INTERDISCIPLINARY COMPLEX DESIGN OF MODERN HIGH AND LOW PRESSURE TURBINES

M.Ja. Ivanov*, S.V. Kharkovski*, L.A. Magerramova*,
R.Z. Nigmatullin*, V.D. Venediktov*
***Central Institute of Aviation Motors, Moscow, Russia**
ivanov@ciam.ru; nigmarz@ciam.ru

Keywords: *turbine, optimization, cooling scheme*

Abstract

This paper presents unified interdisciplinary mathematical models of gas dynamic, heat transfer, strength and vibration processes, which take place in high and low pressure turbines of modern aircraft engines. These models are relevant to high class models based on real 3D geometry of whole flow path. They are also based on three-dimensional (3D), quasi-three-dimensional (quasi-3D), two-dimensional (2D) and one-dimensional (1D) approaches. The models can be applied either in isolated unit components or in entire turbines. All approaches are closely connected among themselves. Together they form the dynamic system for efficiency analysis and design of turbine flow path. These methods of working process modeling consider all main features of turbine working process (viscous losses, air bleed and blow out, leakage from flow path, rotor and stator thermal dilatation, air humidity, rotor inertia and so on). Steady and transient modes of turbine operation could be simulated via these models.

1 Introduction

The unified gas dynamic model of the entire high and low turbine flow path is considered below. The direct problem for specified flow path is being solved from the position of internal aerodynamics. The initial system of equations (Euler or Navier-Stokes) should be written in divergence form for the cylindrical coordinate system, which coincides with engine axis [1]. Rotor motion equations should be added to the initial system.

For the convenience of numerical integration the initial system of equations can be written with the use of curvilinear coordinate system adapted to surfaces of flow path elements. The writing form of initial system of equations remains divergent. Equations can be integrated via CFD method based on Godunov’s scheme [1]. Turbulence effects are described via two-parameter turbulence model (see [1] for details).

Unified 2D models play an important role in the analysis of turbine aerodynamics. These models can be obtained from the initial system of equations via radial or circumferential coordinate averaging. The 2D problem definition on S_1 plane in variable thickness layer containing cascade can be obtained via radial coordinate averaging. The problem on S_2 plane is obtained via circumferential averaging. Equations of transient 1D flows can be obtained from 3D equations via radial and circumferential averaging (or via radial averaging of S_2 plane equations). The method preserves a many features of S_2 approach: exact solution near inlet and outlet edges, transonic effects, compatibility with shock waves and so on [2].

Proposed methods are extensively used for optimization of turbine parameters (stage distribution of heat drops, the selection of reactivity ratio and so on) under input limits. The methods are also used for performance calculation of turbine or its subassemblies.

The work contains a lot of practical applications for high and low turbine designing with the use of considered approaches. The results of such calculations practically coincide with experimental data and parameters of already realized turbine projects.

2 Aerodynamic design

Design of modern turbines is a complex multi-disciplinary problem.
Common scheme of aerodynamic turbine design is shown in the Fig. 1 (for cooled turbines).

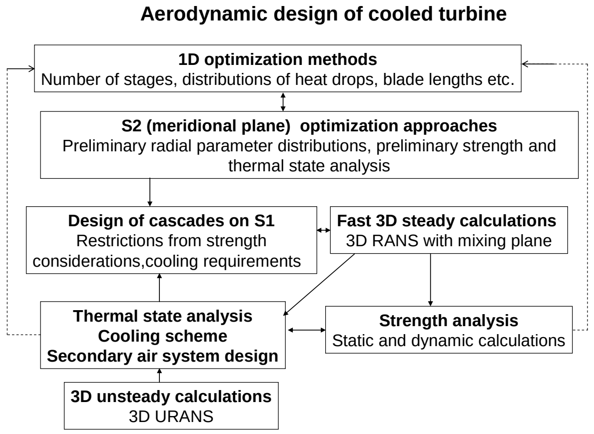


Fig. 1. Common scheme of aerodynamic design of turbine.

At the initial stage of the design a determination of turbine flow path shape is performed, the flow path geometry determination can be combined the optimal distributions of parameters along stages and rows. The flow path geometry determination is performed at the given geometrical restrictions. For example, inlet section can be given (fixed), or tip surface radius can be restricted etc. Similarly, main gas flow parameter distributions can be selected under given restrictions. Some of these parameters are fixed, for example, inlet flow parameters: total pressure p_0^* and temperature T_0^*, flow angles, mass flow rate G_0. Rotor speeds n_j are also usually given. At the exit section total or static pressure can be specified, or output power is given etc. Heat drops along stages and rows can usually be selected arbitrary within some limits.

To get optimal parameter distributions, an averaged problem (1D) of gas flows in the multistage turbine is solved. Losses are estimated based on semi-empirical dependencies for turbine (or compressor – for outlet guide vanes) cascades and rows.

Based on this information, an optimization of turbine gas flow (and geometrical) parameters is fulfilled based on some descent methods. At the optimization process it is important to choose criterion function. In many cases optimal requirement is (for given pressure ratio): $N = max$, where N – output power of the turbine. In this case swirl at the turbine exit is usually automatically small. Sometimes it is rational to require maximum of efficiency: $\eta^* = max$, but in this case often swirl appears behind turbine and OGV can be used.

