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AERODYNAMIC IMPROVEMENT OF TURBOJET ENGINE FLOWPATH USING 3D VISCOUS FLOW COMPUTATION

Sergey V.YERSHOV, Andrey V.RUSANOV
Podgorny Institute of Mechanical Engineering Problems,
National Academy of Sciences of Ukraine
Kharkov, 61046 Ukraine
yershov@ipmach.kharkov.ua

Abstract

The statement of problem of aerodynamic optimisation of the 3D shape of turbine stage bladings is considered. The criterion of stage flowpath quality is determined by the computation of viscous three-dimensional flow with use of a programs complex ***FlowER-U***®. The selection of the optimal solution is carried out with the help of a search method. The optimisation of spatial shape of turbojet engine blades is considered taking into account the influence of film cooling on the flow pattern and turbine performances. The efficiency of low-pressure turbine stage has been increased more than by 2 percent.

Nomenclature

Symbols

b	blade chord
D	mean diameter
G	mass flow rate
H	source term
I	enthalpy
J	Jacobian of co-ordinate transformation
k	turbulent kinetic energy
l	blade length
M	turbine stage torque
p	pressure
q_j	heat flux
r	distance to rotation axis
s	blade pitch
t	time
T	temperature
u_j	Cartesian velocity components
U^i	contravariant velocity components
x_j	Cartesian co-ordinates x, y, z
γ	specific heat ratio
δ_{ij}	Kronecker's delta function
λ	heat conductivity
μ	dynamic viscosity
ρ	density
τ_{ij}	tensor of viscous stresses
η	adiabatic efficiency
ϖ	rotation speed
ψ^i	curvilinear co-ordinates ξ,η,ζ
$\overline{\psi}^i_j$	metric coefficients

Indices

0	stage inlet
2	stage exit
*	total value
EL	LPT exit
HL	HPT/LPT axial space
IH	HPT inlet
i,j,k,l	integer upper and lower indices corresponding to curvilinear and Cartesian co-ordinates respectively
is	isentropic value
m	molecular
t	turbulent

Abbreviations

CFD	computational fluid dynamics
ENO	essentially non-oscillatory
HPT	high pressure turbine stage
LPT	low pressure turbine stage
PT	power turbine stage
RANS	Reynolds-averaged Navier-Stokes equations
SST	shear stress transport
TD	transitional diffuser

Introduction

The problem of increasing turbine efficiency remains important. Until recently, the methods of the turbine design and optimisation were based on the 1D, 2D and quasi-3D flow models [1-5 and others]. However, the reliable information about turbine performance can be often obtained using the 3D flow analysis only. Therefore, the turbine flowpath optimisation problem based on the modern 3D flow computations attracts more and more attention [5–9 and others].

Turbine blades of the up-to-date turbojet engines operate under high temperature and it forces a use of film cooling that influences significantly on the main flow. This factor is usually not considered when optimising the turbine blading and the authors of the present paper try to make up for a deficiency in this matter.

Problem statement of blading optimisation

We consider the problem statement of optimisation of spatial shape of the turbine stage blading that is formulated as follows: it is necessary to find a local maximum of the stage efficiency under constraints imposed on the flow conditions and varied geometric parameters. The main varied geometric parameters of stage blades are considered to be blade number, stagger angle, twist angle, lean and sweep angles, compound lean and compound sweep. Here the shape of the blade sections generating the blade remains constant whereas the blade generatrices that define spatial relative position of blade sections are varied.

To ensure the constancy of the flow conditions the constraints is imposed on the mass flow rate. If it is necessary, some other aerodynamic parameters, such as the stage reaction and the absolute flow angle at the stage exit can be fixed additionally.

The optimisation problem is solved with the deformed polyhedron method proposed by Nelder and Mead [10]. Also it is possible to use some other search methods developed by Hook and Jeeves [11] and Torczon [12].

