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TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

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A method for calculation of characteristics of one-stage and two-stage axial-flow turbines

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Abstract

This paper presents a model and block diagrams of two programs enabling determination of the characteristics of a reaction axial-turbine of an aircraft engine. The method employed to describe the flow phenomena with the application of the similarity criterion of thermo-gasdynamics processes can be reduced to an iterative solution of algebraic equations. The T62003 and TURB297 programs developed by WSK PZL-Rzeszów S.A. provide a full theoretical analysis of the influence of rims geometrical size and aerodynamic stream values on the turbine characteristic patterns. The Mukhtarov model elaborated by CIAM was used to determine aerodynamic losses. The results calculated with the application of the above mentioned programs are within the spread of the characteristics that were obtained via the CAT program, for which the Ainley-Mathieson method, confirmed by experimental tests, is applied.

Keywords: Aircraft engine; Turbine characteristics

Nomenclature

a	– speed of sound or diameter of throat,	M	– Mach number,
A	– mass flow parameter,	n	– rotational speed of shaft,
c	– absolute velocity,	p	– pressure,
D	– mean diameter of duct,	R	– gas constant,
F	– section area	t	– pitch,
G	– mass flow rate,	T	– temperature,
h	– effective specific work of expansion,	u	– tangential rotor blade velocity,
k	– ratio of specific heats,	w	– relative velocity,
α	– absolute flow angle,	ρ	– density,

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β	–	relative flow angle,	φ	–	absolute velocity loss factor, c_l/c_{lt}
η	–	efficiency,	ψ	–	relative velocity loss factor, w_2/w_{2t}
ξ	–	loss coefficient,	$q(\lambda)$	–	mass flux density, $c\rho/c_{crit}\rho_{crit}$
λ	–	Laval number,	$Y(\lambda) \equiv Y$		ratio: $q(\lambda)/\pi(\lambda)$

Subscripts

crit	–	critical value,	*t*	–	isentropic,
dp	–	design point condition,	*u*	–	tangential (circumferential),
f	–	final value,	0	–	turbine entry,
i	–	initial value,	1	–	turbine nozzle vane outlet (rotor entry)
min	–	minimal section,	2	–	rotor outlet,
l^*	–	stagnation,	I	–	first stage,
st	–	stage,	II	–	second stage.

1 Introduction

For an aircraft gas turbine engine system, the design-point performance of a turbine determines the most advantageous distribution of gas available energy between the nozzle rim and rotor rim by adjusting their geometry to the stream kinematics parameter. This range, usually corresponding to the engine Take-Off rating, usually ensures minimal flow losses. In different engine operational conditions, as a result of changing its operation ratings necessary to achieve the required flight heights and speeds, the rotor rotational speed, turbine entry pressure and temperature, mass flow rate, and rotor outlet gas pressure are changed [17, 21]. Of these five main physical turbine parameters mentioned above, only four are independent. Therefore, all quantities describing the turbine functions under off-design conditions, such as power, efficiency, gas velocities, and mass flow parameters, may be expressed as a function of these four independent variables. However, a graphic or tabular presentation of the function of four variables is very complicated. That is why complexes of independent variables are used for calculations of turbine characteristics. Simultaneously, these complexes are flow similarity criteria. By doing so it is possible to decrease the number of variables and thus make the graphic presentation of turbine characteristics easier.

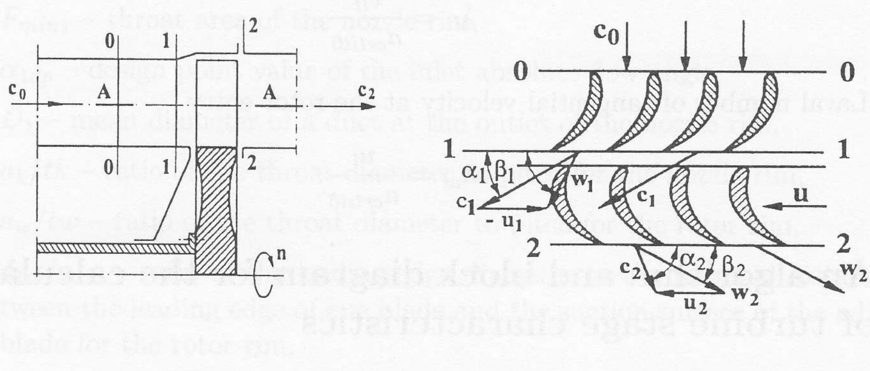
The similarity of compressible, viscous, and gravitational fluid flows and heat exchange flow requires fulfilling the geometrical similarity of flow ducts (or the identity of boundary surfaces) and the equality of criterial numbers that condition the kinematics similarity (velocity triangles similarity) and dynamic similarity (similarity of pressure and temperature fields). The kinematics and dynamic similarity conditions require the equality of the following criterial numbers

- Laval number (or Mach number) – taking into account compressibility,
- Reynolds number – taking into account viscosity,
- Peclet number for heat exchange,
- Froude number – taking into account the gravity force,
- Strouhal number – defining the flow type,

and the equality of isentropic exponent, k.
It should be stated that the problems of determining the characteristics of one-stage and two-stage turbines (most commonly used in aviation turbine engines) are presented in the available literature marginally. This condition forced the authors of the paper to find their own procedure, which would enable to determine turbine characteristics with a satisfactory accuracy for the design practice.

