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Optimization of a Multistage Axial Compressor in a Gas Turbine Engine System

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ABSTRACT

The work presents a procedure to determine the design parameters of multistage axial compressor (MAC) rows, the parameters optimum from the point of view to assure the best integrated indices of gas turbine engine (GTE) both at the design and off-design operation mode.

Effectiveness of the proposed approach has been demonstrated with regards to solving the problems of optimum contouring by the radius of 7 rows of 4-stage fan included in a two-shaft turbofan. For the examples under consideration respective problems of non-linear programming have been set whose dimensionality reached up to 63 of the design parameters of fan blade rows.

It is shown, that the requirement to provide the best engine characteristics, integrated matching both GTE component parts (in our case these are compressor blade rows) and integrated characteristics of components included in an engine is of more importance than assuring the highest efficiency of separate components under consideration.

NOMENCLATURE

GTE - gas-turbine engine
IOSO - the method of indirect optimization on the basis of self-organization
π^* - overall pressure ratio
π^* - pressure ratio
T^* - full temperature
m - by-pass ratio
G - air flow rate
M - Mach number
H - altitude of flight
x - vector of fan rows parameters being optimized
β_{1k} - angle at the inlet to the blade
ε - angle at the airfoil curvature
(b/t) - grid solidity
C_s - specific fuel consumption
R^s - engine thrust
ΔK_s - gas-dynamic stability margin
n - rotation rate
η^* - efficiency

Indices:

o - design regime
k - k-th flight regime (optimization)
red - reduction parameter
f - parameter of fan
c - parameter of compressor
h - parameter of high-pressure turbine
l - parameter of low-pressure turbine
d - desired value of parameter

INTRODUCTION

GTE integrated performance parameters depend essentially on the efficiency of its components and, in particular, on the efficiency of compressor cascades.

Turbomachinery design has a multitude of interconnected problems. The development of an acceptable version of compressor aerodynamic lay-out is an important one. This process allows to determine the main design parameters of a turbomachine.

Many works and papers are dedicated to the problem of MAC parameters optimization, but they differ in the level of mathematical modelling of the processes in a turbomachine, in setting tasks of non-linear programming which determine formalization of a problem to be solved etc. (Tunakov, 1979; Hearsey, 1989; Massardo et al., 1989; Tuccillo, 1989; Egorov et al., 1990).

Compressor parameter optimization tasks consists not only in a difficulty in adequate mathematical modelling of an object, but also in serious problems pertaining to solving the tasks of non-linear programming.

First of all it is a lot of computer time required to calculate a turbomachine design. This results in the necessity to develop quite "high speed", but adequate algorithms to calculate compressor parameters. From the point of view of minimization of computer time the most efficient are MAC mathematical models which allow to determine turbomachine characteristics in mean radius (1-D arrangement).

This approach is widely used (Tunakov, 1979; Egorov et al., 1984; Massardo et al., 1989). However the given design version doesn't include the information on the change of parameters with radius and full consideration of specific features of complex processes in a turbomachine. Thus this approach is only acceptable at initial stages of an object design.

More reliable results can be obtained by using in investigations MAC mathematical model that includes space change of flow parameters along with tip effects.

This level of modelling allows to adequately describe the

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distribution of radial and axial flows in a turbomachine, but it is undoubtedly more intricate and requires more computer time for investigations.

The number of compressor design parameters can reach in this case up to 100 or more variables which results in serious problems in solving optimization tasks.

The problem of turbomachine optimum gasdynamic design is very complicated and labour consuming. This has likely resulted in the fact that a typical concept of MAC parameter optimization consists in investigation of, first of all, a separate turbomachine and, secondly, investigation in design mode (Hearsey,1989; Tuccillo,1989; Massardo et al.,1989; Egorov et al.,1990).

Nevertheless it seems that one can most fully investigate into feasibility of turbomachine parameters improvement by carrying out the design as part of an engine when optimum matching of MAC characteristics with other components of GTE is carried out. Solving the problem of building up optimum configuration of a compressor in full scale (considering weight, dimensions, strength, cost, operation and other parameters) is highly problematic even when investigating into separate turbomachine let alone determining turbomachine design parameters as part of an engine.