Method of 3D viscous flow simulation

The 3D viscous compressible flow is simulated with a set of unsteady RANS equations written in a curvilinear body-fitted co-ordinate system, rotating with a constant angular speed:

$$\frac{\partial Q}{\partial t}+\frac{\partial E^i}{\partial \psi_i}=H\ ,$$

where

$$Q=J\begin{pmatrix}\rho\\ \rho u_j\\ h\end{pmatrix};\quad E^i=J\begin{pmatrix}\rho U^i\\ \rho u_j U^i+p\overline{\psi}^i_j-\tau_{jk}\overline{\psi}^i_k\\ (h+p)U^i-(u_l\tau_{kl}-q_k)\overline{\psi}^i_k\end{pmatrix};$$

$$h=p/(\gamma-1)+\left(u_l u_l-\varpi^2 r^2\right)/2\ ;\quad U^i=u_l\overline{\psi}^i_l\ ;$$

$$\overline{\psi}^i_j=\partial\psi^i/\partial x_j\ ;\quad \tau_{ij}=2\mu\left(S_{ij}-S_{ll}\,\delta_{ij}/3\right)-2\rho k\delta_{ij}/3;$$

$$\mu=\mu_m+\mu_t\ ;\quad q_j=-\lambda\partial T/\partial x_j\ ;\quad \lambda=\lambda_m+\lambda_t\ ;$$

$$S_{ij}=0.5\left(\partial u_i/\partial x_j+\partial u_j/\partial x_i\right).$$

Here the summation over repeated indices is performed.

The simulation of statistic influence of turbulence on the mean flow is performed with the Menter SST model [13].

The governing equations are numerically integrated by the Godunov’s type implicit ENO scheme of the second order of accuracy suggested by Yershov [14]. The scheme has acceptable computational efficiency and is characterized by high reliability at the off-design flow condition and for nonoptimal computational grids that is of great importance for optimisation problem solving.

The code ***FlowER-U***® developed by the authors was used for the flow computations. The code comprises the following program modules: ***MultiStage*** (multistage turbomachinery flow computations), ***OptiStage*** (optimisation of the 3D shape of turbine stage blading), ***TotalFlow*** (3D flow computation in arbitrary domains). The problem statement and the numerical approach is described in detail in [15,16].

The results of the flow computations are used for determination of the stage performances. The stage efficiency (objective function) is calculated as follows:

$$\eta = \frac{M\varpi}{G_0(I_0^* - I_{2is})} .$$

The mass flow rate, the stage reaction and the absolute flow exit angle defined using the 3D flow computation can be used for implementation of the optimisation constraints.

Turbine flowpath

Fig. 1 shows the subject of the study, the turbojet engine two-stage turbine, composed of the HPT and LPT stages, with the downstream turbomachine units, namely TD and PT. A distinctive feature of HPT and LPT is the intensive film cooling. Shown in Fig. 2 is the outline scheme of the cooling air injection.

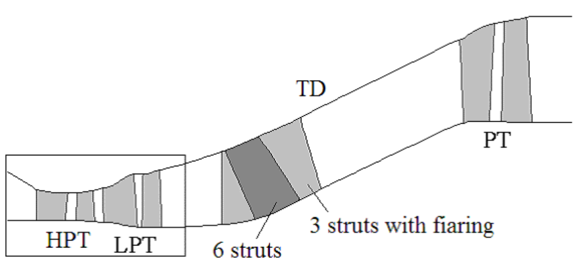


Fig.1: Turbomachine setting, including two-stage turbine (HPT and LPT stages), TD with struts and PT

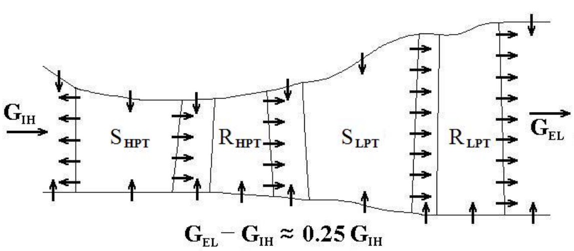


Fig.2: Outline scheme of cooling air injection for HPT and LPT stages

There are nine struts in TD, six of them are usual strengthening struts, and three others are complemented by fairings. Fig. 3 displays the cyclic part of TD with the computational grid.