2 Assumptions concerning the flow model

Figure 1 presents a scheme of a single-stage axial-turbine or one stage of a multistage turbine and the velocity triangles in particular characteristic sections.
In this paper, the following assumptions simplifying the determination of



(a) (b)

Figure 1. A scheme of the reaction axial-turbine stage showing characteristic calculation sections (a) and blade row with velocity triangles at the rotor entry and outlet (b).

characteristics were made in relation to a three-dimensional and unsteady flow of the real medium:

a) The stream flow is treated as one-dimensional and steady.
b) The heat exchange between stream filaments and the heat transferred through the turbine case walls to the environment are omitted.
c) The working medium is a perfect gas, satisfying the Clapeyron equation, whereas specific heats, C_p and C_v, gas constant R, and adiabatic exponent, k are constant.

d) The changes of the working medium stream parameters in stage characteristic sections are examined on one calculation radius equal to the medium radius.

e) Energy losses in nozzle rims and rotor rims only are considered. The losses are dependent on the rim geometry, gas stream angles, and also on the flow condition determined by suitable values of Laval numbers. An increase in medium entropy on the length of rim-to-rim clearance is omitted.

Only by considering the above mentioned assumptions, are we able to determine sufficient flow similarity conditions used for calculations of turbine characteristics. Thus, while making characteristic calculations of a chosen turbine with given geometry, the criterion of geometrical similarity is automatically met by geometrical identity. Then, acceptance of the above assumptions makes it possible to omit Strouhal, Peclet, Froude, and Reynolds numbers because for basic turbine operating regimes Re > $Re_{crit} = (0.6\text{-}1.0)\cdot 10^5$, sufficient conditions of flow similarity are reduced to the preservation of two Laval numbers, namely [16]

- Laval number of isentropic absolute velocity at the outlet of the nozzle rim

$$\lambda_{lt} = \frac{c_{lt}}{a_{crtit0}}, \tag{1}$$

- Laval number of tangential velocity at the rotor entry

$$\lambda_{ul} = \frac{u_l}{a_{crtit0}}. \tag{2}$$

3 An algorithm and block diagram for the calculation of turbine stage characteristics

With the above assumptions in mind, the equations which describe the flow through turbine rims, and experimental relations which express the changes in loss values in off-design conditions, the following mathematical model of turbine stage characteristics calculation was established.

The mathematical model of processes taking place in axial-turbine rims is based on three basic conservation equations: mass, energy, and momentum ones. Generally, the description of gas flow through the blade passage is divided into two parts:

- the flow to the throat,
- the flow through the region beyond the throat (between throat and exit section).

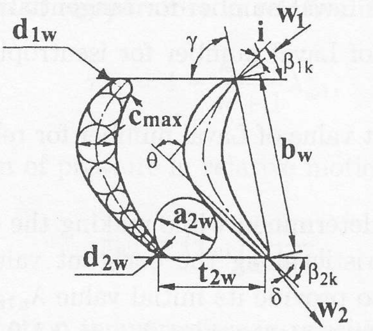


Figure 2. Geometrical parameters of rotor profile blade row.

Fig. 2 shows the geometrical parameters of the rotor blade row with marked characteristic values. The essential calculations of turbine performance proceed as follows: the input data are geometrical and aerothermodynamic parameters of turbine rims at the design point operation, namely:

- φ_{dp} – design point value of absolute velocity loss factor for the nozzle rim,
- F_{min1} – throat area of the nozzle rim,
- α_{1dp} – design point value of the inlet absolute flow angle,
- D_1 – mean diameter of a duct at the outlet of the nozzle rim,
- a_k/tk – ratio of the throat diameter to pitch for the nozzle rim,
- a_w/tw – ratio of the throat diameter to pitch for the rotor rim,
- d_{1w}/a_{1w} – ratio of the leading-edge diameter to the minimal distance between the leading edge of one blade and the suction surface of the adjacent blade for the rotor rim,
- Ψ_{dp} – design point value of the relative velocity loss factor for the rotor rim,
- F_{min2} – throat area of the rotor rim,
- β_{1k} – design point value of the inlet relative flow angle,
- β_{2dp} – design point value of the outlet relative flow angle,
- D_2 – mean diameter of a duct at the outlet of the rotor rim,
- ξ_u – tip-clearance loss coefficient for the rotor,
- k – ratio of specific heats,
- R – gas constant,
- λ_{u1i} – initial value of Laval number for tangential velocity at the rotor inlet,

- λ_{u1f} – final value of Laval number for tangential velocity at the rotor inlet
- λ_{1ti} – initial value of Laval number for isentropic absolute velocity at the rotor inlet,
- λ_{w1dp} – design point value of Laval number for relative velocity at the rotor inlet.

The parameters are determined while making the assembly design. In order to determine a characteristic along the constant value line of λ_{u1} (tangential velocity) it is necessary to provide its initial value λ_{u1i} and the final one λ_{u1f}.

Assuming the initial parameter value λ_{1ti} = 0.1-0.4, which corresponds to a low turbine load, this load is then increased gradually by changing λ_{1t} or λ_{w2} until the limit of turbine mass flow parameter $A_{T0} = A_{T0\,\max}$ is obtained. Having obtained the limit of the turbine mass flow parameter, the value of λ_{u1} is changed. The Laval number of the true outlet absolute velocity from the nozzle rim is calculated from the relation

$$\lambda_1 = \varphi_{dp}\lambda_{1t}. \tag{3}$$

The obtained value of λ_1 enables one to find the absolute flow angle, α_1 (from the equation of flow continuity), the relative flow angle before the rotor, β_1 and gasdynamics functions [2] from the following relations

- gas relative flow angle

$$\beta_1 = \arctan\left(\frac{\sin\alpha_1}{\cos\alpha_1 - \frac{\lambda_{u1}}{\lambda_1}}\right), \tag{4}$$