The present work is dedicated to a more particular but often met with problem which involves determination of possibility to improve integral characteristics of a two-shaft turbofan (considering both design and off-design operation modes) at the expense of optimum contouring of rows by radius of compressor cascades.

To solve this problem it is necessary to have an adequate mathematical model of GTE where the characteristics of compressor cascade (or cascades) are determined with regards to the change of flow parameters by radius.

Following parameters of a hypothetical engine under investigations have been selected: total compression ratio $\pi^*_{\Sigma o}=25$, turbine entry temperature $T^*_{ho}=1700K$, bypass ratio $m_o=1,5$. Design operation mode corresponded to the flight at $H_o=500\ m$ and speed $M_o=0,74$.

The investigations, presented in this work have been constrained by determination of design parameters by radius of 7 rows of 4-stage fan of a two-shaft turbofan.

It seems that using this approach the task can be significantly enlarged.

GTE MATHEMATICAL MODEL

The peculiarity of GTE mathematical model in our case consists in necessity to calculate characteristics of compressor cascade (or cascades) with regards to the change of flow parameters by radius in a turbomachine.

In this paper, while modelling processes in an engine, we assumed a non-linear elementwise mathematical model of an aircraft GTE as a basis. The model, described in work (CIAM,1980), allows to determine turbomachine characteristics in steady-state and unsteady operation modes.

In steady-state operation modes a mathematical model of an engine is a system of non-linear algebraic equations, presenting operation of separate components and their matching when included in an engine. This system is based on the equations of energy conservation, continuity and state using the magnitudes of enthalpy and entropy in design sections of gas passage. The initial system is reduced to the minimum possible dimensionality and is presented as discrepancies, which can be solved by the modified Newton-Raphson method.

The block pattern of a calculation algorithm permits to change the level of detalization of engine components modelling over a wide range to provide for extensive investigation in accordance with the preset task.

With regards to our problem, the development of a given mathematical model consisted in complication of modelling the level of compressor cascades whose characteristics have been determined using the calculation method (Egorov et al.,1989; Egorov et al.,1990). The method allows to investigate into the peculiarities of turbomachine radial and axial flows distribution.

The basis of the compressor 2-D mathematical model is a method of flow lines curvature (Novak,1976), which is essentially an iterative numerical solution of the equations of motion, continuity, energy and state of axisymmetrical flow in a turbomachine. The equations have components describing inclination and curvature of meridional flow lines whose coordinates are approximated by splines. For each iteration there is a clarification of flow lines state and recalculation of geometry to the flow inclination surface.

To close the system of gasdynamic equations for the axisymmetrical flow there is used the relation to calculate flow lag angles and loses, based on corrected generalizations of experimental data in blowing flat cascades, blade rows and stages (Lieblein et al.,1953; Burmistrov et al.,1973).

The corrected Carter relationship is used to calculate flow lag angles. At high inclination angles of the duct and flow lines to the compressor axis we conduct an equivalent recalculation of the geometry of blade row cascades, by which we evaluated the lag angles.

Mathematical model to calculate losses includes the definition of: profile losses, wave losses (when there are flows with dislodged head waves and closing shock-wave, and a realized system of oblique shock-waves), end-surface, secondary and radial clearance losses.

To determine the latter three types of losses we calculate the parameters of a near-wall boundary layer (Mellor et al.,1971) by which, unlike the usual boundary layer, we understand the area of secondary flows effect. There is also determined the thickness of pulse loss, thickness of displacement and thickness of the near-wall boundary layer itself within which there is distribution of the mentioned losses and correction of the flow lag angle.

Mathematical model of a compressor provides for the calculation of compressor maximum efficiency and vertical branches of a characteristic.

For the approximate estimation of a steady operation boundary there are used several criteria of aerodynamic loading which permit to determine local and integral loading of rows (Lieblein et al.,1953; Mellor et al.,1971). Along with this we analyse the appearance of reverse flows in the compressor passage.

Investigation of a large set of compressors proved the reliability of this procedure to determine characteristics of turbomachines within a wide range of the change of MAC parameters and operation modes.

