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INFLUENCE OF AXIAL COMPRESSOR STAGE SPATIAL OPTIMIZATION ON THRUST-ECONOMICAL CHARACTERISTICS OF CARGO AIRCRAFT GAS TURBINE ENGINE

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The article considers the research results of D-27 gas turbine engine thrust-economical characteristics change due to of axial compressor flow path optimization. The applied procedure of optimization takes into account a difference in the shapes of axial compressor stage blades at rest and design mode, redistribution of kinetic energy losses along the blade height. The estimation of parameters of a gas flow in the stage flow path is made by the solution of Navier-Stokes equation complete set.

Introduction

The aircraft should correspond to a particular mission which is determined by a performance specification, and should provide the completion of flying mission with the most effective utilization of the on-board equipment. The performance of flying mission should be provided both favourable and adverse weather conditions, during the day and at night by one airplane and in a group, according to the aircraft destination.

Conventional development trends of cargo aviation are increasing flight speed and range ability, improving aircraft performance characteristics. These characteristics include all parameters of the aircraft necessary for the execution of assigned tasks.

More powerful, economical and reliable power plants are necessary to meet the demand. Engine perfection is characterized by the following factors:

– thrust augmentation with simultaneous specific weight decrease;
– decrease of overall dimensions and volumes;
– decrease of specific fuel consumption.

The main tendency of the engines further improvement is development and application of new engine structures and its units, which would ensure better economy, extension of speed and altitude range.

One way to meet the requirements is to improve cargo aircraft gas-turbine engine thrust-economical characteristics. The purpose can be achieved by losses decrease in the engine axial compressor flow path, i.e. by increase of their efficiency. Low level of losses allows for designing a high-performance compact compressor having low specific weight and moderate price. High efficiency of the compressor ensures high engine parameters: low fuel consumption and increase of the flight range which is important for cargo aircraft.

Analysis of loss decrease ways

General loss of total pressure in the axial compressor can be divided conditionally into profile and secondary [1]. A level of both of them under design conditions is approximately the same.

At present three main ways of loss decrease based on the results of research of three-dimensional flow structure near the blades tips are offered [2]. The first way of the secondary loss decrease is the selection of airfoil profile rational shape as well as blade passages and airfoil cascade geometry which ensure the minimal intensity of secondary flows. The second way is using additional structural elements in the blade passage, which hinders in the development of intensive secondary flows. The third mode consists of direct influence on spatial boundary layer by suction or pressure charging.

Secondary loss decrease mode selection depends on the type of airfoil cascade (active or reactive), its operating and geometric parameters and design of air-gas channel. It is obvious that none of the offered ways can be considered universal. However the most perspective is the first way oriented to the application of rational airfoil shapes and blade passages.

Decrease of axial compressor losses is a pretty old problem as well as axial compressor itself. The works by J.Gostelow [3], K.V. Holshchevnikov [4], A.V. Bojko, J.N. Govorushchenko [5] and others were devoted to this issue. Nevertheless, the majority of specialists which work in the field of perfection of axial compressor flow path were engaged basically in airfoil losses. At the same time compressor secondary losses have the same value, as airfoil sometimes exceeding them. A great deal of research concerns secondary losses level decrease in the axial compressor. These are the followers of professor J.M. Tereshenko: V.M. Dyhanovskij, A.A. Arhipov, S.D.Severin, M.V. Tapol.

To improve aerodynamics of axial compressor flow path it is not enough to decrease secondary losses level, as the level of airfoil and total losses can increase. Due to this it is necessary to create a procedure of axial compressor stage optimization with the criteria of total level of losses.

The existing axial compressor stage procedures of optimization have certain shortcomings, namely:

– flow calculation of axial compressor transonic stage is conducted on a fixed grid (the best results are obtained with adaptive grid because it helps to trace all peculiarities of transonic flow [6]);

– the blade height loss distribution, as well as the blade height efficiency distribution are not taken into account (blade cross-section efficiency and efficiency of the whole blade can not coincide);

– blade strain due to gas and inertia forces during engine operation in design mode is not taken into account (blade geometrical shape of axial compressor in quiescent state differs from the shape of the same blades in design mode [7]).