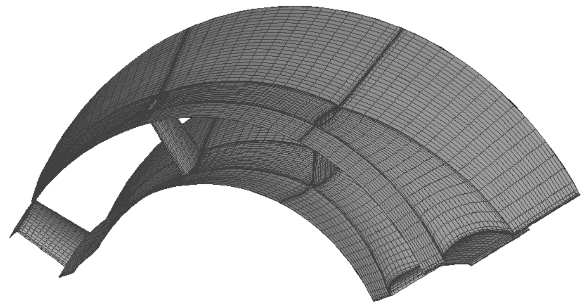


Fig.3: TD geometry

The geometric characteristics of the HPT and LPT stages are given in Table 1.

Parameter	HPT Stator	HPT Rotor	LPT Stator	LPT Rotor
Relative blade length[1], *l/b*	0.62	1.46	0.95	2.59
Relative blade pitch, *s/b*	0.76	0.81	0.69	0.79
3D channel opening, *D/l*	15.4	15.3	10.5	8.4
Blade number	40	86	45	86
Stagger angle, degree – hub	-50.1	22.9	-42.8	18.5
Stagger angle, degree – tip	-50.0	44.3	-46.3	37.0
Twist angle, degree	0.11	21.4	-3.5	18.5
Straight lean, degree	0	0	0	0
Straight sweep, degree	0	0	0	0

Table 1: Geometric characteristics of the HPT and LPT stages

Numerical results

At the first step of the study the preliminary computations of the 3D flow are performed for the two-stage turbine of initial design. The meridian plane of the initial LPT stage and its blades profiles

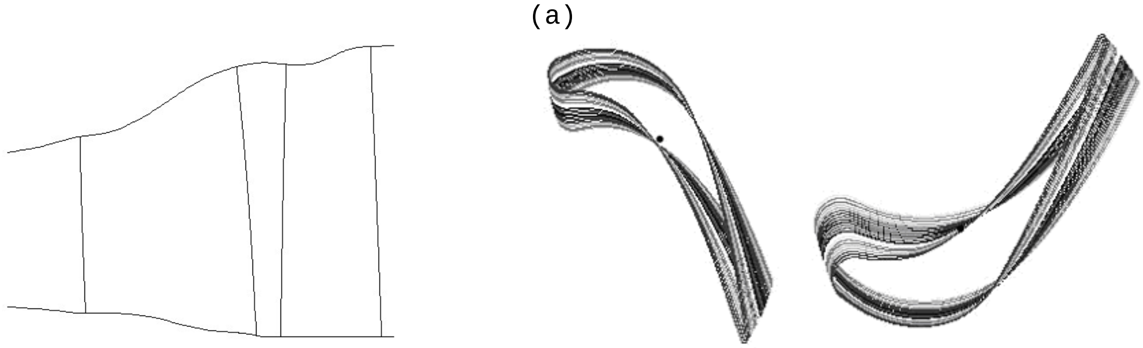
[1] Here the parameters varied along blade length are given for the mean diameter

are given in Fig. 4,a. The fine grid consisted of about 2.3 million cells has been used. Shown in Fig. 5 are the temperature contours for the root, the mid and the tip sections of the HPT stator.

The modernisation of the LPT blading using the described above optimisation approach has been done at the second step. The coarse grid with 145 thousand cells was used. During the optimisation the stagger and twist angles of the stator and the rotor, and the stator lean are being varied as it shown in Table 2. Fig. 4,b demonstrates the modified design of LPT. The preliminary estimate (for the coarse grid) of the LPT efficiency increase is about 1.9 per cent.

At the third step of the investigation the computations of the 3D flow in the modified two-stage turbine were performed at the fine computational grid with about 2.3 million cells.

(a)



(b)