Considering our problem, a very important factor is that this approach permits to determine the effect of a multitude of row design parameters by radius both on the characteristics of a separate row, considered as included in a compressor, and on integral characteristics of a turbomachine, investigated as included in an engine. Thus, using this procedure of calculation one can study not only intricate processes in a turbomachine, but also consider specificity of an effect of compressor row design parameters on the matching of all GTE components as included in an engine.

Solution of the problem of determining design parameters of a two-shaft turbofan fan made possible to simplify the calculation of characteristics of other turbomachine cascades which had been determined by 1-D (mean radius) procedures (Egorov et al.,1984; CIAM,1980).

Based on the data on a distribution of flow parameters by radius at the outlet, obtained during the process of matching the fan with other engine components, determination of integral magnitudes of flow parameters has been conducted separately for the outer and inner engine contours. It was made on the basis of averaging the parameters diagrams at the fan outlet by areas whose relation was determined by the actual bypass ratio, calculated in solving a system of non-linear algebraic equations that describe operation and matching of the components included in GTE.

Numerical solution of a gasdynamic equations system within 2-D axisymmetrical mathematical model of a turbomachine provides for the matching of row parameters by the fan radius. Solution of a system of non-linear algebraic equations, describing joint operation of all engine components, provided for the matching of the fan integral data (with regard to the parameters difference at the entry of contours), which determine the location of an operating point in the field of its characteristics and, respectively, of the diagrams of changing the parameters at the outlet by radius along with other engine elements.

Thus, while matching engine components behind each blade row and, in particular, in design section behind the fan, there were obtained data on the nature of distribution of flow parameters (2-D approach) which in design section at the entry of outer and inner engine contours were transformed by means of the above mentioned way into 1-D flow, but with different parameters for each contour.

Comparison of integral and engine inner parameters, calculated at different levels of turbomachine modelling and given in Fig.1...4, shows that the use of this approach doesn't result in significant distortion of physical processes in an engine.

Fig.1 shows the field of integral characteristics of the fan obtained by using this method of calculation and experimentally. The figures show engine operating lines.

Fig.5...7 shows the change of fields by the radius of local magnitudes of pressure ratio, efficiency and temperature in elementary jet by the radius at the fan outlet along the turbomachine operating line included in GTE at the throttle regime.

GTE modelling with account for the fan flow spatiality increased considerably the computer time required to calculate one point of GTE integral characteristics, that is to calculate the criterion of optimization and constraints.

It should be noted that requirements to the determination of the fan gasdynamic stability margin for the engine operation mode resulted in the necessity to calculate the respective part of the head branch. This required the development of a special algorithm and additional computer time.

Fig.8 shows the change of a time required to calculate a point of throttle characteristics with reference to the most common designs of aircraft GTE (modelling of the fan and high pressure compressor in two-shaft designs has been conducted using the 2-D axisymmetrical model used in this work).

Thus, the proposed mathematical model of an engine permits to evaluate the effect of design parameters by compressor cascade radius (and in particular of the fan) on GTE integral exponents,

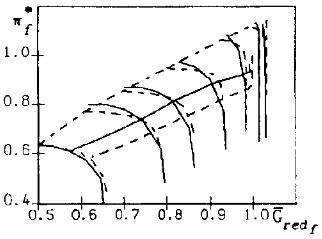

Fig.1 Field of fan characteristics:
—— proposed model of GTE (two-dimensional fan model);
- - - one-dimensional model of GTE (experimental characteristics of the fan).

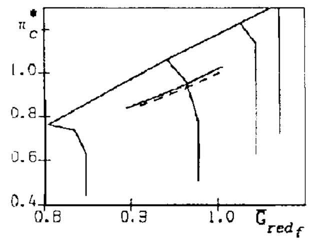

Fig.2 Field of characteristics of high-pressure compressor (designations are the same).

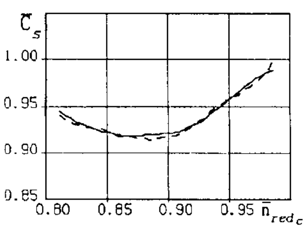

Fig.3 Change of specific fuel consumption (C_s) while throttling the engine.

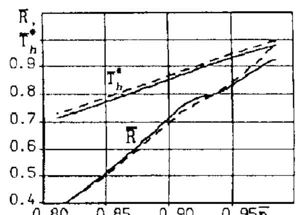

Fig.4 Change of engine thrust (R) and gas temperature before the turbine (T_h) while throttling the engine.

and hence to determine the optimization and constraint criterion according to the preset task.