Therefore there apparent a necessity of improvement of optimization procedure for axial compressor stages by the total energy losses in axial compressor flow path.

For optimization of axial compressor flow path of the gas-turbine engine the procedure explained in [8] was used.

The main problem in turbomachinery design is to provide turbomachine high efficiency in the operating mode. For optimization problem the next main suppositions were assumed:

– the flow relative to the rotor, which rotates with a steady angular rate or the flow relative to the inlet guide vanes, is steady;

– the fluid is compressible, inviscid and non-heat-conducting; the effect of viscosity forces is taken into account in the form of heat recovery in energy-conservation equation (i.e. friction losses are taken into account energetically);

– mass flow rate of fluid through the compressor stage is constant.

Optimization problem

Optimization problem consists in determining the inlet and outlet flow angles α_i , β_i that ensure the minimum of compressor stage losses at the same pressure.

Losses in a compressor stage are used as efficiency criteria.

These losses are function of thermo- and gas-dynamic and geometric parameters of axial compressor blade row gap.

Flow path for axial-flow compressor is divided into N stream surfaces, air consumption doesn't change along each surface. The stage consists of inlet guide vanes, rotor, guide vanes.

The flow path for axial-flow compressor is shown on fig. 1.

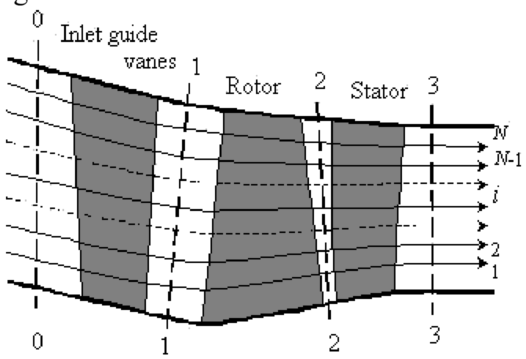


Fig. 1. Flow path for compressor stage

The velocity diagrams for compressor stage (middle section) are shown on fig. 2.

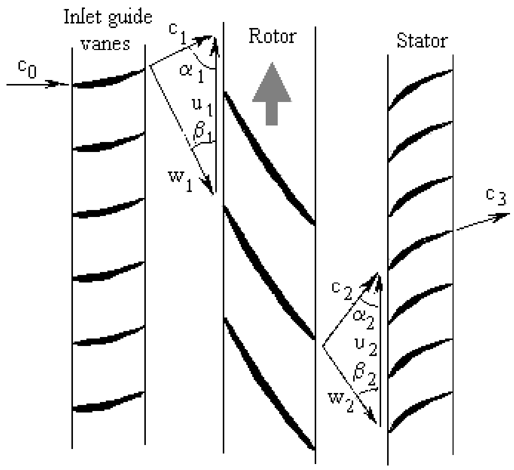


Fig. 2. The velocity diagrams for compressor stage

The axial compressor gasdynamic optimisation problem is solved for all stream surfaces simultaneously.

Optimization parameters are inlet and outlet flow angles α_{1i} , α_{2i} for each stream surface of flow path.

The objective functional can be written as follows:

$$F(\alpha_{11},\alpha_{21},...,\alpha_{1i},\alpha_{2i},...,\alpha_{1N},\alpha_{2N})= =\sum_{i=1}^{N}\xi^{*}(\alpha_{1i},\alpha_{2i}), \qquad (1)$$

where $\xi^{*}(\alpha_{1i},\alpha_{2i}), i=\overline{1,N}$ are nondimensional losses for every stream surface.

According to the Penalty Function Method determination of min$F$ is equivalent to determination of minF',

$$F'(\alpha_{11},\ \alpha_{21},...,\ \alpha_{1i},\alpha_{2i},\ ...,\ \alpha_{1N},\ \alpha_{2N})= =\sum_{i=1}^{N}\left[\xi^{*}(\alpha_{1i},\alpha_{2i})+\Lambda\sum_{j=1}^{4}A_j^2(\alpha_{1i},\alpha_{2i})\right], \qquad (2)$$

where Λ is penalty coefficient; $A_1, A_2,...,$ $A_i,..., A_N, A_c$ are limitations (energy conservation equations are written for every blades row and for compressor stage as a whole).