This optimization procedure is accompanied by cooling and strength estimations, additional geometrical restrictions appear, so this procedure is solved several times.

Obtained at this stage averaged (at mean radius) turbine parameters can then be used at the generation of radial parameter distributions in the flow passage.

Initially, these radial distributions are determined using meridional calculation methods, when the flow field is considered on so called S_2 surface. Both Euler and RANS calculations methods can be used.

In these approaches governing equations are written in conservative form using curvilinear coordinates $\xi = \xi(z, r, \varphi)$, $\eta = \eta(z, r, \varphi)$, $\zeta = \zeta(z, r, \varphi)$. The coordinates (ξ,η,ζ) are chosen so that the surfaces ζ=const are stream surfaces. Then the relation takes place:

$$u\zeta_z + v\zeta_r + w\frac{1}{r}\zeta_\varphi \equiv 0 \qquad (1)$$

where (u,v,w) is velocity vector components in cylindrical coordinates. Other coordinates (ξ,η) can be chosen so that the conditions are fulfilled:

$$\begin{cases} \xi_z \zeta_z + \xi_r \zeta_r + \dfrac{1}{r^2} \xi_\varphi \zeta_\varphi = 0, \\ \eta_z \zeta_z + \eta_r \zeta_r + \dfrac{1}{r^2} \eta_\varphi \zeta_\varphi = 0 \end{cases} \qquad (2)$$

As a result, the main governing equations can be written in the next conservative form:

$$\frac{\partial}{\partial t}\left(\frac{r\overline{U}}{J}\right) + \frac{\partial}{\partial \xi}\left(\frac{r}{J}\left(\overline{F}\xi_z + \overline{G}\xi_r + \overline{H}\frac{1}{r}\xi_\varphi\right)\right) + \frac{\partial}{\partial \eta}\left(\frac{r}{J}\left(\overline{F}\eta_z + \overline{G}\eta_r + \overline{H}\frac{1}{r}\eta_\varphi\right)\right) = \frac{\overline{h}}{J} + \overline{h}_1 \qquad (3)$$

where right hand side does not contain derivatives of gasdynamical parameters.

One of the main advantages of this approach is its robustness for the cases when strong discontinuities are in the flow passage, so it is efficient also for trans- and supersonic turbine stages (for more details see [1]).

The described direct problem is used in the optimization process. As for the averaged methods, it is convenient to use the requirement *N = max*, where *N* – is turbine output power. In this case flow direction at the turbine exit usually is fairly uniform and close to axial direction.

The described optimization procedure is repeated several times with additional restrictions for cooling and strength.

Obtained distributions of parameters can then be used for the profiles generation at different sections of the vanes and blades (in this process optimization methods are applied on the surfaces of revolution S_1). Simultaneously, cooling system is designed, and strength calculations are performed.

Then the turbine geometry optimization is fulfilled using 3D RANS calculation methods. It is iteration process (Fig. 1).

Finally, unsteady URANS calculations are performed to get more accurate temperature fields, etc.

Some examples of realized turbine design are presented.

The first example is a designed turbine for small aviation engine (Fig. 2). Single stage high pressure turbine is cooled, total pressure ratio is π*~4.0. In these conditions either vane or blade row (or both) work at supersonic velocities. The comparisons of calculated and experimental data for the turbine efficiency are shown in the Fig. 3.

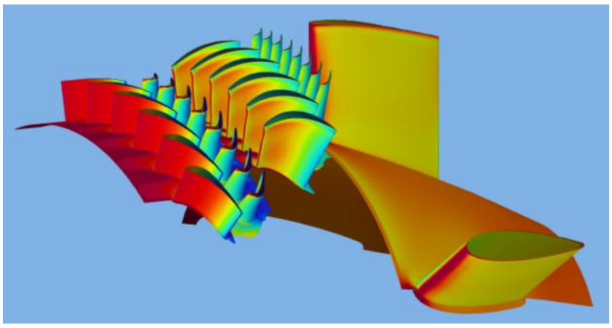


Fig. 2. High and low pressure turbines for small aviation engine. Isentropic Mach number field.

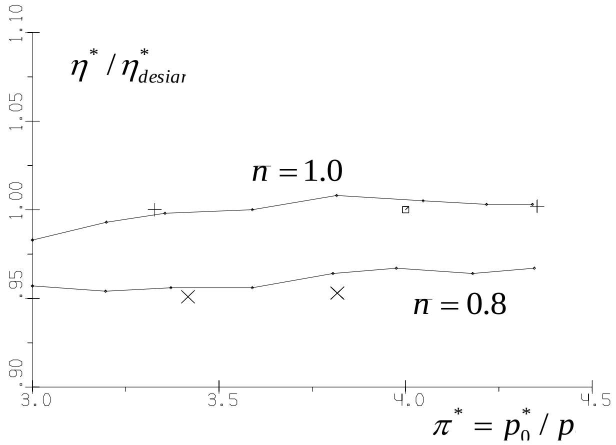


Fig. 3. Some results for High Pressure Turbine: solid lines – experimental data for $\bar{n}$ =80%, 100%;
□ – design intent;
+ - 3D RANS calculation at $\bar{n}$ =100%;
× - 3D RANS calculation at $\bar{n}$ =80%.