OPTIMIZATION PROCEDURE

Solving non-linear programming problems requires high efficient computer and sufficiently efficient optimization procedures.

The method of indirect optimization on the basis of self-organization (IOSO) (Egorov, 1988; Egorov, 1990) proposed earlier by the author, has been used to determine optimum gasdynamic design of a turbomachine included in an engine.

The essence of this method, its software and algorithm provision, comparative analysis including well-known procedures of non-linear programming, evaluation of the effectiveness of solving the problems with different tests (smooth, non-differential stochastic functions and multiextremum functions), as well as other problems and question have been described in papers (Egorov, 1988; Egorov et al., 1989; Egorov, 1990).

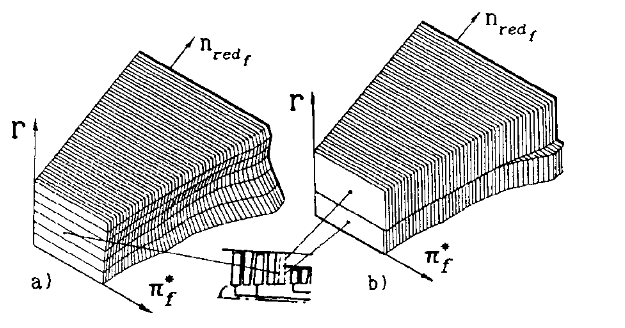

Fig.5 Change of local values of pressure increase level due to the radius while throttling the engine in the calculated sections:
a) behind the fan
b) at the inlet into the outer and inner profiles.

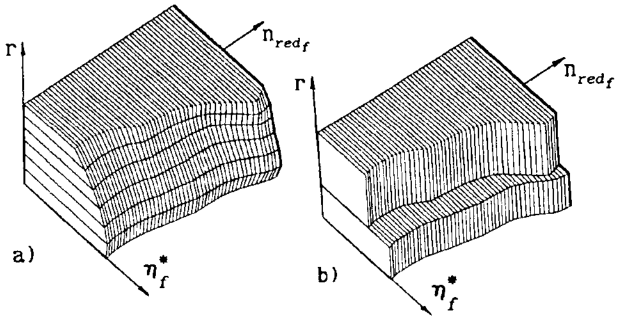

Fig.6 Change of local efficiency values due to the radius while throttling the engine in the calculated sections:
a) behind the fan
b) at the inlet into the outer and inner profiles.

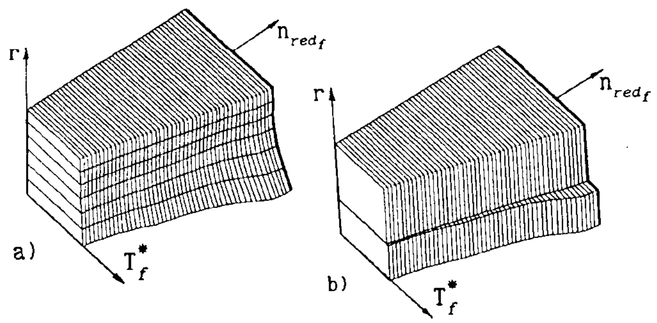

Fig.7 Change of local air temperature values due to the radius while throttling the engine in the calculated sections:
a) behind the fan
b) at the inlet into the outer and inner profiles.

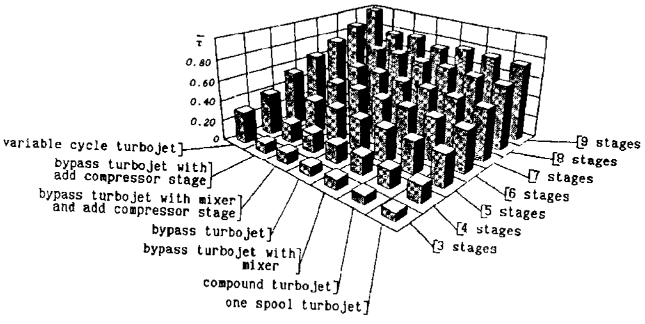

Fig.8 Change of time required to calculate one point of throttle characteristic according to the number of compressor stages with a computer ($\bar{\tau}$=1.0 is equal to 11,3 minutes of CPU time of a computer with operating speed of 6 million operations per second.)

