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DESIGN OF POWER TURBINE FLOW PATH OF SMALL AEROENGINE

ABSTRACT *An approach to the design of a turbine flow part is presented. The approach is based on the analysis of design and operational constraints, on the definition of areas of engineering solutions that ensure the achievement of defined parameters with an acceptable technical risk. The considered turbine is a Power Turbine (PT) of a small aviation gas-turbine engine. The PT is an uncooled single-stage axial turbine with a shrouded rotor. Before PT there is a diffuser Inter-Turbine Duct from the high-pressure turbine. The constraints, assumptions and criterion of effective designing of the PT flow path at the stage of one-dimensional design (based on the mean diameter) are considered. They include the constraints on the Inter-Turbine Duct expansion, on the mechanical loads of rotor blades, the flow parameters at the outlet of the turbine, and others. The solution scope defined as region in a "middle diameter – blade span ratio" and a rotational speed coordinates. For designed flow path the blade rows was profiled and verifying 3D calculations was carried out. 1D calculations performed by in-house code. For 3D calculation CFD code FlowER used. According numerical results PT flow path ensure specified parameters. The works were carried out within the Framework Programme 7 (FP7) EU project "Efficient Systems and Propulsion for Small Aircraft" (ESPOSA) – under the Grant Agreement number №: ACP1-GA-2011-284859.*

Keywords: *power turbine, flow path, optimization, efficiency, constraints.*

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ПРОЕКТИРОВАНИЕ ПРОТОЧНОЙ ЧАСТИ СИЛОВОЙ ТУРБИНЫ МАЛОРАЗМЕРНОГО АВИАЦИОННОГО ДВИГАТЕЛЯ

АННОТАЦИЯ *Представлен подход к проектированию проточной части турбины, который основан на анализе конструктивных и режимных ограничений, определении области возможных инженерных решений, обеспечивающих достижение заданных параметров при допустимом техническом риске. Рассмотрены ограничения, допущения и критерии эффективного проектирования проточной части силовой турбины малоразмерного авиадвигателя на этапе одномерного проектирования – расчета на среднем диаметре. Работа проведена в рамках 7-й рамочной программы ЕС "Эффективные системы и силовая установка для малой авиации" (ESPOSA) – Соглашение о предоставлении Гранта №: acp1-GA-2011-284859.*

Ключевые слова: *силовая турбина, проточная часть, оптимизация, эффективность, ограничения.*

Introduction

Designing of flow paths of the aircraft engine turbines is a complex multidisciplinary iterative process of finding compromises between many, often conflicting, factors. In general, the task of designing a turbine is reduced to achieving specified operating parameters thus providing strength, reliability, service life, manufacturability within the given dimensions with minimal weight and cost of an assembly. Such task is difficult to formalize for the mathematical optimization. Therefore, the aerodynamic designing is usually divided into a number of sub-tasks to be solved at different levels. At each level of the design a search for the most efficient compromise solution is performed.

The first level is a one-dimensional design, in which a number of stages is determined, a flow path shape and dimensions are selected. This is the most important phase of the turbine design because at this stage lays the boundaries (basic parameters), within which shall be to implement the project and which largely determine the potential results that can be achieved using of more sophisticated techniques of numerical analysis of the flow (on next levels). Accepted decisions at this stage effectively retained throughout the life cycle of the turbine [1].

This paper demonstrates an approach for designing of the flow path of the small uncooled single-stage Power Turbine. The main purpose of the paper is to describe the some criteria and results of the optimization of the turbine flow path.

The work carried out at the SE Ivchenko-Progress within the FP7 EU project "Efficient Systems and Propulsion for Small Aircraft" (ESPOSA) – under the Grant Agreement number №: ACP1-GA-2011-284859ESPOSA.