In the second example a redesign of 2-stage power turbine for industrial Gas Turbine is considered (Fig. 4,5). In the initial turbine velocity distributions along the vanes and blades profiles had unfavorable character (see Fig. 4, boxes). The profiles are fore-loaded with large zones of decelerating flow at suction side of rotor blade row. After the redesign process (on the base of the described methods) the blades have more favorable velocity distributions (see fig.4, solid line). As result, the modified turbine has significantly smaller losses (fig.5) and higher efficiency.

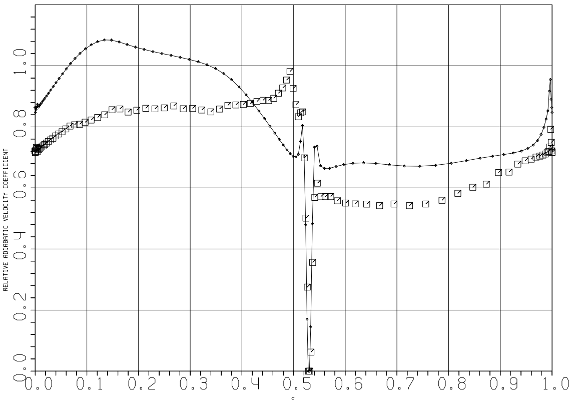
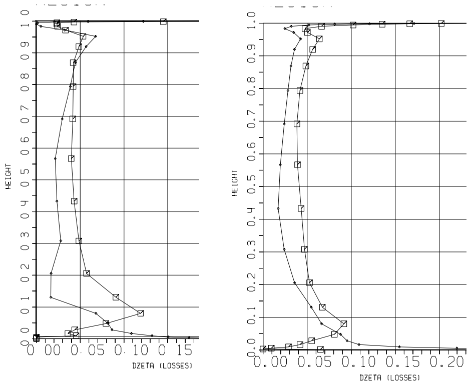


Fig. 4. Isentropic Laval number distributions along the profile arc length. Hub section of rotor blade row. Initial and modified versions. (Boxes – initial geometry, solid line – new design).



I stage II stage

Fig.5. Distribution of kinetic energy loss coefficient along height for initial (boxes) and modified (solid line) rotor blade rows.

In the next example a result of whole turbine design for industrial Gas Turbine is shown. The turbine is 3-shaft, high pressure turbine is cooled (Fig. 6).

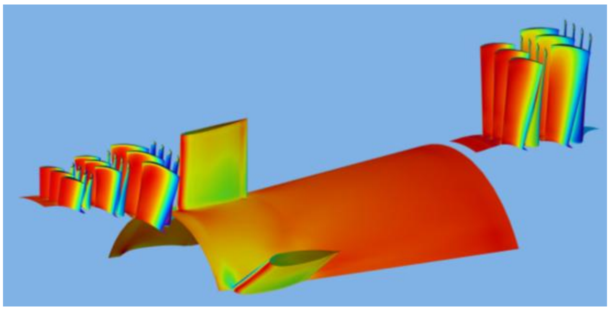


Fig. 6. Turbine for industrial Gas Turbine (Isentropic Mach number distributions).

During the design of power turbine a number of problems were solved.

Initial versions of the power turbine (Fig. 7) had high efficiency and satisfy static strength requirements. But 3D vibration strength analysis for whole blade row has shown that dangerous resonance can appear near main working regimes.

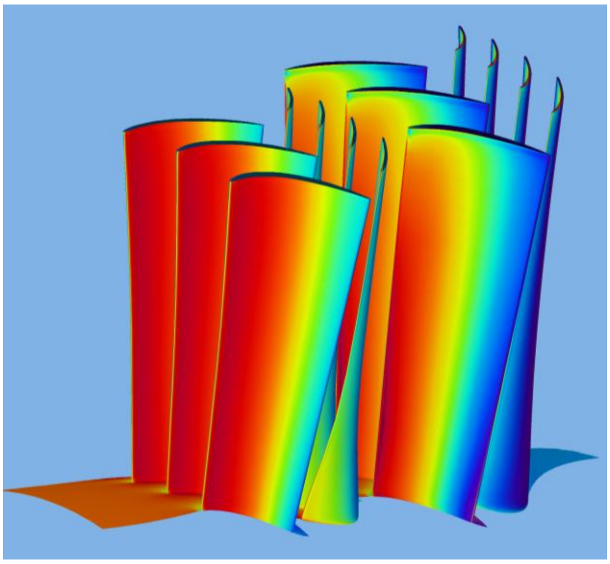


Fig.7. Power turbine for perspective Gas Turbine. Initial version of geometry. Isentropic Mach number distribution.

After a number of iterations a variant was generated where all strength requirements were satisfied and the turbine efficiency was high (Fig. 8).