Fig.4: Initial (a) and modified (b) geometry of LPT

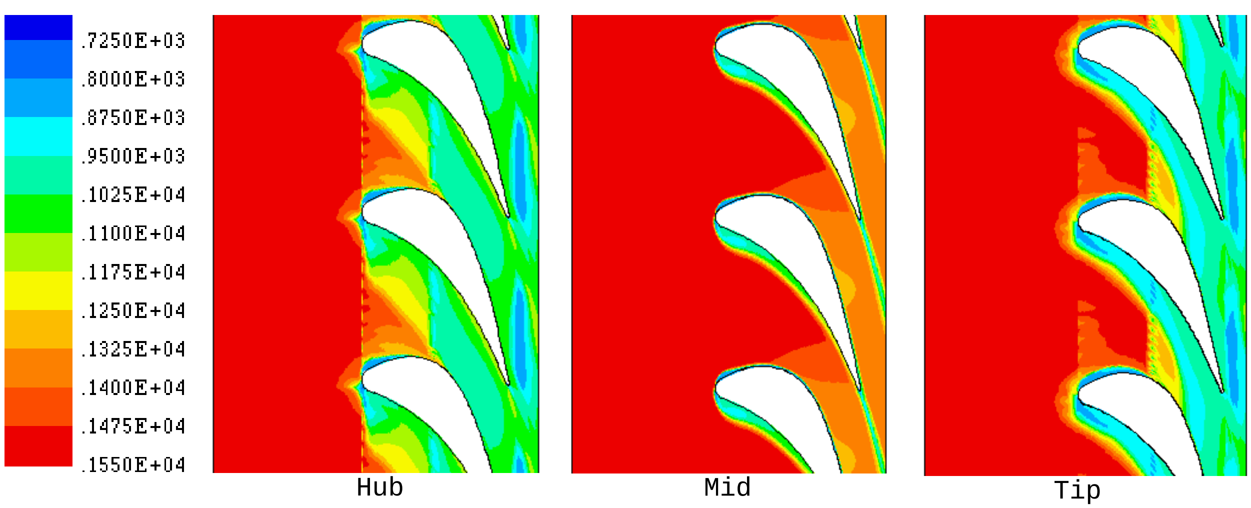


Fig.5: Temperature contours in film-cooled HPT

The performances obtained in the 3D throughflow computations of HPT and LPT for the initial and modified turbines are given in Table 3. The mass flow rate and the heat drop remained almost unchanged where as the efficiency and the capacity of turbine were increased substantially. It was achieved due to the rise of the LPT stage reaction at the root that can be seen in Fig. 6.

Parameter		Stator		Rotor	
		I	M	I	M
Stagger angle, degree	hub	-42.8	-37.0	18.5	21.2
	tip	-46.3	-53.7	37.0	41.5
Twist angle, degree		-3.5	-16.7	18.5	20.3
Straight lean, degree		0	0.9	0	0

Table 2: Geometric characteristics of initial (I) and modified (M) LPT stage

Parameter	Two-stage turbine throughflow computations	
	Initial	Modified
Inlet mass flow rate for HPT, G_{IH}, kg/s	67.3	67.3
Exit mass flow rate for HPT, G_{HL}, kg/s	81.1	81.1
Exit mass flow rate for LPT, G_{EL}, kg/s	84.0	84.0
Absolute flow exit angle for LPT, degree	-13.7	-16.1
HPT capacity, kWt	23678	23627
LPT capacity, kWt	16949	17532
Total capacity, kWt	40627	41159
HPT efficiency	0.904	0.905
LPT efficiency	0.815	0.836

Table 3: Performances of two-stage turbines of initial and improved design

As a result of the optimisation, a flow overacceleration at the suction side root sections near the leading edge, as well as the flow separation evoked by it, have been eliminated almost completely (Fig. 7, here the points are the cell centres where velocity vectors start). In the issue the kinetic energy losses were diminished because of an improvement of the flow behaviour. The LPT efficiency for the 3D HPT/LPT throughflow computations was increased by about 2.1 per cent. However, the absolute flow exit angle for the modified LPT became slightly larger as seen from Table 3.