Initial data for the design

Table 1 contains the general PT operating parameters obtained from engine thermodynamic calculation. The analysis of presented data shows, that the turbine is small-sized, it means that we should expect a strong influence of the scale factor (axial and diametrical size of the flow path and profiles, gaps, ledges) on efficiency. The PT specific work at the Design Point is 204.5 kJ/kg and a total pressure ratio is 2.49. For these parameters a single-stage turbine is an optimal solution.

Table 1 – PT operating parameters

Parameter	Design Point 3000 m	Take-Off, sea level
P_0^* [kPa]	189.5	227.3
T_1^* [K]	997.9	968.9
G_1 [kg/s]	1.986	2.387
π^*	2.491	2.118
N [kW]	406.5	406.5
η^*	0.873	0.892
n/n_{DP}	1.0	1.0

The rotational speed and turbine power at basic operating conditions are equal, and the gas temperatures are close; it means that turbine parts will be equally highly loaded in terms of mechanical and thermal loading at operating conditions that will affect their service life. The stage load factor ($\mu = \frac{N}{GU^2}$ at Take-Off is 16.7 % lower, and the total pressure ratio is 17.6 % lower than that at Cruise. In other words, these operating conditions (Take-Off and Cruise) differ greatly in terms of aerodynamic parameters.

Fig. 1 presents the PT flow path scheme. This is an uncooled single-stage axial turbine with a shrouded rotor. Before PT (between HPT and PT) there is a diffuser Inter-Turbine Duct (ITD).

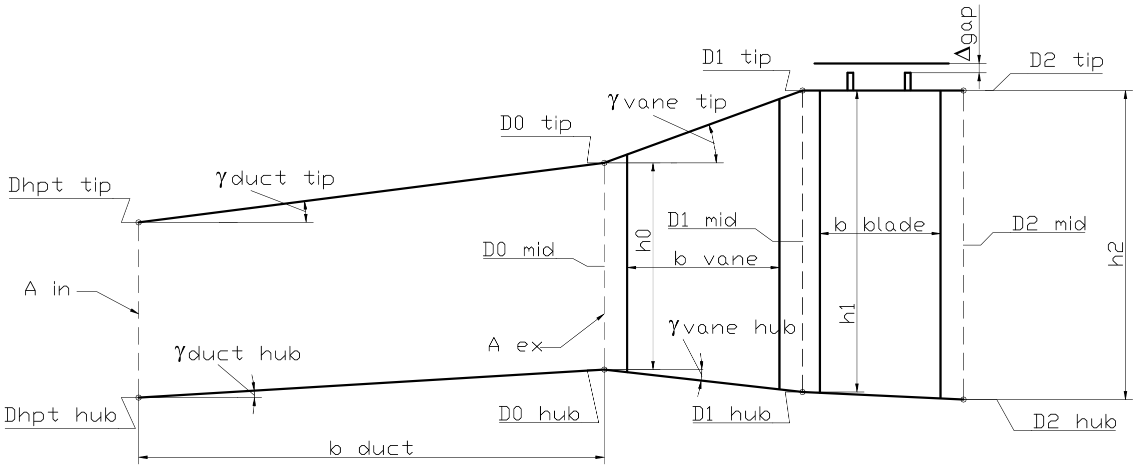


Fig. 1 – PT flow path scheme

General constraints and assumptions

During designing of the flow path shape, throughout the entire available range of variational parameters, depending on the target function (high efficiency, low weight, etc) it is possible to get a set of essentially different solutions that at the same time, can not satisfy the other ("non-target") criteria. In order to exclude from consideration obviously unsatisfactory solutions on a given parameter, as well as to cut down of the solutions search, it is necessary to impose constraints using experience and available information concerning design and operation of the turbines for such application. Obviously, the choice of such constraints on the stage of turbine starting point is directly related to technical risk of the project, time and resources needed to create and develop a unit.