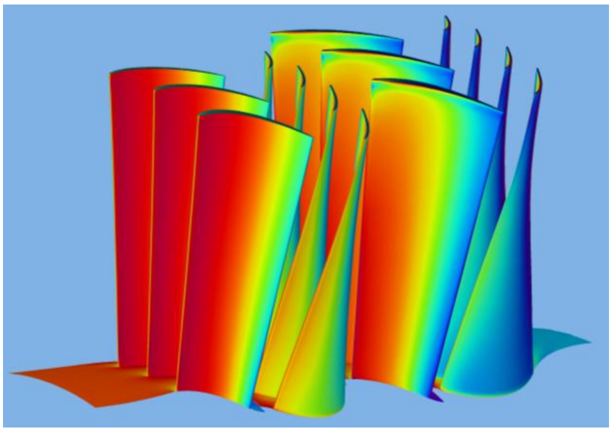


Fig. 8. Power turbine for perspective Gas Turbine. Next version of geometry. Isentropic Mach number distribution.

But the blades become thick and heavy, and as a result more material costs were expected. Besides, increased Mach number level behind the turbine led to increased losses at outlet the diffuser.

Final optimal geometry satisfied to all requirements (low cost, static and vibration strength requirements, high efficiency), Fig. 9. It is interesting that for all considered versions of geometry the turbine efficiency had practically the same (high) value.

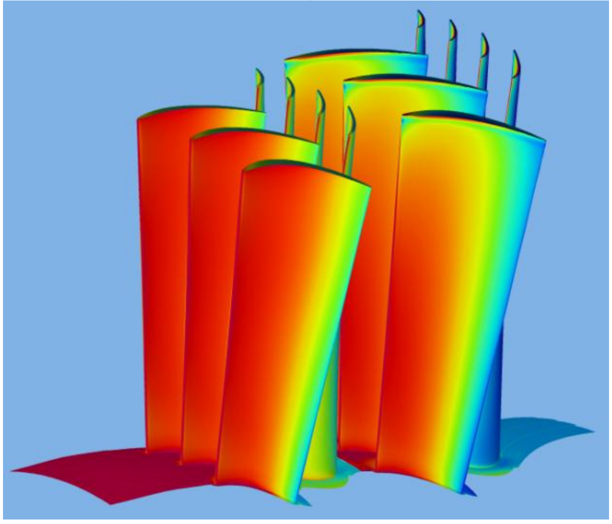


Fig. 9. Power turbine for perspective Gas Turbine. Final version of geometry. Isentropic Mach number distribution.

2 Design of cooling system

Reliability and working capacity of gas turbine engine during all life cycle depend first of all on a thermal condition of elements of a design of turbines - blades, disks, cases and others, both on stationary, and on transitive modes. Experimental definition of fields of temperature of the turbine on operating conditions (for example, on a mode of the maximum loading) engine works is practically impossible. Therefore, a basis for calculation of static durability and cyclic durability of elements of the turbine in all spectrum of operating conditions are settlement fields of temperatures. This field is also a basis for calculation of a condition of backlashes, both in labyrinth consolidations, and between the case and working shovels.

The field of temperature of each detail is defined by heat transfer conditions on its surfaces (borders) and material thermal properties of a detail. Boundary conditions of heat transfer are defined by both of gas streams and cooling air parameters. Parameters of air stream depend through heat transfer on temperature of a surface of a detail, that is from a counted temperature field. The problem, in which boundary conditions depend on the solution, is called as conjugated. Thus, there is a necessity of the decision of the interfaced problem of heat transfer or, in other words, definition of a thermal condition of a detail. The thermal condition of a detail is interconnected set of a temperature field of a detail and boundary conditions of heat transfer on its borders.

It is necessary to notice, that recently a wide circulation in the world including leaders Design Buro of Russia, receive 3D methods of modeling of a stationary thermal condition of turbine details, first of all - cooled blades. Modeling is conducted in joint statement of the decision of a problem of heat transfer between gas and a solid body. Various models of turbulence are used. Problems 3D external heat transfer, 3D a viscous flow and heat transfer in cavities of cooling system and 3D the heat conductivity equation are generally solved. It is possible to underline that methods $3D^3$ modeling of a stationary thermal condition, as a matter of fact, are developed. As well as any other settlement method, $3D^3$ requires verification with use of the various experimental data received both in modeling, and in natural conditions. Now verification processes 3D methods of calculation of heat transfer proceed, there is a gradual generalization of settlement-experimental results.

However application $3D^3$ methods remains very much and very much labour-intensive process, that practically does not allow to count a non-stationary thermal condition of cooled blades and other basic details and units of GTE.

Therefore objectively there is a necessity of modeling of non-stationary processes of heat transfer and heat conductivity by means of fast, exact and, certainly, verified methods.

In CIAM the wide spectrum of techniques and complexes of applied programs on numerical modeling of a thermal condition of details GTE which includes flat, axisymmetrical, quasi 3D and three-dimensional models is developed. The given spectrum of models allows to count cooled vanes and blades of the turbine, disks of rotor wheels and covered deflectors, shaft, regiments nozzle guide devices, the case, stator design details.

