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MULTIDISCIPLINARY ANALYSIS OF HIGH AND LOW PRESSURE TURBINES ON TRANSITIVE MODES IN THE FLIGHT CYCLE

S.V.Kharkovsky*, R.Z.Nigmatullin*, V.S. Kinzbursky*, V.V. Starodubtsev*
***Central Institute of Aviation Motors**
111116, Moscow, Russia

Abstract

In the design process of modern high and low pressure turbines it is necessary to provide optimal combination of defining characteristics, such as high gasdynamic efficiency, minimal radial gaps, effective cooling, long lifetime, cyclic durability, axial forces, minimal weight.

Design and the analysis are conducted on the basis of the incorporated multidisciplinary approach to the solution of gas dynamics, a heat transfer and heat conductivity, durability and vibrating condition problems. Along with stationary modes the developed models allow to calculate transitional working modes of the engines and to define their characteristics – efficiency, thermal states, secondary air system state, strain stress state.

1 Introduction

The united mathematical model of working process for whole turbine flow path is considered. From a position of internal aerodynamics the direct problem is solved for the given 3D geometry of whole turbine flow path. The initial system of the governing equations (Reynolds averaged Navier-Stokes equations) is written in the divergent form in the cylindrical coordinate system [1]. The initial equation system is closed with the rotor motion equations equations state for multicomponent mix.

Following methodic requirements to simulation of unsteady heat-hydraulic condition of cooled turbines are developed.

1. The solution in uniform formulation of problems of hydraulics, boundary conditions of heat transfer, heat conductivity
2. Calculation of air heating at each time step
3. Heat transfer calculation on disk surfaces taking into account variation of swirled flow parameters.
4. Calculation of non-stationary heat transfer coefficients taking into account natural convection on surfaces.

For modeling of GTE details mode of deformation at design and operational development the models of various levels are used, which together with gas dynamic and thermal state calculations allow to obtain optimal design.

2 Aerodynamic models

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).

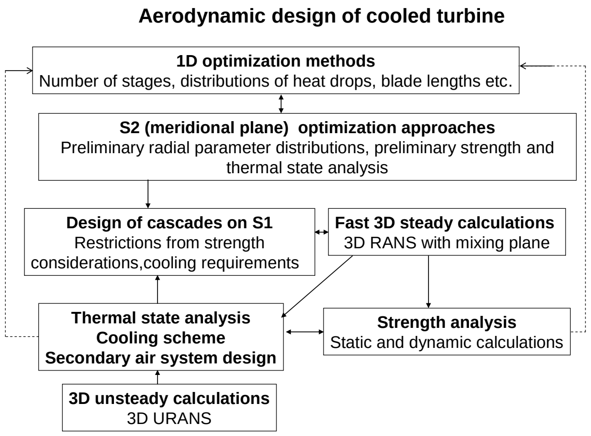

Fig. 1. Common scheme of aerodynamic design of turbine.

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.

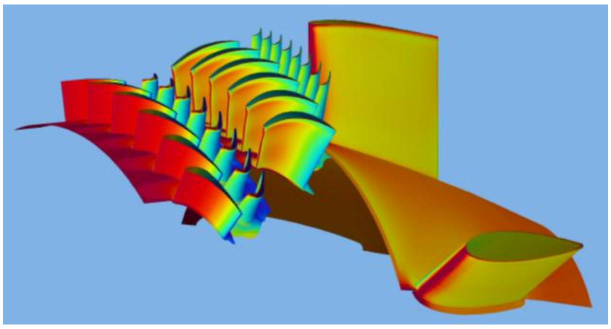

Fig. 2. High and low pressure turbines for small aviation engine. Isentropic Mach number field.

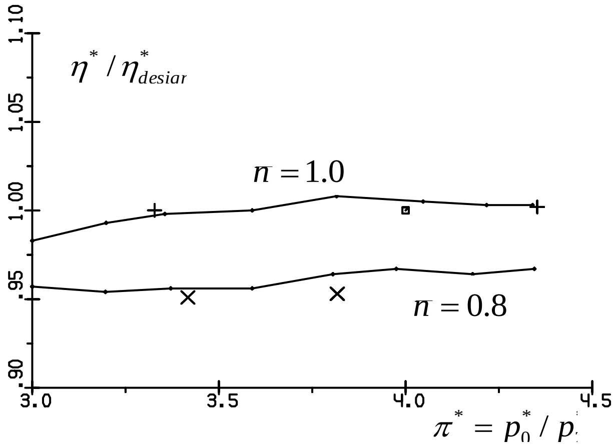

Fig. 3. Some results for High Pressure Turbine: solid lines – experimental data for n =80%, 100%;

□ – design intent;

\+ - 3D RANS calculation at n =100%;

× - 3D RANS calculation at n =80%.