Using the gasdynamic and kinematic equations [2; 7] and *T–s* diagram of gas compression process for the compressor stage (fig. 3) the objective functional can be written in the form convenient for optimization problem solving.

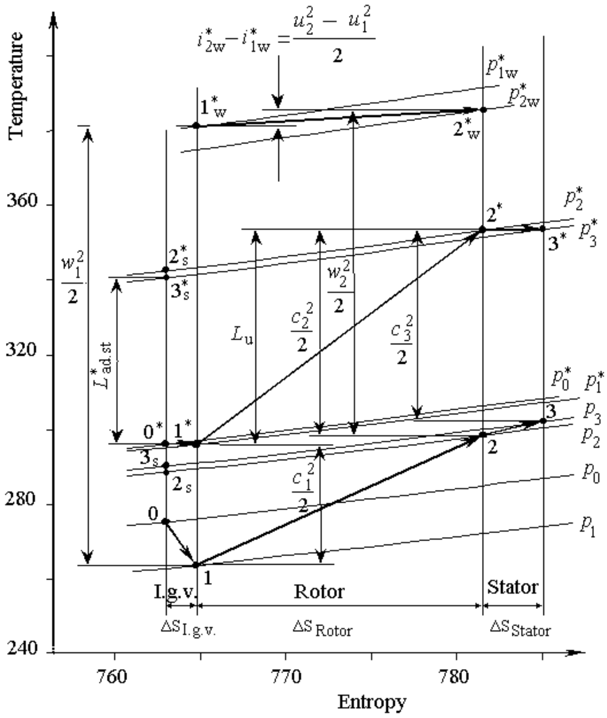


Fig. 3. *T–s* diagram of gas compression process for the compressor stage

The losses of flow kinetic energy in elementary stage:

$$\xi^*_{st.i} = 1 - \eta^*_{stage} = 1 - \left(\frac{L^*_{ad.st}}{L_u}\right)_i =$$

$$= 1 - \left(\frac{\frac{k}{k-1}R\left(T^*_{3ad} - T^*_0\right)}{c_{2u}\,u_2 - c_{1u}\,u_1}\right)_i =$$

$$= 1 - \left(\frac{\frac{k}{k-1}RT^*_0\left(\pi_{st}^{*\frac{k-1}{k}} - 1\right)}{c_{2a}u_2\mathrm{ctg}\alpha_2 - c_{1a}u_1\mathrm{ctg}\alpha_1}\right)_i .$$

Adiabatic compression work for elementary stage:

$$L^*_{ad.st} = \frac{k}{k-1}R\left(T^*_{3ad} - T^*_0\right) = \frac{k}{k-1}RT^*_0\left(\pi_{st}^{*\frac{k}{k-1}} - 1\right).$$

Supplied work in elementary stage (from Eiler's equation):

$$L_u = c_{2u}u_2 - c_{1u}u_1 = c_{2a}u_2\mathrm{ctg}\alpha_2 - c_{1a}u_1\mathrm{ctg}\alpha_1 .$$

Energy conservation equation for the inlet guide vanes:

$$A_1(\alpha_1) \equiv \frac{i_1 - i_0 + \frac{c_{1a}^2}{2\sin^2\alpha_1} - \frac{c_{0a}^2}{2\sin^2\alpha_0}}{i_0^*} = 0 .$$

Energy conservation equation for the second blade ring (rotor):

$$A_2(\alpha_1,\alpha_2) \equiv \frac{1}{i_1 + \frac{c_{1a}^2 + (u_1 - c_{1a}\mathrm{ctg}\alpha_1)^2}{2}}$$

$$\left[i_2 - i_1 + \frac{c_{2a}^2 + (u_2 - c_{2a}\mathrm{ctg}\alpha_2)^2}{2} - \right.$$

$$- \frac{c_{1a}^2 + (u_1 - c_{1a}\mathrm{ctg}\alpha_1)^2}{2} -$$

$$\left. - \left(c_{2a}u_2\mathrm{ctg}\alpha_2 - c_{1a}u_1\mathrm{ctg}\alpha_1\right)\right] = 0 .$$