- gasdynamics function of temperature in absolute motion

$$\tau_1 = 1 - \frac{k-1}{k+1}\lambda_1^2, \tag{5}$$

- Mach number in absolute motion

$$\mathrm{M}_1 = \lambda_1\sqrt{\frac{2}{(k+1)\tau_1}}, \tag{6}$$

- Mach number in relative motion

$$\mathrm{M}_{q1} = \mathrm{M}_1\frac{\sin\alpha_1}{\sin\beta_1}, \tag{7}$$

- Laval number in relative motion

$$\lambda_{w1} = \mathrm{M}_{w1}\frac{\sqrt{\frac{k+1}{2}}}{\sqrt{1+\frac{k+1}{2}M_{w1}^2}}, \tag{8}$$

- gasdynamics function of temperature in relative motion

$$\tau_{w1} = 1 - \frac{k-1}{k+1}\lambda_{w1}^2, \tag{9}$$

- gasdynamics function of pressure in relative motion

$$\pi_{w1} = (\tau_{w1})\frac{k}{k-1}, \tag{10}$$

- the quotient of stagnation temperatures in relative and absolute motion

$$\tau_{w1}^* = \frac{T_{w1}^*}{T_0^*} = \frac{\tau_1}{\tau_{w1}}, \tag{11}$$

- the quotient of stagnation pressures in relative and absolute motion

$$\pi_{w1}^* = \frac{p_{w1}^*}{p_0^*} = \frac{\pi_{1t}}{\pi_{w1}}, \tag{12}$$

- mass flow parameter on the nozzle rim outlet (rotor entry)

$$A_{T1} = \frac{G\sqrt{T_{w1}^*}}{p_{w1}^*} = \frac{\sqrt{\tau_{w1}^*}}{\pi_{w1}^*}. \tag{13}$$

To determine gas stream parameters in the output section of the rotor rim (2-2), first, the Laval number value of theoretical relative velocity, λ_{w2t} is determined by means of the method of successive approximations from the product of gasdynamics functions $\pi_{w2t} \cdot Y_{w2t}$. Next, according to the method of M.K. Mukhtarov [15, 18], the actual value of relative velocity loss factor is calculated:

$$\psi = \sqrt{\psi_{dp}^2 - \Delta\xi_w}, \tag{14}$$

where: $\Delta\xi_w$ – increment of loss coefficient at the rotor rim.

Determining the Laval number for relative motion at the rotor outlet from the relation

$$\lambda_{w2} = \psi\lambda_{w2t}, \tag{15}$$

makes it possible to find the outlet rotor relative flow angle – β_2, and entry rotor absolute flow angle α_2, as well as individual gasdynamics functions of stream parameters ($\tau_{w2}, \mathrm{M}_{w2}, \tau_2$, etc.) from relations similar to the ones presented for the turbine nozzle rim.

Figure 3 shows a block diagram of axial-turbine characteristics calculation. On the basis of the scheme, the T62003 program was elaborated, written in