The first constraint for the considered turbine is an axial area (A_{ex}) at the exit of the Inter-Turbine Duct (at the PT inlet). The area at the ITD inlet (A_{in}) is fixed and defined by the dimensions of the HPT. The axial length of the ITD (b_{duct}, see Figure 1) is determined by the dimensions of the turbine support. To ensure acceptable performance of the ITD the value of the equivalent diffuser opening angle must be not more then 20 deg. For the available values of A_{in} and b_{duct} from the geometrical relations the constraint was obtained $A_{ex} \le 1.5A_{in}$. Therefore, the ITD diffusion factor must be 1.5, that is also acceptable.

Another constraints associated with the ITD are meridional angles of the duct hub and tip walls. A flow in the ITD inlet section is high-speed, very non-uniform and swirling. It is very important to avoid flow separation at the diffuser duct walls. For this purpose it is desirable to avoid reducing of the duct hub and high slope of the duct casing. In such case for the duct hub wall the following constraint is used:

$$\gamma_{duct\ hub} \ge 0 \text{ deg}, \tag{1}$$

where in Fig. 1 the direction from the engine shaft counterclockwise is taken for the positive direction of γ angle.

For the outer wall of the duct the following constraint is taken:

$$\gamma_{duct\ tip} \le +25 \text{ deg}. \tag{2}$$

The next constraint is the axial area of the PT exit section. A blade mechanical load factor ($A{\cdot}n^2$) will be used to determine the required area. Increasing of the $A{\cdot}n^2$ factor gives usually (within certain limits) a positive effect in terms of stage gas-dynamic efficiency. All other conditions being equal, this allows, for example, to increase the blade height (and hence reduce the tip losses), to reduce the exit velocity (and hence the losses with the exit velocity and losses in the duct downstream the turbine), to increase the rotation speed (and thus reduce the aerodynamic load). But, per contra, this increases the centrifugal mechanical load at a hub section of rotor blades and on a turbine disc.

Based on existing experience in the turbine design and taking into account the expected operating conditions in order to ensure the blade strength the following constraint is used:

$$A \cdot n^2 \leq 30 \cdot 10^6 \text{ m}^2 \cdot \text{rpm}^2. \qquad (3)$$

To obtain acceptable exit losses the maximum relative exit velocity is limited by the value:

$$\lambda_{c2} \leq 0.5. \qquad (4)$$

Additionally, there are requirements to the PT outlet section flow exit angle. High flow swirl increases the energy losses in the exit duct. Due to the fact that the use of the straightening vanes is not provided in the structure, there should be a constraint for the angle at basic operating conditions $\alpha_2 = 90$ deg ± 10 deg. Or, based on operation conditions parameters ratio, for the Design Point the following is accepted:

$$80 \text{ deg} \leq \alpha_2 \leq 90 \text{ deg}. \qquad (5)$$

During the process of the blade and vane axial chord selection the following constraints will be taken into account. In order to avoid high secondary losses it is necessary to ensure the aspect ratio of the blades:

$$h/b \geq 2. \qquad (6)$$

For the same reasons, and to avoid a flow separation at the hub, we restrict the slope angles of the flow path line $\gamma_{vane\ hub} \leq -10$ deg and $\gamma_{vane\ tip} \leq 25$ deg.

In order to avoid large additional losses at the Design Point under the conditions of rarefied gas it is necessary to provide the following values of Reynolds number:

$$\text{Re}_{vane} \geq 1.5 \cdot 10^5 \qquad (7)$$

and

$$\text{Re}_{blade} \geq 0.8 \cdot 10^5. \qquad (8)$$

Here, the value Re_{blade} was based on experimental results of the blade investigation fulfilled by VZLU in the high-speed wind tunnel [2], where it was found that the most intense increase of profile losses is at $\text{Re}_{blade} < 0.8 \cdot 105$. The similar to VZLU results were obtained numerically by CIAM. In the absence of such an experiment for the vane profile Re_{vane} value was selected according to the same principles, but from the generalized relationship [3].