2 Models of cooling system and thermal state

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 gaps, both in labyrinth seals, and between the case and working blades.

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 (for more details see [2]).

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.

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 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 transverse 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 flow on branches of the equivalent hydraulic model with use of typical hydraulic resistance. Distributions of mass flow G, tangential V_φ and radial V_r components of velocity, pressure P and temperature T along disk cavities are defined from the calculation of the one-dimensional differential equations system of movement (4)-(5), energy (6), indissolubility (7) and a state (8):

$$G\frac{d}{dr}\left(rV_\phi\right)=2\pi r\,\tau_\Sigma \tag{4}$$

$$V_r\frac{dV_r}{dr}-\frac{V_\phi^2}{r}=-\frac{1}{\rho}\frac{dP}{dr}-\frac{1}{\rho}\frac{\tau_r}{dr} \tag{5}$$

$$\frac{d}{dr}\left(T+\frac{V_\phi^2}{2C_P}+\frac{V_r^2}{2C_P}\right)=\frac{1}{C_PG}\frac{dL}{dr}+\frac{1}{C_PG}\frac{dQ}{dr} \tag{6}$$

$$\frac{d}{dr}\left(\rho F_r V_r\right)=0 \tag{7}$$

$$\rho=\frac{P}{RT} \tag{8}$$

where ω is rotation frequency. For friction factor $\tau_\Sigma=k_1\tau_1+k_2\tau_2$ on rotor and stator surfaces are used experimental criteria correlations. τ_1 and τ_2 – stresses of circumferential tangential friction on disk (9) and stator (10) correspondingly at local radius r.

$$\tau_1=0.0274\,\mathrm{Re}_\omega^{-0.2}\cdot\rho\cdot(\omega\cdot r)^2\cdot\left(1-\beta_\varphi\right)^{1.2} \tag{9}$$

$$\tau_2=0.047\,\mathrm{Re}_\omega^{-0.2}\cdot\rho\cdot(\omega\cdot r)^2\cdot\beta_\varphi^{1.8}, \tag{10}$$

$$\mathrm{Re}_\omega=\frac{\omega\cdot\rho\cdot r^2}{\mu},\quad \beta_\varphi=\frac{V_\varphi}{\omega\cdot r}$$

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.

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

The calculations of stress strain state (SSS) and strength of these wheels is necessary to made with take into account elastic, plastic and creep deformations, temperature fields and the changing of properties of blade and disk materials 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 wheels 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 most accuracy data of the durability and dynamic behavior of turbine wheels 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.

4. Radial gaps on transient modes

At the initial stage the design of turbines is carried out based on steady working mode of the engine, for example, at cruiser mode. Expert values of radial gaps over turbine blades are accepted. Gasdynamic parameters on other operating modes are defined on the same geometrical model, at the same values of gaps, as at the design point. For air system model expert values of radial gaps in labyrinth seals are also accepted. Steady thermal and strength state of the turbine is calculated at the design point, and then the "cold" geometry is defined.

Then correction of the turbine flow path geometry is performed for other working modes under the assumption about steady temperature fields. However, as our experience shows, for steady state for many modes of flight mission is not realized.

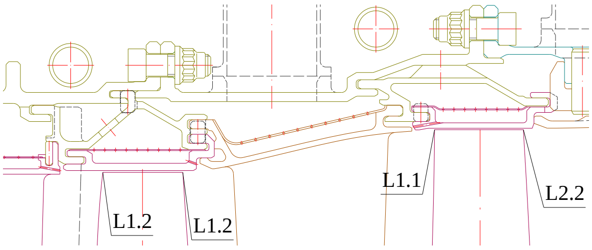

Fig.4 Typical design of twin stage HPT tip.