In short, the peculiarity of IOSO is that every iteration of the search for the extremum has two stages, the first being the synthesis of a statistical analogue $\hat{y}$, the second - determination of the extremum of this function x^*, i.e. $\hat{y}(x^*)\Rightarrow extr$. Within one iteration a direct use of mathematical model is carried out only in the point x^* to clarify the magnitude of the optimization criterion $y(x^*)$.

This point is included in a diagram, then a new approximation function is being constructed, and so on. The procedure is over when the extremum has been determined with required accuracy. The work (Egorov et al.,1989) presents in detail the proposed by the author twenty IOSO algorithms which differ in the way of constructing an approximation function, adaptation of the area of search, method of using and generalizing the obtained in search information on topology of the optimized function, possibility of adaptive change in optimization algorithm structure etc. While developing IOSO, the author aimed at assurance of its invariance to the topology of the target function. Invariant properties of the proposed optimization method are given in work (Egorov et al.,1989) with reference to the test optimization problems and in work (Egorov,1990) with reference to the model task from the field of compressor manufacture, where on the basis of applied statistics procedures at the level of significance P = 0.99 the hypothesis of statistical dependence of the criterion of IOSO extremum search effectiveness on the topology of the optimized function has been rejected.

On the whole the proposed procedure of calculation allows to reduce direct use of the mathematical model. Since in our problem of extremum search determining the magnitude of optimization criterion accounts for the most part of calculations (up to 90%), a decrease in required number of optimization criterion direct calculations results in reduction of a total number of calculations during the investigation.

To demonstrate IOSO effectiveness, Fig.9 shows a multiextremum function topology that has a set of local extremums in which the values of the function are close to the value of a total extremum. Evidently there is no need to convince someone that it is a very difficult test. Analysis of the results of this function extremum search and the search for other extremums of the same family (Fig.9) proves that, first, the total extremum has been determined by using IOSO; second, the number of direct calculations of optimization criterion is not large; third, there are demonstrated invariant properties of the procedure (to equivalently optimize unimodal or multiextremum function with parameter m=0.9 by means of the required number of the function calculations).

In referense to the problems of optimization of the components and GTE on the whole, the use of the procedure of indirect optimization on the basis of self-organization is reduced to adaptive use of three types of mathematical modeling: functional models, models of the transfer functions type (response surfaces) and simulation models - Fig.10.

Constructing GTE models of the transfer functions and simu-

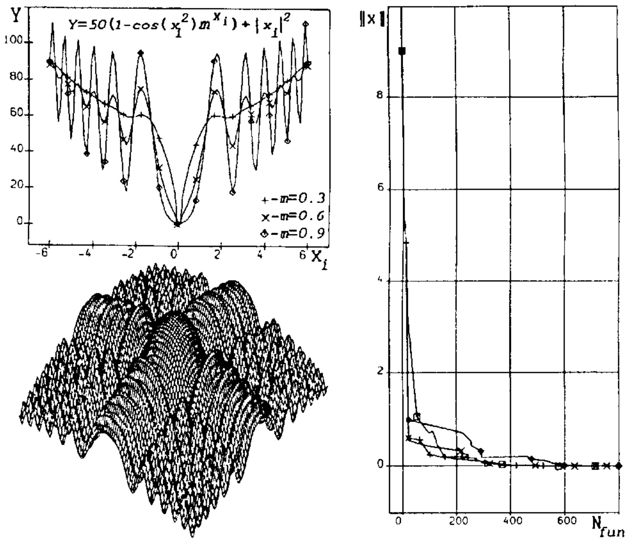

Fig.9 Topology and optimization results of multiextremum test function.

lation models type is conducted algorithmically using IOSO software on the basis of an available engine functional model. The model considered by us can serve as an example of this functional model.

Fig.10 shows that using IOSO to solve extremum problems, with referece to the aircraft GTE, provides for significant saving of time at a complex functional shape and mathematical model of an engine. This saving of time can reach the factor of 30 and oven more as compared to the procedure of random search. This fact was of particular importance in selecting non-linear programming procedure in the present work, where the problem of search of the fan blade row optimum design parameters included in an engine has been set.