To a first approximation, it was assumed that the PT has a constant inner diameter, and a rotor blade has the same height at the inlet and outlet section (see Fig. 1):

$$D_{0\ hub} = D_{1\ hub} = D_{2\ hub}, \quad h_1 = h_2. \qquad (9)$$

The absolute magnitude of the radial gap above PT rotor (Δ_{gap}, see Fig. 1) is chosen from the experience of design and operation of similar dimension turbines and remained unchanged in the course of calculations (certainly it is an assumption). But its relative magnitude is changed versus blade span.

Solutions scope

In consideration of imposed constraints and assumptions, the problem of optimizing the PT flow path is reduced to the determination of values of a "middle diameter – blade span ratio" (D_{mid}/h), a rotational speed (n) and a stage reaction (ρ). These parameters will fully define the shape of the flow path and velocity triangles, and hence the PT efficiency.

Using constraints (1) and (2), assumptions (9), and axial chords defined from the constraints (7) and (8), the possible maximum and minimum PT diameters are determined by geometrical relationships. Using simple calculations, there was defined the practical significant scope of solutions satisfying at the same time the constraints (3) and (6). That is

$$4.6 \leq D_{mid}/h \leq 7.1, \ 30600 \text{ rpm} \leq n \leq 35600 \text{ rpm}. \qquad (10)$$

The degree of reaction is accepted typical for aircraft turbine's stages $0.3 \leq \rho \leq 0.45$.

Variative gas-dynamic calculations

The gas-dynamic calculations of the turbine at middle diameter (1*D*-calculation) were carried out with the SE Ivchenko-Progress' in-house code. The procedure is based on the theoretical and experimental research and correlations carried out at CIAM and SE Ivchenko-Progress. The procedure allows to determine losses in a cooled turbine depending on the geometrical and operating parameters and on the cooling air parameters.

To determine the total losses in a turbine cascade the following losses are taken into consideration: friction losses, edge losses, secondary losses, losses due to meridional opening of the channel, losses due to Reynolds number and Mach number (relative velocity), as well as the losses due to the flow turbulence, tip clearances leakage and some design peculiarity of the flow path. Also for cooled turbine the losses due to cooling are determined with the account for blow-in place and cooling air parameters. Thus, the current procedure takes into consideration the majority of factors having influence on the efficiency of any turbine. It allows to determine the achievable efficiency level of a turbine with specified dimensions and with the optimally profiled blades. This procedure was used and approved its effectiveness in the course of designing modern aircraft engines.

In the Fig. 2 some results of variative turbine computations at different D_{mid}/h and n values are shown. Here the mechanical loading parameter was accepted as a constant value $A\cdot n^2 = 30\cdot 106$ m^2·rpm^2, the stage reaction remained invariant $\rho = 0.35$. The absolute magnitude of the blade-tip clearance also remained invariant. Thus the value of the clearance leakage was changing proportionately with its relative magnitude Δ_{gap}/h_{blade}.

For preliminary comparative assessment of the turbine mass the next formula is used [1]:

$$M = K\cdot N_{st}\cdot D_{mid}^{2.5}\cdot U_{mid}^{0.6},$$

where K – empirical coefficient, includes the SE Ivchenko-Progress experience; N_{st} – number of stages; D_{mid} – middle diameter; U_{mid} – middle circumferential velocity.

The required number of rotor and nozzle blades was calculated, at a first approximation, for the Zweifel's coefficient value $Zw_{vane} = Zw_{blade} = 0.9$. However, such an assessment does not take into account, for example, a possibility of arranging the blades at the disc rim.