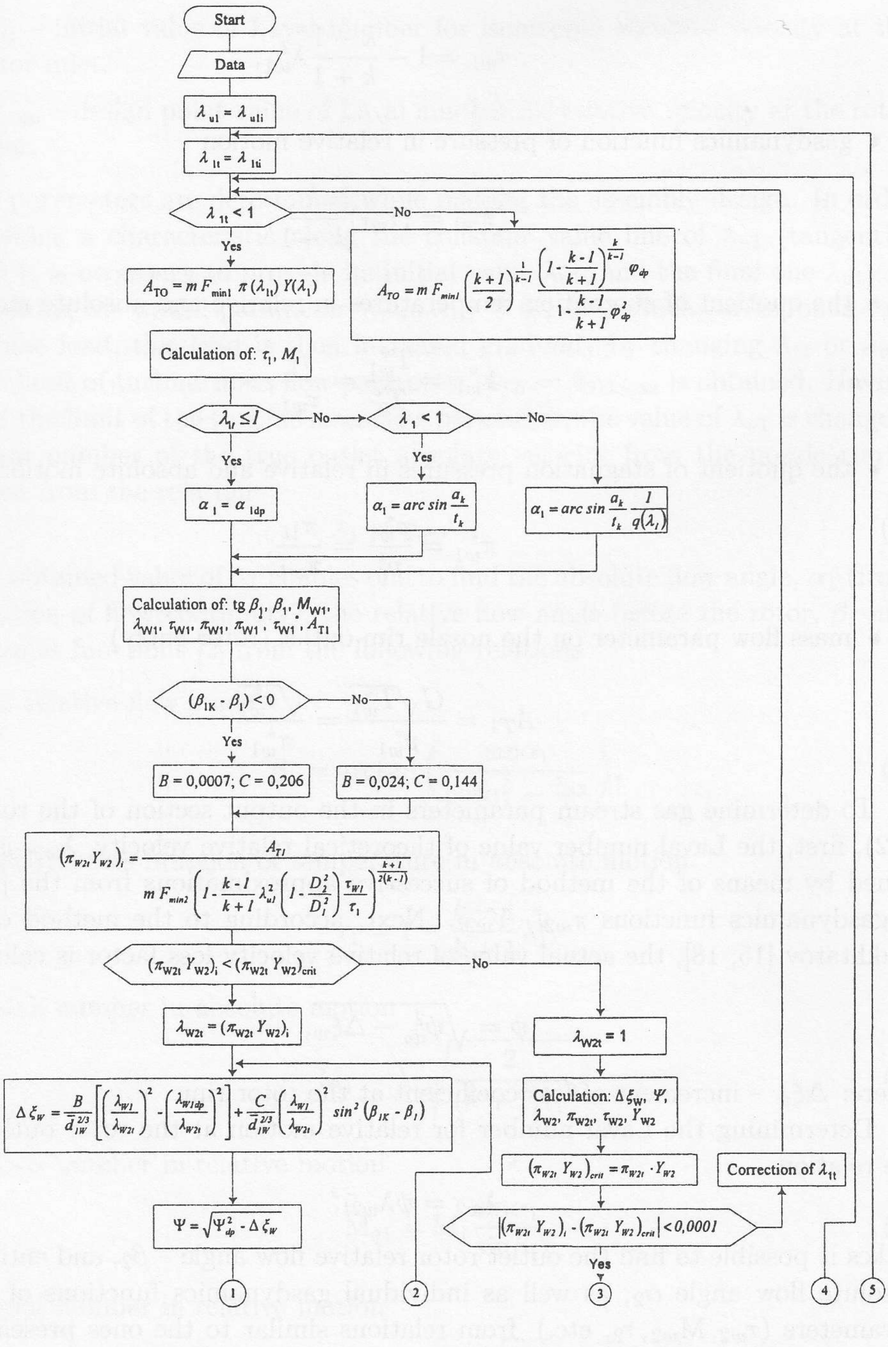


Figure 3a. Block diagram of one-stage axial-turbine characteristics calculation.

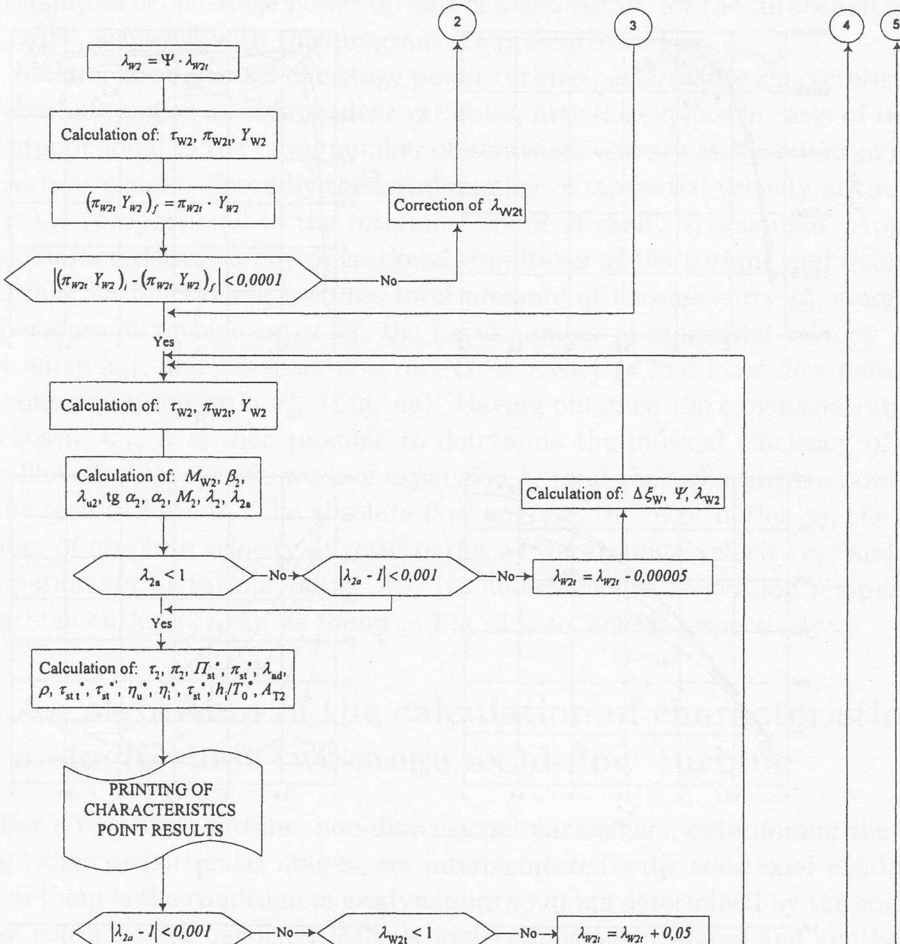


Figure 3b. Block diagram of one-stage axial-turbine characteristics calculation.