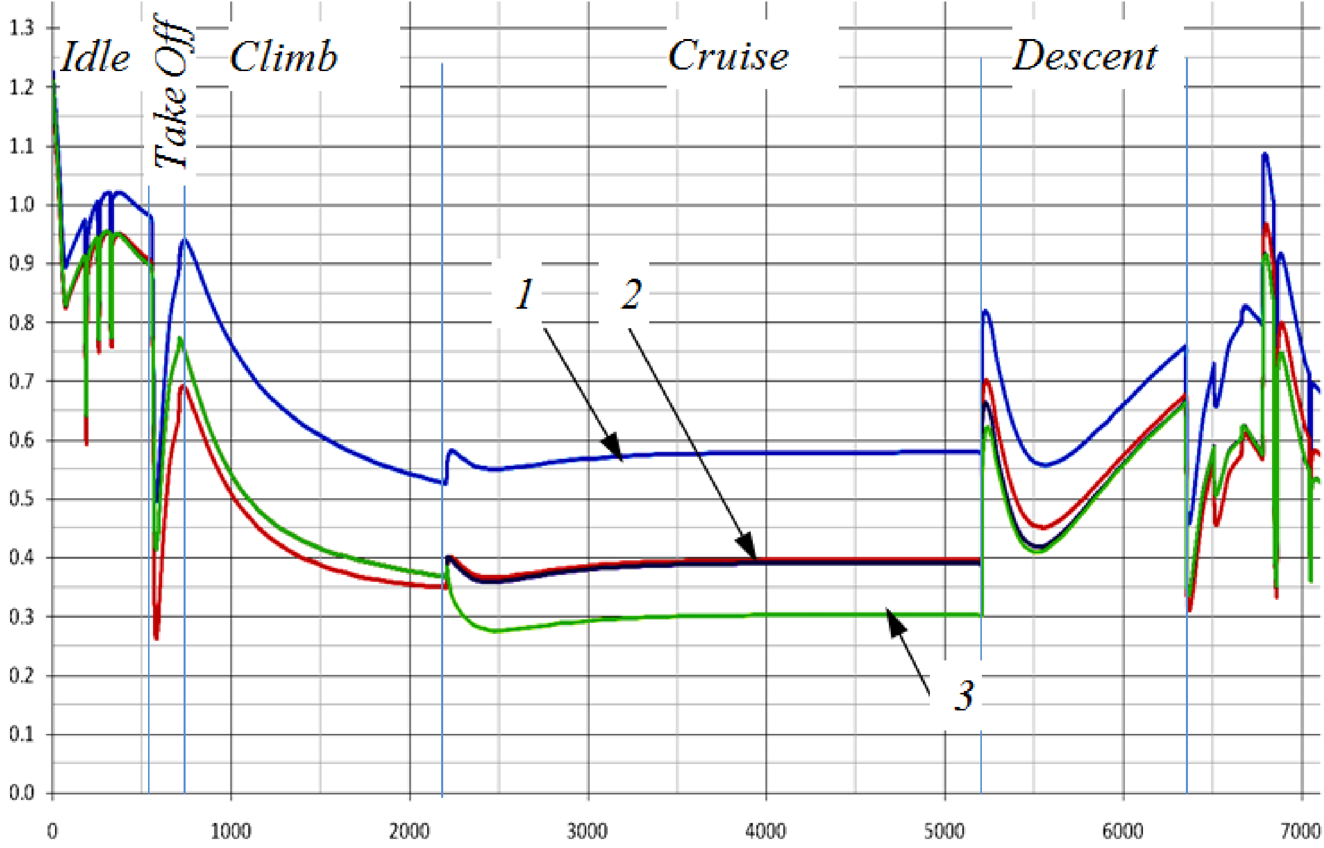

Fig. 5. Radial gap above the HPT blade for flight missions at different environment conditions: 1 - “cold”, 2 – “normal”, 3 – “hot” condition.

Simulation of the thermal and strength state of the turbine for the flight mission is performed and control system of radial gaps is designed. Values of assembly gaps are chosen. As result the behavior of radial gaps in the turbine is defined. The geometry of the turbine flow path and other turbine design elements is defined at working steady and transitional regimes in the flight mission. In the subsequent analysis more accurate calculation of the turbine efficiency, thermal state, axial forces are performed for the various time moments during the flight mission.

Figure 4 shows typical design of twin stage HPT tip. And figure 5 presents the results of radial gap calculation above the HPT blade for generalized flight missions at different environment conditions. Designed control system allows providing minimal acceptable gaps during cruise mode, avoiding cut-in of blade tip for whole flight mission and thus decreasing degrading of the turbine efficiency during life time. According to calculations the use of the control system increases HPT efficiency in our example by 0.92% for cruise.

But at take off mode we have increased gaps (by 1.5…2 times) in the turbine. It results in gas temperature increasing 15-20 K at most hot regimes. It should be taking into account at the design of the HPT. Figure 6 shows design of LPT stage tip with shrouded blades. Typical behavior of the gaps is presented in figure 7. Similar to the considered above HPT minimal acceptable gaps take place during the cruise mode and decreases fuel consumption for this most continuous working regime.