Each of complexes of programs essentially consists of following blocks:

- The module of construction of geometrical model and its automatic splitting into final elements;
- The module of construction of hydraulic model;
- The module of an establishment of conformity between geometrical and hydraulic models;
- The module of calculation of hydraulic networks;
- The module of calculation of boundary conditions of heat transfer on design surfaces;
- The module of the decision of the stationary and non-stationary equation of heat conductivity (two-dimensional or three-dimensional).
- Modules of visualization of the initial information and results of calculation of a thermal condition (the flat and three-dimensional drawing).

The heat conductivity equation dares in the presence of thermal sources (drains), under boundary conditions of the second and third sort, including radiant heat transfer, conditions of contact heat transfer.

Integration of the equation of heat conductivity is carried out with use of a method of final elements. Result is the system of the linear algebraic equations, concerning unknown values of temperature in grid knots. For a two-dimensional case as a final element are used three or six central triangles. In a three-dimensional case triangular prisms with 6 and 12 knots, and also volume elements of higher order are applied four or ten central tetrahedrons. Integration of a linear triangle and a tetrahedron is carried out analytically, and other final elements - numerically.

The technology of construction of model of a heat-hydraulic state of cooled turbines is developed and applied. The technology consists of following stages:

1. On the basis of the computer drawing of the engine (AutoCAD, UniGraphics) construction of geometrical model, a portrayal of hydraulic model, a conformity establishment between geometrical and hydraulic models, initialization of geometrical sub-areas is carried out.

2. Construction of finite elements mesh

3. Initialization of hydraulic sites, construction of a hydraulic network

4. Information generation on factors of hydraulic resistance, the throughput areas, heat transfer laws on hydraulic sites. Formation of a contact heat transfer zones

5. Formation of zones of heat transfer on other surfaces and the specification for them heat transfer laws. Formation of angular coefficients for calculation of radiant heat transfer

6. The specification thermophysical properties for geometrical sub-areas.

7. Formation of data for definition of parameters in boundary knots of hydraulics and heat transfer calculation on design surfaces (for a non-stationary mode - for example, in a flight cycle).

Calculation of a stationary and non-stationary thermal condition of rotors is carried out with application interfaced axisymmetrical models of a thermal condition of design GTE. Distribution of air mass flow on branches of cooling systems GTE is defined at calculation of an one-dimensional current on branches of the equivalent hydraulic model with use of typical hydraulic resistance. Distributions of mass flow and tangential components of velosity, pressure and temperature in disk cavities are defined from the calculation of system of the one-dimensional differential equations of movement, energy, indissolubility and a sate. For friction factor on stator and rotating surfaces are used experimental criteria correlations. For calculation of flow in other elements of cooling system the generalized data about pressure losses are used. Calculation of heat transfer coefficients on a rotating disk surface is defined on a basis criteria equations obtained from the calculations of the boundary layer equations with use of experimental data about a radial profile velocity in an boundary layer of a disk, rotating in unlimited space. For calculation of heat transfer coefficients on other surfaces the generalized data on heat transfer are used.

The example of modeling of a non-stationary thermal condition of HPT disk in a cycle «ground idle», «flight idle», a mode «0.7 rated loads», "take off" is resulted. Parameters in supplying air system are calculated for each of four modes. Calculations have been carried out at constant gap values in labyrinth seal. Calculations results - values of tangential and flow rate velocities, temperature and pressure on hydraulic network branches - were used for calculation of heat transfer boundary conditions on each time step at the calculation of a heat conductivity problem.

Parametrical investigation of influence of the account natural convection on a disk thermal state is carried out. On the fig. 10 variations of heat transfer coefficients in characteristic points of disk surface during unsteady process is shown. Results of comparison of non-stationary temperature fields at various heat transfer models it is shown on the fig. 11. It is clear, that difference makes to 40°C and therefore, should be considered at an estimation of the strength-strain state.

On the fig. 12 comparison of calculation results of a unsteady thermal state in characteristic points of disk with experimental data is resulted. As a whole satisfactory coincidence is observed. The greatest divergence takes place for points 28 and 35 - from 40÷60°C. As points 50 and 36, located on a stream below a point 28, give better coincidence, that, possibly, indications of the thermocouple 28 are a little overestimated. As to higher experimental temperature values for a point 35 and, partially, the points 36, located on a back disk surface probably here takes place inflow gas from turbine gas path.

On the basis of the considered example, and also on the basis of other various parametrical researches carried out in CIAM, following methodical requirements to modeling of a unsteady heat-hydraulic state of cooled turbines have been developed

1. The calculation in uniform statement of problems of hydraulics, boundary conditions of heat transfer, heat conductivity