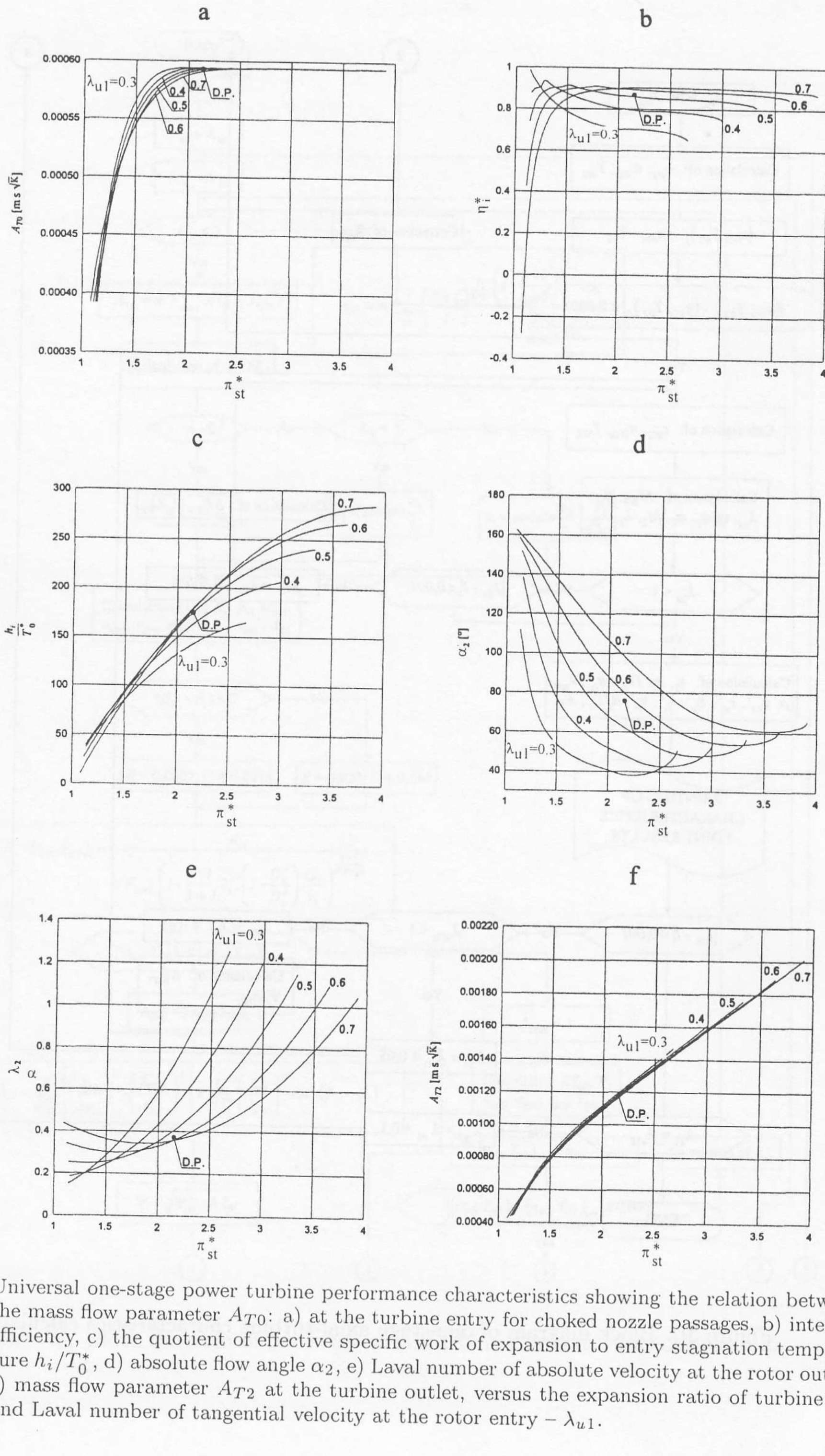


Figure 4. Universal one-stage power turbine performance characteristics showing the relation between the mass flow parameter A_{T0}: a) at the turbine entry for choked nozzle passages, b) internal efficiency, c) the quotient of effective specific work of expansion to entry stagnation temperature h_i/T_0^*, d) absolute flow angle α_2, e) Laval number of absolute velocity at the rotor outlet, f) mass flow parameter A_{T2} at the turbine outlet, versus the expansion ratio of turbine π_{st}^* and Laval number of tangential velocity at the rotor entry – λ_{u1}.

FORTRAN language for the personal computer.

Examples of one-stage power turbine characteristics, for the turboshaft engine PZL-10W, achieved with this program are presented in Fig. 4.

Making the universal one-stage power turbine performance characteristics of a turboshaft engine as independent variables, first the expansion ratio of turbine π^*_{st} (proportional to the Laval number of isentropic velocity at the outlet of nozzle rim λ_{it})was chosen. Secondly the Laval number of tangential velocity at the rotor entry λ_{u1} (proportional to the rotational speed of shaft, n) was used. Applying these characteristics to any operational conditions of the turbine and quantities describing its functioning such as: total pressure at turbine entry p^*_0, stagnation temperature at turbine entry T^*_0, the Laval number of tangential velocity at the rotor entry λ_{u1}, and gas mass flow rate G, it is easy to find mass flow parameter A_{T0} and expansion ratio $\pi^*_{st.}$ (Fig. 4a). Having obtained the expansion ratio $\pi^*_{st.}$ for chosen λ_{u1}, it is then possible to determine the internal efficiency η^*_i (Fig. 4b). The effective specific work of expansion h_i (and thus, the turbine power N_i) can be seen in Fig. 4c. The absolute flow angle at the rotor outlet α_2, the Laval number of absolute velocity at rotor outlet λ_2 (or absolute velocity c_2) and mass flow parameter at turbine outlet A_{T2} (to determine gas stagnation temperature at turbine outlet T^*_2) can be found in Fig. 4d, 4e, and 4f respectively.

4 An algorithm of the calculation of characteristics of a single-shaft two-stage axial-flow turbine

For a two-stage turbine, non-dimensional parameters, determining the operating range of particular stages, are interconnected with additional conditions. One of them is the condition of gasdynamics coupling determined by the equation of gas continuity at particular calculation sections of the stages and another one is the equality of the rotational speed of both stages $n_I = n_{II}$ resulting from a mechanical coupling.