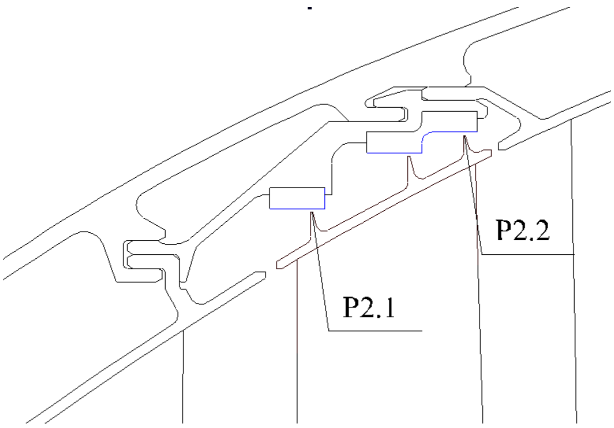

Fig.6 Typical design of LPT intermediate stage tip.

Increased gaps occur at take off mode. It leads to LPT efficiency decreasing by 1-1.2%.

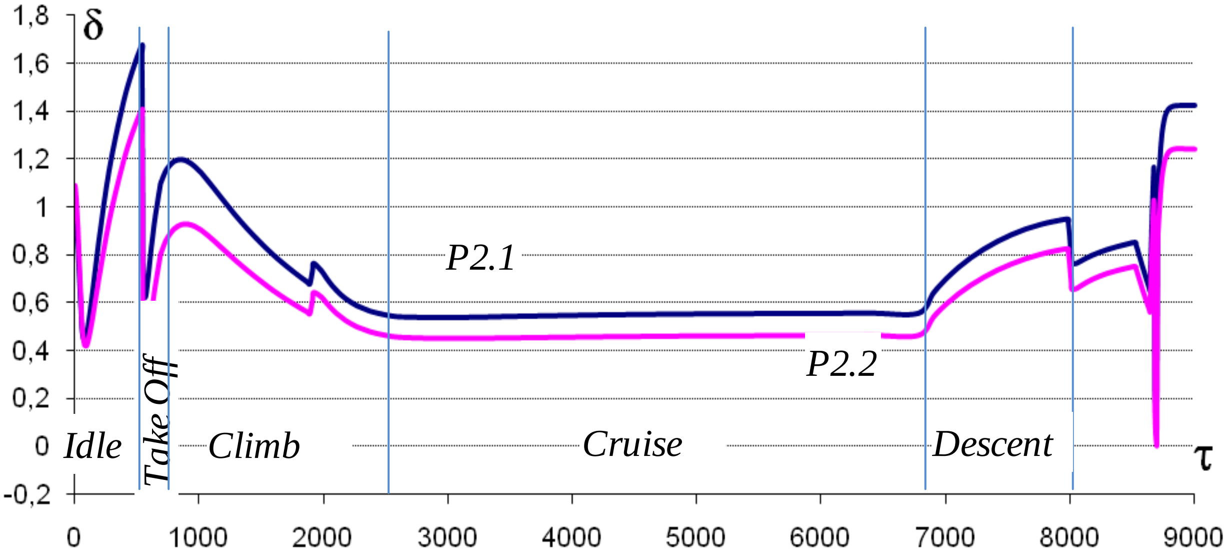

Fig. 7. Radial gap above the LPT blade for flight missions.

Conclusion

The paper presents unified interdisciplinary mathematical models of gas dynamic, heat transfer, strength, which takes place in high and low pressure turbines of modern aircraft engines.

Along with stationary modes the developed models allow to calculate transitional working modes of the engines and to define their characteristics – efficiency, thermal states, secondary air system state, strain stress state.

It is shown that for typical design of HP and LP turbines active control system allows providing minimal acceptable gaps during cruise mode, avoiding cut-in of blade tip for whole flight mission and thus decreasing degrading of the turbine efficiency during life time.

At take off mode there are increased radial gaps in the turbine. It leads to necessary inlet gas temperature increasing at most hot regimes. It should be taking into account at the design of the HP and LP turbines.

References

[1] 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.

[2] Kharkovskij S.V., Pochuev V. P, Bulchinskij J.S., Mukhin A.A., Rykachev J.J. Modelling of a thermal condition of details and units of high-temperature GTE. The collection of articles «the Scientific contribution to creation of aviation engines» the Book 2. CIAM, 2000.

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