2. Calculation of air heating on each time step

3. Heat transfer calculation on surfaces of disks taking into account change of parameters of the swirled stream

4. Calculation of unsteady heat transfer coefficients taking into account natural convection on construction surfaces.

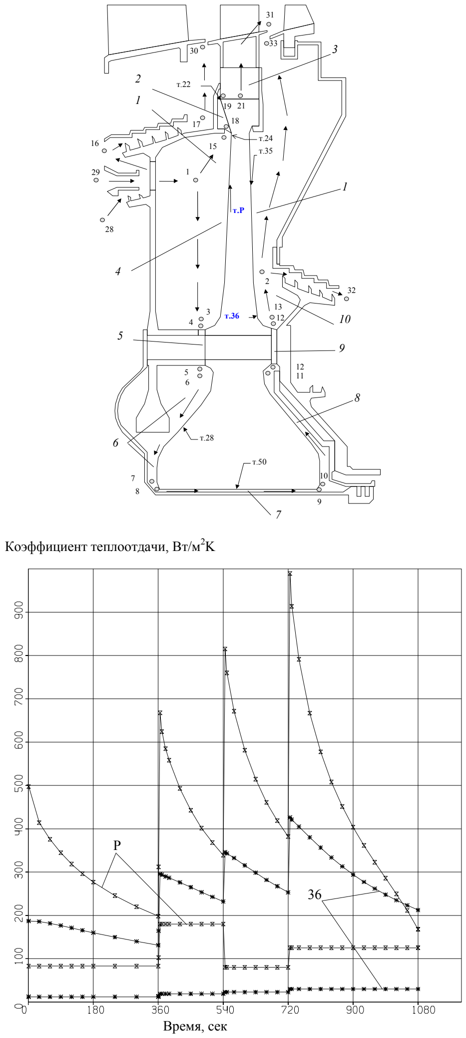


Fig. 10. Comparison of heat transfer coefficients calculated as for forced and natural convection

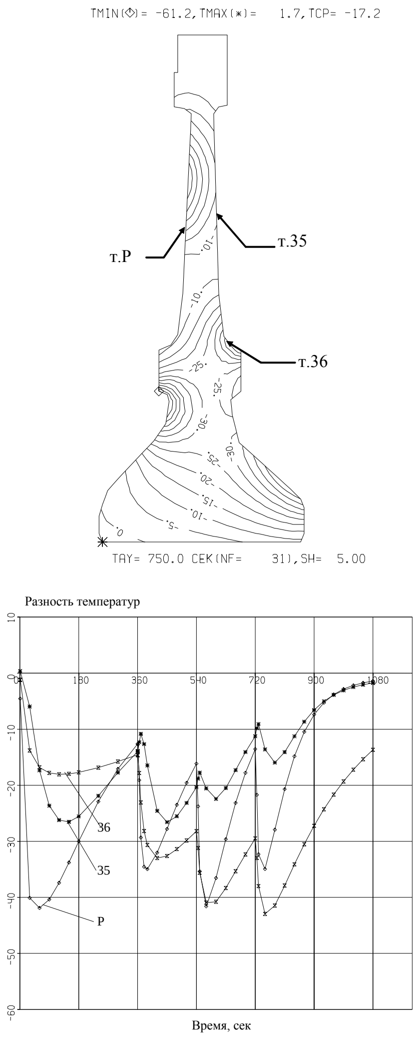


Fig. 11. Variation of temperature difference $\Delta t=t_{fc}-t_{nк}$ of calculation results with out take into accont (t_{fc}) and take into account (t_{nc}) natural convection in some point of disk

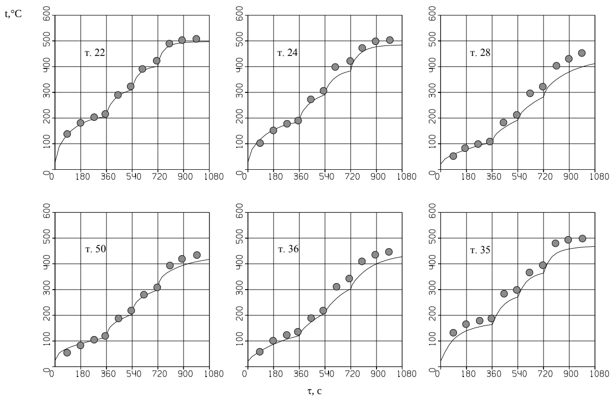


Fig. 12. Comparison of calculated and experimental values of temperature for some points of disk on unsteady modes (for pointg number see fig. 10)

3 The strength investigations

The turbine wheels are one of main subassembly of gas turbine engine, which formed its key parameters. Turbine parts work at high level of temperature on stationary and un-stationary regimes on the assumption of cyclic loading and evolutions of aircrafts.

Turbine blades undergo of the hostile environments, high temperature gradients, centrifugal and gas loads.

The calculations of stress strain state (SSS) and strength of these blades is necessary to made with take into account elastic, plastic and creep deformations, temperature fields and the changing of properties of blade alloys on continuous duty. The load factors, multiduty operations on the assumption of flight cycles, stationary and transient regimes are necessary to take into consideration for strength calculation of turbine blades also.

GTE designing for blade's strength calculations different level models are used [3]. These calculations in the aggregate with calculations of gas dynamic and temperature state allow to made optimal structure.

The strength reliability assurance of turbine blades in the conditions of the disturbing factor such as high cycle fatigue and deterioration come to be by calculation and tests methods. Particularly the works for exception of fluid-induced vibrations and dangerous resonance oscillation are carried out for prevention of fatigue failure with help the test determinations of vibration stress and endurance limit.

The modern design methods of complex blades and nozzle vane are based on generations of mathematical models, which are used for gas dynamic, thermal and strength calculations. The different models are used on the difference stage of a project.