For the case in question, the continuity equation, written for the inlet and outlet section of successive stages, is reduced to the equality of mass flow parameter:

$$A_{T2I} = A_{T0II}, \tag{16}$$

and for rotor rims of the stages

$$\pi_{w2t} Y_{w2} = \pi_{w1} Y_{w1} \frac{F_1 \sin\beta_1}{F_2 \sin\beta_2}. \tag{17}$$

This equation makes it possible to divide the enthalpy drop between individual rims at changeable operating conditions. The performance calculations of a two-stage turbine are made similarly to the ones given for a one-stage turbine (see Fig. 3), namely: defining the gasdynamics and geometrical parameters of turbine rims of first-stage and second-stage at the design point (input data are obtained from the preliminary design or the technical design of the assembly) and the parameters for a chosen value of Laval number of tangential velocity at the first-stage rotor entry,λ_{u1I}, the gas flow from one rim to another rim is traced. As a result, we obtain a complete representation of flow parameters in all control sections of both stages.

An estimation of the two-stage turbine performance based on defined gas flow parameters at the turbines different stages, is made according to the following relations [3]:

- the ratio of exit-total to inlet-total pressure of two-stage turbine

$$\Pi_T^* = \Pi_{stI}^* \Pi_{stII}^*, \tag{18}$$

where:

$$\Pi_T^* = \frac{p_{2II}^*}{p_{0I}}, \tag{19}$$

- the quotient of isentropic stagnation temperature at turbine outlet and total temperature at turbine inlet

$$\tau_{Tt}^* = \frac{T_{2tT}^*}{T_{0I}^*} = \Pi_T^{*\frac{k-1}{k}}, \tag{20}$$

- the quotient of stagnation temperature at turbine outlet and total temperature at turbine inlet

$$\tau_T^* = \frac{T_{2II}^*}{T_{0I}^*} = \tau_{stI}^* \tau_{stII}^*, \tag{21}$$

- the ratio of inlet-total to exit-total pressure of turbine

$$\pi_T^* = \frac{p_{0I}^*}{p_{2II}^*} = \frac{1}{\Pi_T^*}, \tag{22}$$

- the quotient of effective specific work of expansion to entry stagnation temperature of turbine

$$\frac{h_{iT}}{T_{0I}^*} = \frac{kR}{k-1}(1 - \tau_T^*), \tag{23}$$

or

$$\frac{h_{iT}}{T_{0I}^*} = \frac{\frac{kR}{k-1}(T_{0I}^* - T_{2II}^*)}{T_{0I}^*}$$

- turbine internal efficiency

$$\eta_{iT} = \frac{(1-\tau_T^*)}{(1-\tau_{Tt}^8)}, \tag{24}$$

- mass flow parameter at the turbine outlet

$$A_{T2T} = A_{T2II} = A_{\tau 0I}\frac{\sqrt{\tau_T^*}}{\Pi_T^*}. \tag{25}$$

During calculations, the type of the flow is observed for particular rims of both turbine stages increasing gradually turbine load by changing $\lambda_{ltI}, \lambda_{ltII}$ and λ_{w2tI} or λ_{w2tII} until reaching the limit of turbine mass flow parameter. Having determined the turbine characteristics along the line, $\lambda_{uII} = idem$, the next value of the Laval number of tangential velocity at the first-stage rotor entry is assumed with the step of $\Delta\lambda_{uII} = 0.05 \div 0.1$ and the calculations are repeated until a complete field of characteristics is obtained. A detailed description of the method of calculations of one-stage and two-stage turbine characteristics is given in [3-4].

A simplified flow diagram of two-stage axial-turbine characteristics calculations is presented in Fig. 5.

The essential characteristics of a two-stage gas-generator turbine of the PZL-10W2 turboshaft engine, available from the TURB297 program are shown in Fig. 6.

The universal characteristics of a two-stage turbine (similar to the ones presented in Fig. 4) fully describe the turbine functioning parameters in off-design conditions.

5 A comparison with experimental characteristics and other computational methods

The algorithms of calculations presented in this paper and the T62003 and TURB297 programs which resulted from them may be used both for designing turbines [9] and analysing the mating of engine assemblies as well as for determining its static and dynamic characteristics [17] and the control parameters. They can also be applied to an initial optimising of the stage rims geometry [11, 19]. The T62003 and TURB297 programs were used for calculations of power and gas generator turbines for the preliminary design of the turboshaft engine PZL-10W2 [3]. After an analysis of different models of losses [1, 7], [10-11], [14, 18] the Mukhtarov correlation of losses was used for the T62003 and TURB297 programs because the turbine characteristics calculated with this correlation of