SETTING OPTIMIZATION TASK

As in any problem of non-linear programming, determination of the turbomachine optimum design parameters is intended to select optimization criterion, variables and constraints.

In case of GTE various integrated parameters may be considered as optimization parameters. Without considering the problem in detail, we assume in the paper the terms of assuring the engine highest economic parameters at a preset flight speed M_k and altitude H_k, i.e. $A(X|M_k,H_k)\Rightarrow min$ as the criterion of the turbomachine perfection. It should be noted that any other criterion or criteria combination can be equally considered.

The traditional approach reduces constructing the turbomachine configuration to the determination of design parameters in design mode which, in our case, is equivalent to the requirement to provide for the engine highest efficiency in a given operation mode. This problem is actual for engines whose operation mode in service changes insignificantly and is close to a design one (for instance, ground, gas turbine plants). But in case of the engines used in multimode flying vehicles more important is the factor of providing for better efficiency in operation modes, which differ from the design ones, i.e. cruise flight of a transport aircraft.

In this case the problem is to determine the fan rows optimum parameters which provide for improved efficiency in one or various operation modes, which differ from the design modes. It should also be noted, that in this case one must introduce respective constraints at a design operation mode (for instance the thrust should be limited).

As is known, optimization of compressor parameters in 2-D setting results in a large dimensionality of a task. The paper considers only those parameters as turbomachine design parame-

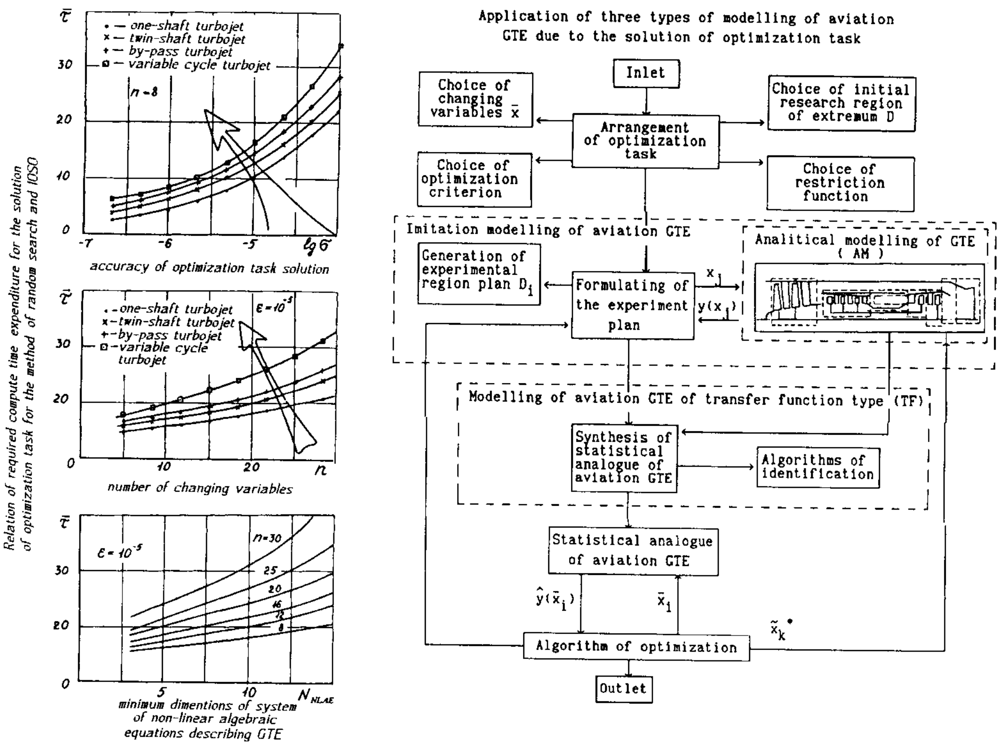

Fig. 10 Scheme of optimization of GTE parameters with proposed method.

ters, whose change is expected to have most significant effect on the turbomachine parameters and, respectively, on the engine integrated parameters.