The static strength of turbine blades fabricated from plastic alloys can be determinate with help the stem calculate scheme and the two-dimensional finite element analysis by calculations of the average stresses of cross sections. The zones of the plastic deformation and local stresses found with help elastic-plastic and creep effect calculations are necessary to determinate for the blades fabricated from low-plastic alloys. The margins of static durability of these blades are necessary to determinate with help alloy characteristics of creep-rupture strength.

At initial stages of the designing the strength calculations of blade airfoil can carry out with help the one-dimensional (1D), two-dimensional (2D) and quasi three-dimensional (Q3D) model which based on flat cross-section hypothesis.

Calculations of the steady-state strength and the cycle fatigue life at all engine working regimes allow to draw a conclusion about the further designing expediency and reveal the most blade working regimes from viewpoints of strength. High-level models are used for more precise determination of SSS in the most stressed zones of a blade.

Three-dimensional (3D) model with three-dimensional finite element method provides the more exact simulation of design features of cooled turbine blades. It is very important for structures of complicated configuration, zones with holes, corners and so one.

The calculation methods for increase of the resource

The calculation methods for increase of the resource are based on:

- The choice of blade and disk alloys,
- The gas dynamic optimization of the blade airfoil,
- The choice of optimal cooling system,
- The optimization of the center of figures locations,
- The design optimization with take into account the preclusion of “dangerous” resonance vibrations,
- The construction of the devices for oscillation damping of blades,
- The local optimization of the zones of holes, fillets, partitions and so ones,
- The design optimization of the blade shrouds, platforms, roots, lock joints,
- The choice of the optimal assembly oversize of the shrouds,
- The optimization of the crystallographic orientation of the single crystal blade alloy,
- The choice of the coatings,
- etc.

The most accuracy data of the durability and dynamic behavior of turbine blades can calculate with help:

- 3D modeling of the observable element,
- Accounting of the material anisotropy,
- Accounting of the changing of the material properties during operation,
- Accounting of the changing of the SSS during flight cycles.

The locations of the “dangerous” zones (on inlet and outlet blade edges, perforating holes, fillets up and dawn platform and shroud etc.) can reveal by 3D modeling. The 3D modeling make possible to design these zones. For example the choices of the rational configuration of the blade outlet edge permit to increase the calculating durability more than 10 times.

The shroud configuration is described by gas dynamic, dynamic objectives, strength and negative allowance during operation which influences to mention parameters. The necessary value of the assembly negative allowance can define on base the stress of “dangerous” zones and correspond to permissible margin.

The recommendations for design of lock joints, its installations angles, presence and sizes of the partitions, radius of the fillets and so ones can be done on base investigations of influence of these geometrical parameters on its strength. For example change of the lock joints installations angles allow to increase cyclic durability of the disk lug in several times.

Special design of single crystal blades

Single crystal (SC) and directionally solidified-cast turbine blades are widely used in modern aircraft gas-turbine engines due to its ability to operate at high temperature.

The basic high strength “superalloys” advantages are the following:

- increased high-temperature creep resistance due to absence of boundaries between the grains,
- decreased modulus of elasticity in the direction of crystallization (<001> direction) comparing with the alloys having an isotropic structure. It leads to considerable decreasing of thermal stresses and rising of the low-cycle fatigue life.

Using the modern SC nickel alloys for turbine blades production gives the opportunity to create high efficient aircraft GTE with increased resource of the hot part.

The properties of these signal crystal alloys on macro level are cubic symmetry. That is be considered as single crystal with ideal face-centered cubic structure.

Essential anisotropy of characteristics of such alloys has brought about a need to create mathematical models of SSS and strength of single crystal blade. The development of the criterion of strength and long life time, simultaneously accounting the stress-rupture strength and low cycle fatigue (LCF) damages, was necessary also.

The design strength calculations of single crystal blade airfoils can carry out with help Q3D model which allow anisotropy properties of elastic, plastic, creep and long-term strength and optimize angles of azimuthal orientation into blade [4].

The calculation investigations [5] were shown that the position of single crystal into blade has an effect on SSS and static durability. The axial orientation is significant influence. The optimal axial orientation is established and used for casting of cooled blades. But the permissible variation (10°) influences to durability too.

The influence of azimuthal orientation on the margin of static strength is insignificantly. But this effect can increase for high temperature and temperature gradients. The influence of azimuthal orientation on the static durability can be appreciably. The regulations of axial and azimuthal orientation allow increasing availability of blades.

In addition the single crystal orientation has an influence on the natural frequency spectrum of blades because the moduli of elasticity for difference directions are differed more than 2 times. The technological deviations of the single crystal orientation are increase scatter of frequencies and danger of resonance on operating regimes. This specificity must be taking into account [6, 7].

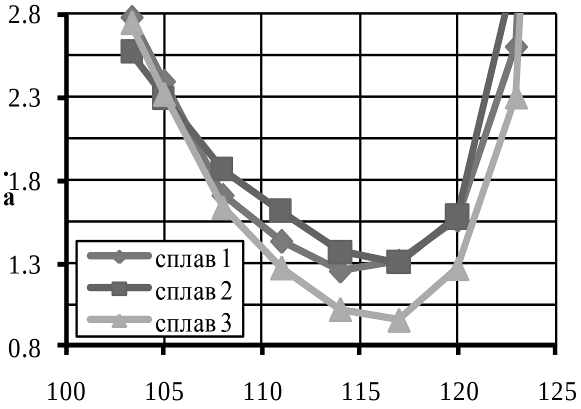
The calculation of static strength with creep effect

The turbine blades work long time in condition uniform temperature fields and high loading. The blade SSS is change during operation because of alloy creep effect.