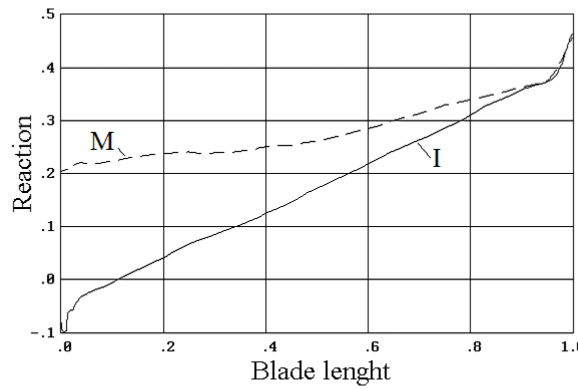


Fig.6: Distribution of LPT stage reaction versus blade length

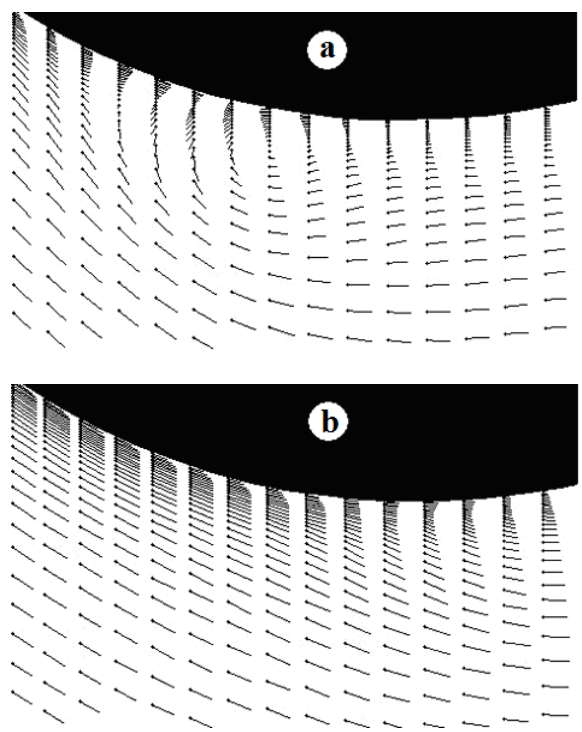


Fig.7: Velocity vectors near rotor suction side of LPT for initial (a) and improved (b) design

To estimate the negative effect of the exit angle rise on downstream units the 3D flow through multistage turbomachine composed of

HPT, LPT, TD and PT (Fig. 1) has been calculated with fine computational grid about 3.5 million cells. The computational grid in TD is displayed in Fig. 3.

Shown in Figs. 8 and 9 are the TD flow patterns for the initial and improved design. The Mach contours are presented for the tangential surface at 75 per cent of strut length from the root (Fig. 8) and for the exit cross section downstream struts (Fig. 9). The separation zones near TD struts for the turbomachine of initial design are clearly seen to be substantially smaller than those of improved design. However, the separation contributes insignificantly to the turbomachine total kinetic energy losses through smallness of the TD heat drop in comparison to the turbine stage ones. The LPT capacity increased more than by 2.2 percent whereas the PT capacity remained almost constant. The efficiency of the turbomachine as a whole is increased by about 0.7 percent.

Summary

The aerodynamic optimisation of the spatial shape of blading is performed for the film-cooled LPT. The efficiency of the LPT stage is improved more than by 2 percent due to the root reaction increase that eliminates the separation near the rotor suction side. The numerical investigation of the 3D flow through a whole turbomachine verifies favourable effect of the flow-path modernisation and demonstrates that the efficiency of the turbomachine as a whole is increased by about 0.7 percent.

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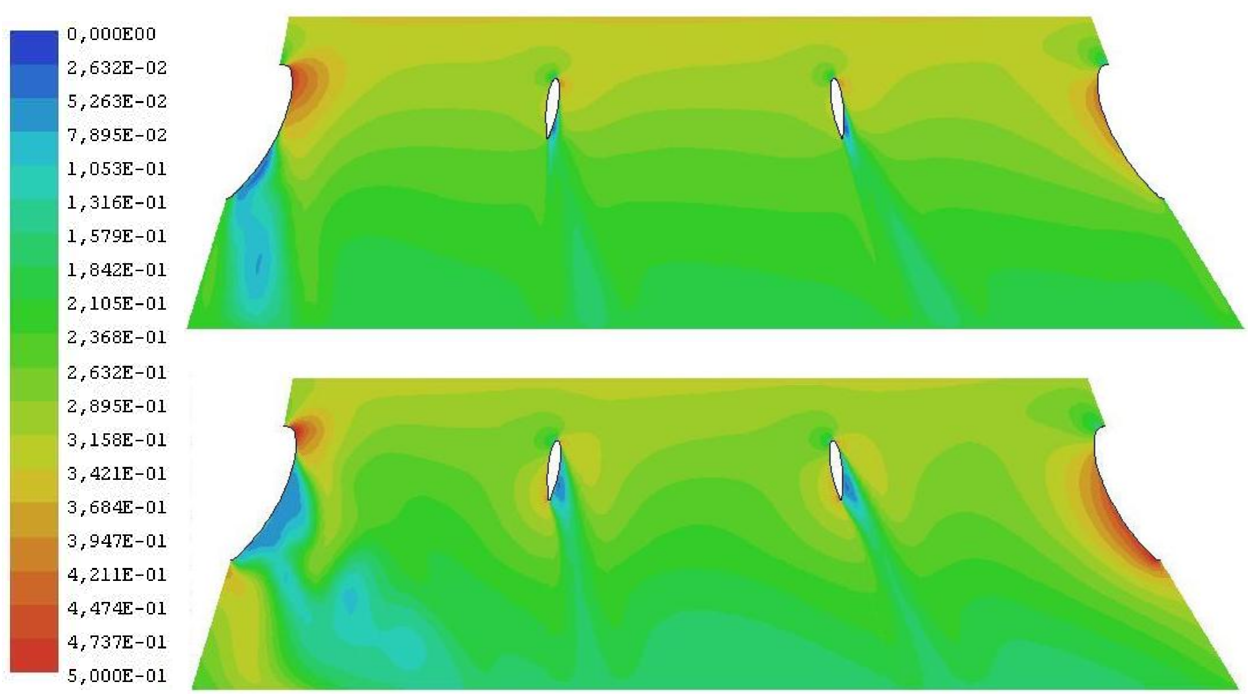