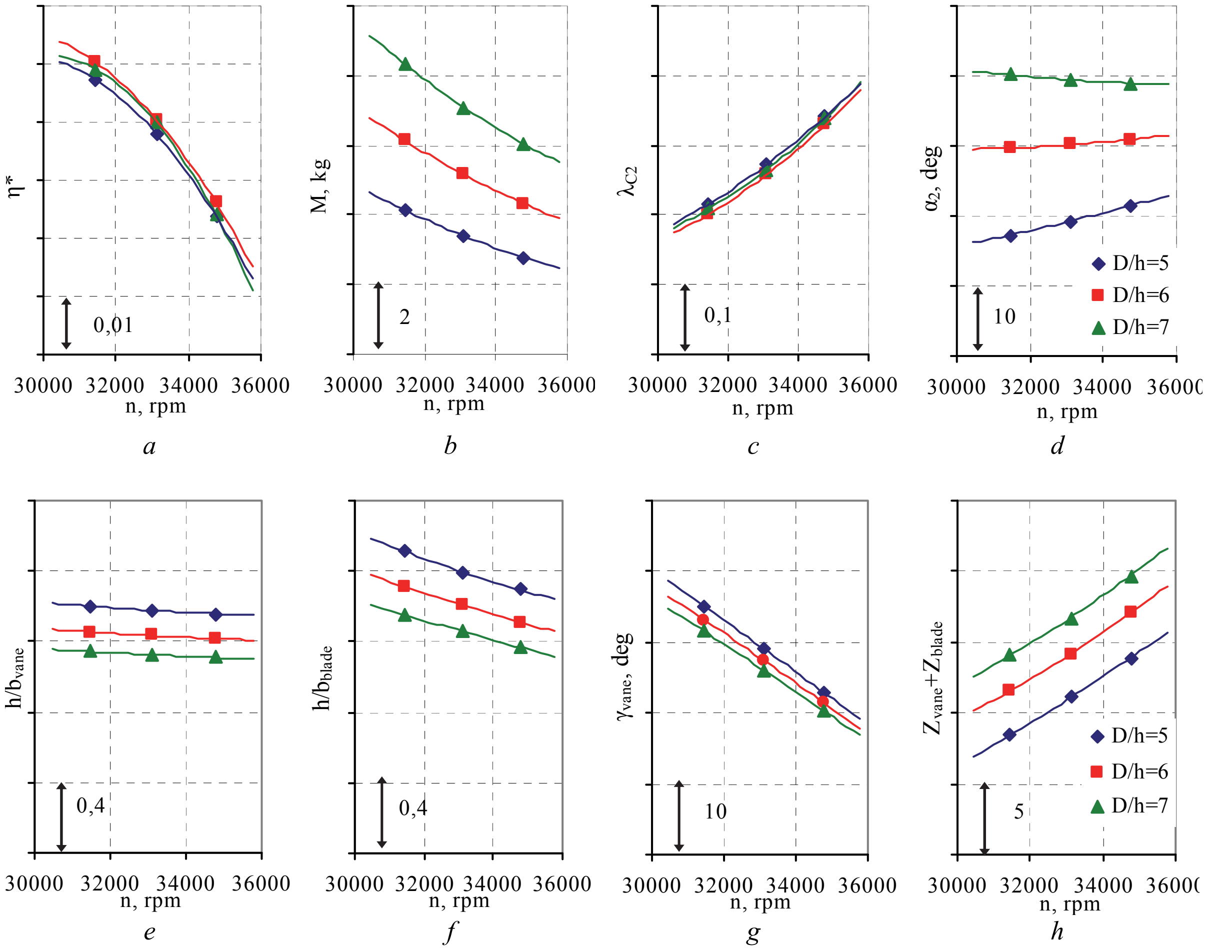


Fig. 2 – Turbine parameters vs. rotation speed and diameter-span ratio:
a – efficiency; b – mass; c – exit relative velocity; d – exit flow angle; e – vane aspect ratio, f – blade aspect ratio; g – vane tip slope angle; h – airfoils total number

An analysis of the obtained results shows the following (see Fig. 2):

The concerned rotation speed range is lying on the drooping region of the $\eta^*(n)$ dependence (Fig. 2(a)). This is conditioned by the fact that here the negative influence of axial area reduction is much greater than the aerodynamic loading reduction gain for all "diameter-span ratio" values.