Three-dimensional models and physically non-linear properties of alloys is necessary to use in calculations for acquisition more reliable results.

The calculations of static durability without taking into account stress relaxation give conservative value of static strength margins.

The performed investigations of the stress relaxation and strength of turbine blades with taken into account different ways and hypotheses of material behavior in conditions of long loading [8, 9] allow to increase calculation resource. In addition the rational choice of alloy may increase of calculation durability in several times.



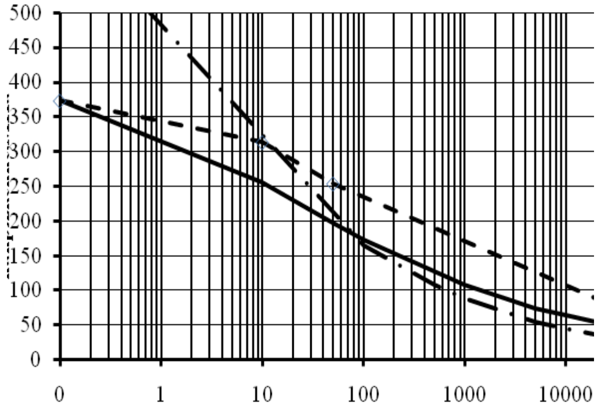


Fig. 13. Changes minimal strength margins along height of the blades manufactured from different alloys (upwardly) and example of determination permissible resource

The changes minimal strength margins along height of the blades manufactured from different alloys is shown at Fig. 13 upwardly.

The determination permissible resource on the blade “dangerous” zones in during operation can make next method. For example there are the changes during operation regime of the acting stress (solid line), the calculating equivalent stress for time interval (hatch) and the permissible stress with given margin (dot-and-dash line) at figure 13 on right. The cross point of the hatch and dot-and-dash line show the value of predictable resource.

So the design of the gas turbine blades with purpose achievement of strength reliability and ascertainment of resource is necessary carry out with taken into account all above mentioned factors.

Conclusion

The paper presents unified interdisciplinary mathematical models of gas dynamic, heat transfer, strength and vibration processes, which takes place in high and low pressure turbines of modern aircraft engines. This simulation relates to high class models based on real 3D geometry of whole flow path and 3D geometry of turbine elements. The results of such simulations practically coincide with experimental data and parameters of already realized turbine projects.

On the whole the presented approach allows us to discover all main problems of occurring processes.

References

[1] *Mathematical Models of Gas Turbine Engines and their Components*. AGARD Lecture Series TCP 02/LS 198.

[2] Ivanov M.J., Nigmatullin R.Z. *Simulation of Steady and Unsteady Working Processes in Gas Turbine Engine.* Some Aero-Thermo-Fluid Aspects in Airbreathing Propulsion. CIAM, 2001, pp. 1-27

[3] Noznitsky Yu.A., Dulnev R.A., Kuevda V.K., Magerramova L. A., … *The improvement of the Strength Standarts of aviation gas turbine engines* // Into book CIAM 2001-2005. The main results of the scientific and technical activity. M.: FGUP CIAM, 2005, v.2, chapter 7.2: The development of normative technical documentations for guaranteeing safety exploitation of aeronautical engineering. P. 233-234.

[4] Magerramova L. A., Gromov M.V., Mironov A.K. *Particularities of calculation stress-strain state of cooled blades of turbines and choice of criterion of strength* // IV Sino-Russia symposium on aircraft structure strength. Proceedings. XI’AN. P.R. CHINA. 1998. P. 1-17.

[5] Magerramova L.A., Vasilyev B. *The influence of azimuthal orientation of the single crystal blades for the high-temperature turbines on stress-strain state and strength* // Herald of the UGATU. 2011. V.15, No 4(44). P.54–58.

[6] Zaharova T.P. Magerramova L. A., Melnikova G.V. *The calculated and experimental investigations of the frequency spectrum of the single crystal blades*: Collected papers //VIII All-Russian congress on theoretical and applied mechanics. Russia, Perm. IMCC. 2001. P. 270-271.

[7] Melnikova G.V., Shorr B.F., Magerramova L. A., Protopopova D.A., Rozanov M.A. *The influence of crystallographic orientation and its technological dispersion on the frequency spectrum of single crystal turbine blades*: Collected papers /The aerospace engineering and technology. Russia, Kharkov. KhAI. 2001. Issue 26. P. 140-144.

[8] Vasilyev B., Magerramova L. A. *The determination of SSS kinetics of the turbine blades with help different variants of creep calculation by ANSYS.* // Journal Engine. 2008. No 6, P.18-19.

[9] Vasilyev B., *Prediction of the kinetics of the 3D stress-strain state of high-temperature gas turbine blades with limited experimental data.* Proc ICAS 2012, Brisbane 2012.

Copyright Statement