Fig.8: Flow through TD. Mach number contours at tangential section. Initial (up) and improved (down) design of LPT

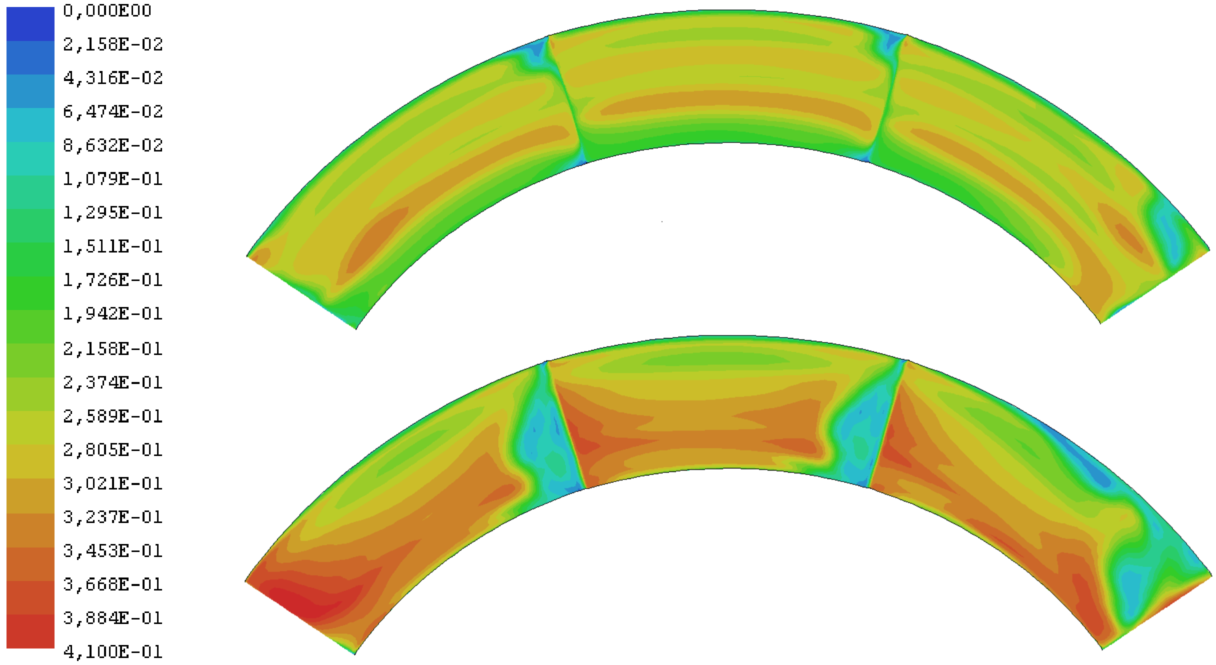

Fig.9: Flow through TD. Mach number contours at cross flow section. Initial (up) and improved (down) design of LPT

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