the authors.

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