These are, first of all, changes by the radius R of an angle at the blade entry, $\beta=f(R)$, of profile curvature, $\varepsilon=f(R)$, and first row cascade density $(b/t)=f(R)$.

Determination of the flow parameters for each row has been conducted in seven design sections. To reduce the number of the variables, direct change of geometrical parameters of a row has been conducted in three sections, in the bush, periphery and mean radius. Determination of parameters of every row in other sections has been carried out on the basis of polynomial relationship of the second degree $[\beta_{1k};\ \varepsilon;\ (b/t)]_1=a_{01}+a_{11}R_1+a_{21}R_1$, where coefficients were determined from the solution of a respective system of algebraic linear equations, based on the known magnitudes of parameters in three sections. This approach has allowed, first, to reduce the dimensionality of the task, second, to simplify the procedure of recalculation of the row geometry at changing the location of the flow lines during the process of iterative solution of a system of gasdynamic equations describing axisymmetrical flow in turbomachine, and, third, while constructing the range of design parameters changes constraints were placed in natural way and did not require the respective recalculation procedure. On this basis the number of optimized parameters, while determining the design parameters of seven rows in a fourstage fan amounted to 63.

In our task the constraints can be conventionally divided in two groups, the first being connected with the constraints placed directly on the row parameters and exponents and, on the whole, turbomachine, the second group - other constraints placed on the engine integrated parameters.

According to works (Egorov et al., 1989; Egorov et al., 1990) such constraints, as permissible fields of changing the variable parameters (linear limitations) - x_{i-}; x_{i+}, whose range amounted to 20% respective to basic values, were considered as the first group of constraints. Non-linear constraints were placed on local magnitudes of aerodynamic loading respectively $\bar{D}$ in all design sections of eight rows of the fan, total number of the constraints amounted to 56. For the tasks, where under optimization criterion a certain integral parameter, representing the record of n_r engine operation modes, was considered, total number of non-linear constraints of this type amounted respectively to $56{*}n_r$ magnitudes.

Under constraints placed on engine integral parameters, there were considered such constraints as minimum permissible stability margins of fan ΔK_{sf} and high pressure compressor ΔK_{sc}; maximum permissible values of economic efficiency in design operation mode $C_s(H_o,M_o)$ - H_o and M_o being respectively flight altitude and Mach number, at which the so called "outset" of an engine is carried out; maximum permissible values of gas temperature at the turbine entry $T^*_{h\,max}$; a value of thrust both in design point $R(H_o,M_o)$ and k - th flight mode $R(H_k,M_k)$, which requires to assure the highest engine efficiency by way of fan optimum recontouring. One should note that at a given task setting there was required to determine not only turbomachine design parameters, but the engine operation mode itself which can be characterized by respective corrected speed of the fan rotor $n_{red\,f}$.

The above said permits to set the task of non-linear programming.

To find such $x \in D \subset R$ when

$$A(x^* \mid M_k,\ H_k) = \underset{x\in D}{extr}\ A\ (x \mid M_k,H_k) \qquad (1)$$

where the permissible area of design parameters D is determined from the conditions:

$$D = \{x \in R^n \mid x_{i-} \le x_i \le x_{i+};\ \Delta K_{sf}(x) \ge \Delta K_{sf_d};\ \Delta K_{sc}(x) \ge \Delta K_{sc_d};$$
$$T^*_h(x) \le T^*_{h\,max};\ C_s(x \mid M_o,H_o) \le C_{s_d}(M_o,H_o);\ \bar{D}_{1j}(x) \le \bar{D}_{cr}; \qquad (2)$$
$$R(x \mid M_o,H_o) \ge R_d(M_o,H_o);\ R(x \mid M_k,H_k) - R_d(M_k,H_k) = 0,$$
$$i = \overline{1,n};\ 1 = \overline{1,n_{br}};\ j = \overline{1,n_s}\}$$

where $x=x(x_1,x_2,\dots,x_n)$ - vector of the fan row design parameters (in our case $x = x[\beta_{1k_{11}},\beta_{1k_{12}},\dots,\beta_{1k_{1j}},\dots,\beta_{1k_{73}},\varepsilon_{11},$ $\varepsilon_{12},\dots\varepsilon_{1j},\dots,\varepsilon_{73},(b/t)_{11},(b/t)_{12},\dots,(b/t)_{1j},\dots,(b/t)_{73}]);$