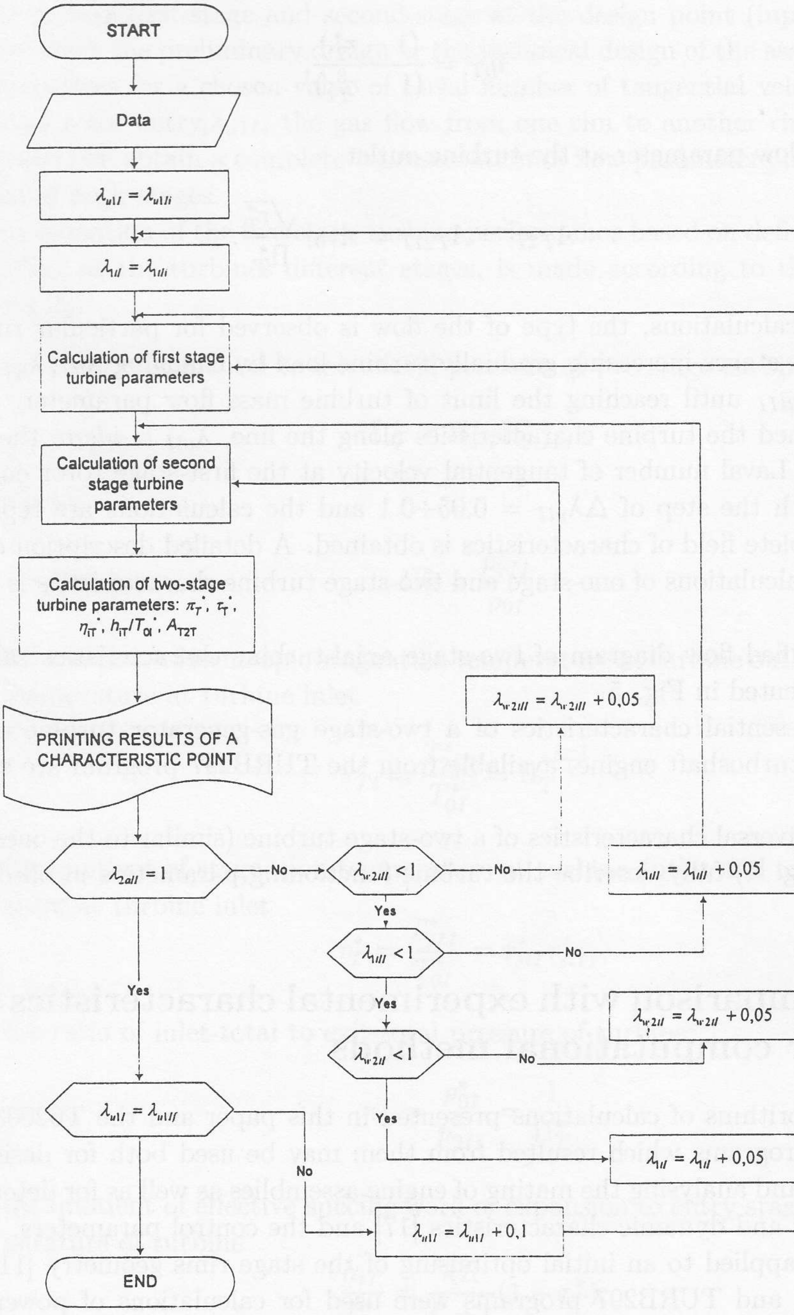


Figure 5. Simplified block diagram of two-stage axial turbine characteristics calculation.

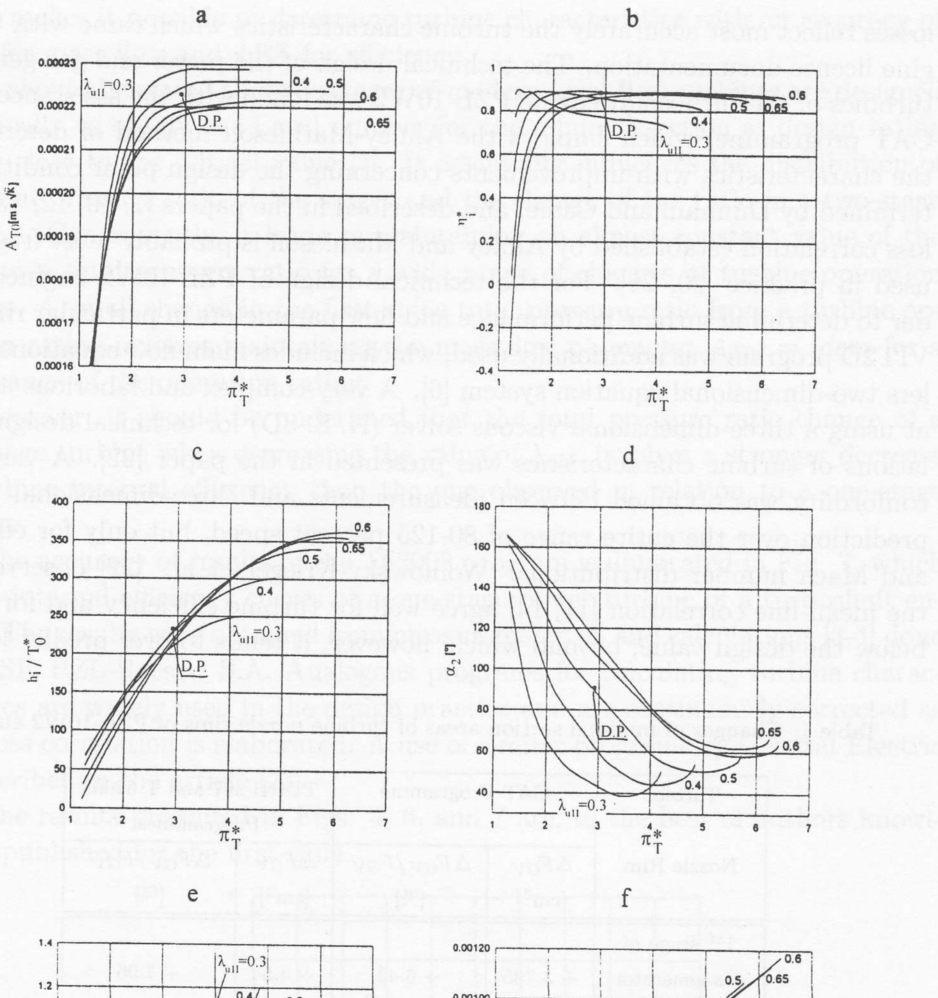


Figure 6. Universal two-stage gas-generator turbine performance characteristics showing the relation between the mass flow parameter A_{T0}: a) the turbine entry for choked rotor passages, b) internal efficiency, c) the quotient of effective specific work of expansion to entry stagnation temperature h_i/T_0^*, d) absolute flow angle α_2, e) Laval number of absolute velocity at the turbine outlet, f) mass flow parameter A_{T2} at the turbine outlet, versus the expansion ratio of turbine π_T^* and Laval number of tangential velocity at the first stage rotor entry – λ_{u1I}.