The turbine mass (Fig. 2(b)) diminishes with the rotor speed increasing and the relative diameter decreasing at the expense of mid diameter decrease.

The relative exit velocity (Fig. 2(c)) increases with the rotational speed increasing, and practically does not depend on the *D*/*h* value. At the same time, the exit flow angle (Fig. 2(d)) depends to a greater degree on the relative diameter.

The vane and blade aspect ratio increases regularly with the *D*/*h* decrease (Fig. 2(e) and 2(f)). The increase of rotational speed decreases of the rotor blade span, but not influences on the vane ones in practice. Besides that, it has been found as a result of computations that it is impossible for the vane within the specified constraints to ensure fulfillment of the condition (6) at the expense of the blade height, and decreasing of their axial chord is inappropriate due to the dramatic increase of losses due to Reynolds number and efficiency decrease.

The slope angle of the vane outer wall decreases with the rotational speed increasing (Fig. 2(g)) at the expense of tip diameter decrease.

The required number of blades (Fig. 2(h)) increases both with the rotation speed and the relative diameter increasing, which is conditioned mainly with the increase of blade exit angles (and convergence ratio) due the flow path height decreasing.

Based on the computational results, with the constraints taken into account, it was determined that the parameters of the target PT flow path must be arranged inside the *ABCDE* figure on the diagram shown in Fig. 3. The shown "D_{mid}/h" and "*n*" boundaries were obtained when any of the limitations is achieved, and limitations conform as follows:

AB line – to minimal exit flow angle, according to the condition (5);

BC line – to maximal relative exit velocity, according to the condition (4);

CD line – to minimal rotor blade height, according to the condition (6);

DE line – to maximal exit angle, according to the condition (5);

The conventional boundary *EA* is determined by (10).

In Fig. 4 some computational results for PT of variable stage reaction are presented. These computations were performed for $D_{mid}/h = 6$ and $n = 33100$ rpm. It is logical to assume that for other values of rotational speed and relative diameter the obtained dependencies will not change qualitatively.

From the received data it is clear that with the stage reaction increasing the stage efficiency increases and the exit flow angle decreases, which is logical. Due to convergence ratio increase of the rotor blades their required number decreases. The relative exit velocity shows a noticeable extremum within the considered boundaries, although the reactivity dependence of the exit velocity is negligible.

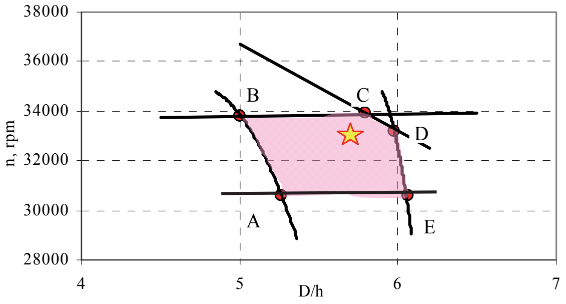
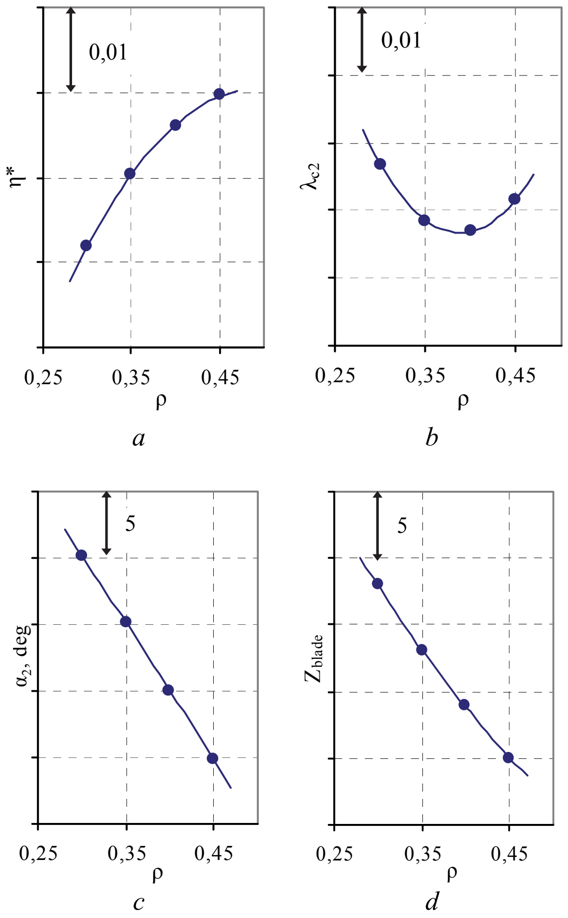