Energy conservation equation for the third blade ring (guide vanes):

$$A_3(\alpha_2) \equiv \frac{i_3 - i_2 + \frac{c_{3a}^2}{2\sin^2\alpha_3} - \frac{c_{2a}^2}{2\sin^2\alpha_2}}{i_2 + \frac{c_{2a}^2}{2\sin^2\alpha_2}} = 0 .$$

Energy conservation equation for the elementary stage:

$$A_4(\alpha_1,\alpha_2) \equiv \frac{1}{i_0^*}\left[i_2 - i_1 + \frac{c_{2a}^2 + (u_2 - c_{2a}\mathrm{ctg}\alpha_2)^2}{2} - \right.$$

$$- \frac{c_{1a}^2 + (u_1 - c_{1a}\mathrm{ctg}\alpha_1)^2}{2} - \frac{k}{k-1}RT^*_0\left(\pi_{st}^{*\frac{k-1}{k}} - 1\right) -$$

$$- L_r\frac{T_3 - T_0}{T_3 - T_0} - \xi_{IVG}\frac{c_{0a}^2}{2\sin^2\alpha_0} -$$

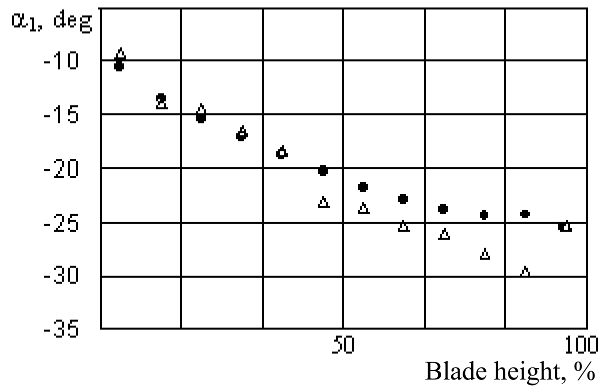
$$- \xi_{Rotor}\frac{c_{1a}^2 + (u_1 - c_{1a}\mathrm{ctg}\alpha_1)}{2} -$$

$$\left. - \xi_{Stator}\frac{c_{2a}^2}{2\sin^2\alpha_2}\right] = 0 .$$

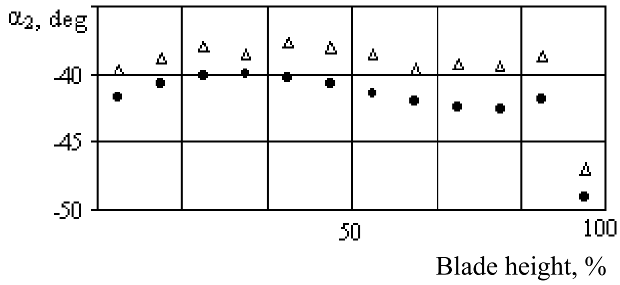
Nelder-Meed method explained in [9] was applied to the solution of optimization problem.

For estimation of axial compressor stage geometric shape influence on gas-turbine engine thrust – economical characteristics with the explained procedure the optimization of D-27 turbo-prop engine compressor stage for cargo aircraft An-70 was carried out.

The angles (α_1 and α_2) in compressor blade row gaps along the blade height *l* before optimization and after it are shown in fig. 4.



a



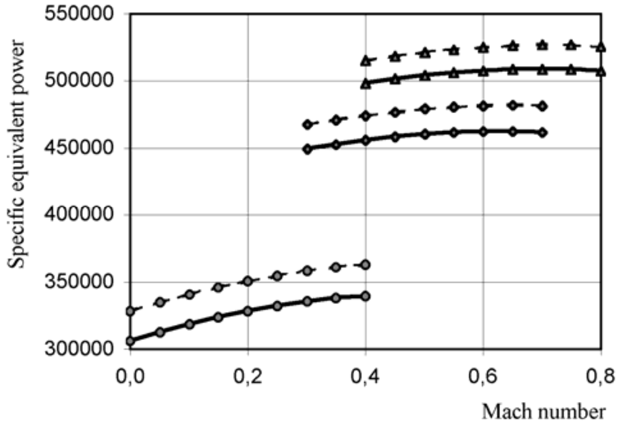
b

Fig. 4. Fluid angles in blade row gap along the blade height from hub to blade tips before optimization (●) and after optimization (**Δ**):
a – for angles α_1; *b* – for angles α_2