losses reflect most accurately the turbine characteristics which came with the engine license documentation. The technical design of the power and gas generator turbines of the turboshaft engine PZL-10W2 was made with the assistance of the CAT programme, which employs the Ainley-Mathieson method of determining the characteristics with improvements concerning the design point condition determined by Dunham and Came, and described in the papers [1, 10, 12, 13]. The loss correlation established by Ainley and Mathieson is probably most frequently used in practice [20, 21]. For the technical design of PZL-10W2 engine, in order to determine turbine performance and flow parameters in particular rims, the VIT2D program was additionally used, which includes main flow equations as Eulers two-dimensional equation system [6]. A very complex and laborious attempt at using a three-dimensional viscous solver (N. S. 3D) for technical design calculations of turbine characteristics was presented in the paper [22]. A very good conformity was obtained between measurements and three-dimensional viscous prediction over the entire range of 80-125 percent speed, but only for efficiency and Mach number distributions. Woinowsky-Krieger et al. [22] observed that the mean-line correlation [11, 14] agree well for turbine efficiency and for speeds below the design value, beyond which, however, it tends to over-predict losses.

Table 1. Changes of minimal section areas of turbine nozzle rims of PZL-10W2 engine

Turbine / Nozzle Rim	CAT Programme		TURB 297 and T 62003 Programmes	
	ΔF_{GV} [cm^2]	$\Delta F_{GV}/F_{GV}$ [%]	ΔF_{GV} [cm^2]	$\Delta F_{GV}/F_{GV}$ [%]
1^{st} stage of gas-generator turbine	+ 3.735	+ 6.43	+ 4.54	+ 7.96
2^{nd} stage of gas-generator turbine	+ 3.774	+ 4.32	+ 4.49	+ 5.47
Power turbine	– 2.31	– 1.51	– 3.05	– 2.0

The comparison of changes of the minimal section areas of turbine nozzle rims, ΔF_{GV}, of gas generator and power turbines of PZL-10W2 engine in relation to adequate minimal section area values of the base PZL-10W engine, obtained by means of the TURB297, T62003, and CAT programs (Table 1), shows that the methods of flow modelling used for these programs have a similar accuracy of calculations. The method of calculating of the turbine characteristics given by D. G. Ainley and G. C. R. Mathieson and improved by J. D. Dunham and P. M.

Came makes it possible to determine turbine characteristics with an accuracy of ±3% for mass flow and ±2% for efficiency.

It should be stated that the stages of modern axial-flow turbines are designed specifically to obtain the Laval number for the minimal section at design rating (T-O) close to the critical value [5]. It essentially influences the distribution of the total pressure ratio of the stages and the change of the ratio in a two-stage turbine. Consequently, it leads to maintaining an almost constant value of the first-stage total pressure ratio for a wide range of changes of turbine operation ratings. A small change in the first-stage total pressure ratio from a turbine operation rating involves maintaining the mass flow parameter $A_{T0I} = idem$ for a wide range of the operation rating.

However, it should be underlined that the total pressure ratio change of a two-stage turbine when decreasing the value of λ_{uII}, involves a stronger decrease in turbine internal efficiency than the one observed in relation to a one-stage turbine.

The accuracy of results of the T62003 program is illustrated in Fig. 7, which shows internal efficiency curves of a one-stage power turbine of a turboshaft engine. The results were obtained from measurements [8] and calculations [3-4] done by WSK PZL-Rzeszw S.A. Analogous programs for calculating turbine characteristics are widely used in the design practice and are continuously corrected as new loss correlation is elaborated. A use of similar programs by General Electric is described in the article [23].

The results presented in Figs. 4, 6, and 7 are, to the best of authors knowledge, published for the first time.

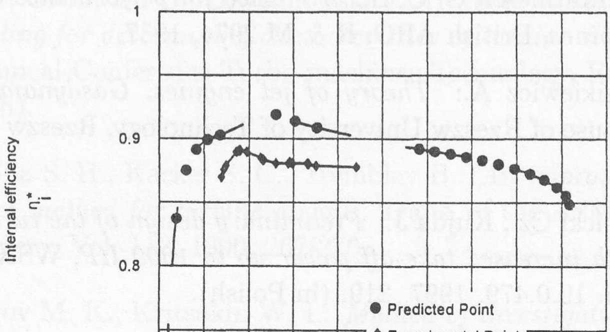


Figure 7. Example of internal efficiency curves of one-stage power turbine of turboshaft engine versus expansion ratio for Laval number of tangential velocity at the rotor entry $\lambda_{u1} = 0.5$.

6 Conclusions

A series of numerical simulations have been performed for the geometry of one-stage and two-stage axial flow turbines to determine their characteristics.

Investigation of the results has led to the following conclusions:

- the mean line prediction method of characteristics for axial flow turbines was described, which can be used for preliminary design,
- presented method was tested against the Ainley/Mathiesson/Dunham/Came loss system,
- the mean-line Mukhtarov loss system prediction at off-design performance (T62003 and TURB297 programs) has shown to agree well with AMDC loss system (CAT program),
- the trends of the predicted results are consistent with the experimental data for efficiency and, quantitatively, the predicted results exhibit a satisfactory agreement with the test data,
- presented method for predicting turbine characteristics gives higher efficiencies compared with the test data.

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