Fig. 3 – Scope of engineering solutions



a *b*

c *d*

Fig. 4 – Turbine parameters vs reaction:
a – efficiency; b – exit relative velocity; c – exit relative velocity; d – blade number

Results of the PT flow path section optimization

The carried out computational investigation allowed to select the PT flow path geometry and the rotor speed on a reasonable basis (Star on the Fig. 3). The rotor speed was matched with the propeller rotational speed (via the reduction gear), after which it made up $n = 33135$ rpm. The rotor blade relative middle diameter was taken equal to $D_{mid}/h = 5.7$. The expansion of the flow path was accomplished at the expense of increasing the vane outer diameter. With the purpose of excluding high losses at the hub, the vane inner diameter was taken as a constant. The rotor blade was accomplished with constant outer diameter and slight decrease of the inner diameter. The axial chords of the vane and blade were selected taking into account the influence of Reynolds numbers on the turbine efficiency at the Design Point. The rotor blade aspect ratio was obtained to be equal $h/b = 2.03$.

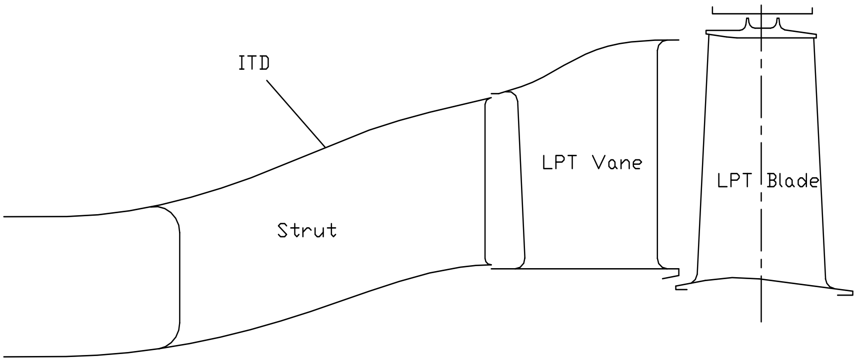


Fig. 5 – PT flow path scheme

Table 2 – Results of the PT 1D gas-dynamic calculation. Design Point

Parameter	Value	Parameter	Value
ρ_{mid}	0.400	Zw_{vane}	0.95
α_1 [deg]	21.0	Zw_{blade}	1.05
β_1 [deg]	58.2	φ	0.963
β_2 [deg]	30.4	ψ	0.951
α_2 [deg]	81.3	U/C_{is}	0.532
λ_{c1is}	0.987	μ	1.429
λ_{w2is}	0.943	C_{ax}/U	0.575
λ_{c2}	0.481	π^*	2.491
Re_{vane}	182000	η^*	0.873
Re_{blade}	87800	$A\cdot n^2$ [$\mathrm{m^2\cdot rpm^2}$]	$28.9\cdot10^6$