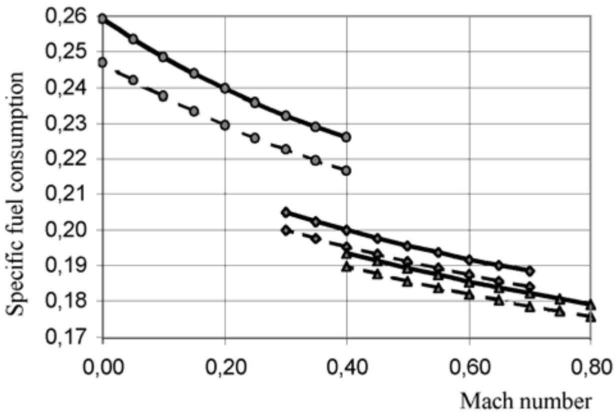
Operating mode parameters of D-27 engine were used as design parameters.
Thrust-economical characteristics changes are shown for different altitudes in fig. 5.
Continuous line shows D-27 engine calculated characteristics before the optimization and dashed line – after optimization for different altitudes.
As a result of thrust-economic characteristics calculation for different gas-turbine engines with axial compressors stages optimized with the explained procedure, the improved thrust-economic characteristics for a wide range of altitudes and flying speeds have been obtained.
Optimization of gas-turbine engine axial compressors with the procedure in the design stages and operational development will enable to improve of engine thrust-economic characteristics, and consequently, to improve performance specification of different purpose airplanes.

Conclusion

The offered procedure allows for providing optimization of axial compressors for a wide class of gasturbine engines.
The use of the procedure will allow to reduce the specific equivalent fuel consumption by 1,8–2,3 % in a wide range of altitudes and flying speeds for cargo and commercial planes with turboprop engines.
To improve the procedure it is expedient to research a fragmentation of axial compressor flow path with stream surfaces, for the purpose of determination of the optimum fragmentation denseness and estimation of the influence of fragmentation denseness on the change of gas-turbine engine optimized axial compressor stage geometric parameters.



a



b

Fig. 5. Thrust-economical characteristics changes:
a – dependence of specific equivalent power in different modes of flight; *b* – dependence of equivalent fuel rate on different modes of flight;
▬▬ – before optimization; after optimization for altitude;
●–● –● – H = 0 km; ◆–◆ – H = 8 km; ▲–▲ –H = 11 km

In further research it is expedient to carry out the optimization of axial compressor flow path as a whole, instead of its separate stages, and to examine the character of a gas flow along the gas-turbine engine compressor flow path.

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Вплив просторової оптимізації ступенів осьового компресора на тягово-економічні характеристики газотурбінного двигуна транспортного літака

Викладено результати дослідження зміни тягово-економічних характеристик турбогвинтового двигуна Д-27 у результаті проведення оптимізації проточної частини осьового компресора. Застосована методика оптимізації враховує різницю між формами робочих лопаток, ступенем осьового компресора в стані спокою, при роботі на розрахунковому режимі та перерозподіл втрат кінетичної енергії за висотою лопатки. Параметри газового потоку в проточній частині ступеня обчислено за допомогою розв'язання повної системи рівнянь Нав'є-Стокса.

Л.Г. Волянская, П.И. Греков, О.В. Юрченко

Влияние пространственной оптимизации ступеней осевого компрессора на тягово-економичные характеристики газотурбинного двигателя транспортного самолета

Изложены результаты исследований изменения тягово-економичных характеристик турбовинтового двигателя Д-27 в результате проведения оптимизации проточной части осевого компрессора. Использованная методика оптимизации учитывает разницу между формами рабочих лопаток, ступенью осевого компрессора в состоянии покоя, при работе на расчетном режиме и перераспределение затрат кинетической энергии по высоте лопатки. Параметры газового потока в проточной части ступени определены с помощью решения полной системы уравнений Навье-Стокса.