Table 3 – Results of PT 1D gas-dynamic calculation. Take-Off

Parameter	Value	Parameter	Value
ρ_{mid}	0.335	μ	1.192
λ_{C2}	0.397	C_{ax}/U	0.503
α_2 [deg]	97.88	π^*	2.118
U/C_{is}	0.594	η^*	0.890

Table 4 – Results of the PT 3*D CFD* calculation

Parameter	Design Point 3000 m	Take-Off, sea level
π^*	2.489	2.131
$G_1\sqrt{T_1^*}/P_0^*$ [kg√K (s·kPa)]	0.330	0.328
N [kW]	424.4	424.4
λ_{C2}	0.51	0.39
α_2 [deg]	78.9	95.9

In Table 2 the results of PT gas-dynamic calculation at middle diameter at the Design Point (see table 1) are presented. Selected turbine rotation speed and the geometry ensure a moderate velocity ratio (U/C_{is}) and aerodynamic load factor (μ). To ensure the required PT efficiency at the Design Point there was accepted a higher middle reaction, which provides acceptable values of the exit angle and relative velocity. At the Design Point the PT features trans-sonic velocities beyond the vane and high subsonic velocities beyond the rotor blades. The PT efficiency makes up $\eta^* = 0.873$. Thus, at the Design Point the PT parameters comply with the technical requirement, without exceeding the main constraints.

In Table 3 some results of the 1*D* verifying calculation at Take-Off power (see table 1) are presented. It is clear that at the turbine outlet the flow has an acceptable relative velocity and swirl. The hub reaction remains positive and sufficiently high, which allows avoiding diffuser flow on the rotor blades. An insignificant underperformance of PT efficiency at the Take-Off is assumed to be eliminated at the expense of rational 3*D* profiling of the blades.

Results of 3*D* gas-dynamic calculation

After profiling turbine rows verifying calculations of PT in the 3*D* definition by solving Reynolds-averaged Navier-Stokes equations with the use of *CFD* code *FlowER* [4] were performed. Simulation of turbulent effects was carried out by k–ω (SST) Menter's model [5]. The equations were solved numerically by the second order implicit difference numerical scheme. The computational domain included the whole turbine flow path (this allowed correct modeling of PT inlet conditions) and is defined by modified *H*–type mesh. The mesh consists of about 500 000 cells on one blade channel.

The main results of verifying 3*D CFD* calculations of the optimized PT are presented in Table 4. The presented results show that the main purposes of PT design and optimization are achieved (see also Table 1–3). We have ensured specified mass flow rate, acceptable values of the exit angle and relative velocity and the same power for both considered regimes. The calculated power exceeds the design power.

Conclusion

The optimization of the flow path shape of the Power Turbine was fulfilled. According to the analysis of the main parameters at the PT operating conditions the number of turbine stages was justified, the number of constraints was selected and areas of design solutions were identified. On the basis of results of variative 1*D* calculations there were selected the basic dimensions of the flow path, the degree of reactivity and the rotor speed that will provide the required performance of PT at the Design Point with a minimal technical risk. After profiling turbine rows the verifying 3*D CFD* calculations of the PT were performed. The results confirmed required parameters.

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АНОТАЦІЯ *Представлено підхід до проектування проточної частини турбіни, який заснований на аналізі конструктивних та режимних обмежень, визначенні області можливих інженерних рішень, що забезпечують досягнення заданих параметрів при допустимому технічному ризику. Розглянуто обмеження, припущення та критерії ефективного проектування проточної частини силової турбіни малорозмірного авіадвигуна на етапі одновимірного проектування - розрахунку на середньому діаметрі. Робота проведена в рамках 7й рамкової програми ЄС "Ефективні системи і силова установка для малої авіації" (ESPOSA) - Угода про надання Гранта №: acp1-GA-2011-284859.*

Ключові слова*: силова турбіна, проточна частина, оптимізація, ефективність, обмеження.*

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