$\Delta K_{sf}(x)$; ΔK_{sf_d} ; $\Delta K_{sc}(x)$; ΔK_{sc_d} ; $T^*_h(x)$; $T^*_{h\ max}$; $C_s(x\ |M_o,H_o)$;
$C_s(M_o,H_o)$; $R(x\ |\ M_o,H_o)$; $R_d(M_o,H_o)$; $R(x\ |\ M_k,H_k)$; $R_d(M_k,H_k)$ -

- current and preset magnitudes of respective parameters;

$\bar{D}_{ij}(x)$; $\bar{D}_{cr}$ - magnitude of criterion of local aerodynamic surface of j-th section, i-th row;

n - number of design parameters of compressor;
n - number of rows in compressor;
n - number of row sections.

The paper presents the solution of four tasks of optimum designing differing in optimization criteria which depend on the preset values of the flight mode (M_k, H_k), at which minimum fuel efficiency was required to be provided.

The first task was reduced to assuring better fuel efficiency in flight at altitude and speed corresponding to design values M_k=0,74 and H_k=500m and trust $R_d(M_k,H_k)$=0,85*$R_d(M_o,H_o)$.

The second task required to achieve the minimum of this value at H_k=500m in cruise flight (M_k=0,49).

The third task was reduced to assuring the highest fuel efficiency in flight at H_k= 1000m and M_k= 0,6.

The fourth task is a problem of constructing the fan gasdynamic configuration which meets all three requirements, mentioned above, most efficiently. The latter problem is a multicriteria task of non-linear programming whose solution was based on the results obtained in the previous tasks (Beknev et al.,1991).

OPTIMIZATION RESULTS

Table 1 shows main results obtained during constructing the fan gasdynamic layout, included in an engine, for three optimization criteria selected above.

Analysis of the results shows, that the most effect in improving engine fuel efficiency has been achieved with regard to the task N1(1.8%) which is accounted for by more considerable change in engine components operation mode as compared to the design operation mode.

Fig.11 shows throttle characteristics of an engine provided with the, that has basic and optimum geometry of rows. There has been achieved engine fuel efficiency improvement within the whole range of operation modes change, which, speaking strictly, was not evident when setting the task. This is probably connected with setting optimization task N1, where the thrust value at minimizing specific fuel consumption corresponded to the lowest value of fuel efficiency at the engine throttle characteristic. It is of interest, that the minimum value of s.f.c. shifted towards lower values of thrust. In this mode the effect,achieved in fuel efficiency improvement, is even higher and is equal to approximately 2%

Interpreting the obtained results, one should bear in mind that the effect has been achieved not only due to the optimum matching of elementary sections of rows included in the fan

Table 1.The results of solving the parameter optimization task of 7 rows of 4-stage fan in the engine system.

Task	N 1	N 2	N 3
$\bar{C}_s = \dfrac{C_s(x\|M_k,H_k)}{C_{s_d}(M_k,H_k)}$	0.9819	0.9869	0.9874
$\bar{\eta}^*_f = \dfrac{\eta^*_f(x\|M_k,H_k)}{\eta^*_{f_d}(M_k,H_k)}$	1.0241	1.0202	1.0199

(that is turbomachine efficiency increase), but due to the means of the optimum matching of all the components included in the engine when changing the fan blade rows geometry. That is, the obtained result should be considered as an integral effect of optimum matching of all engine components including elementary sections of rows.

Fig.12 show that s.f.c. improvement is directly connected with the nature of changing integral magnitude of the fan efficiency along the line of operation modes and the nature of changing other components at engine throttling.

Analysis of these data shows that optimum contouring of MAC included in an engine allowed to improve the nature of proceeding the efficiency indices not only in the fan, but in the low pressure turbine as well, whose geometry remained unchanged. The compressor and high pressure turbine efficiency has not practically changed, though high pressure rotor corrected speed has somewhat increased and, respectively, corrected airflow has increased, and pressure ratio decreased in the design operation mode as compared to the basic version. The fan stability margins have increased within the whole range of engine operation. Please note, that at optimum recontouring of the geometry of the fan blade rows the total engine airflow has increased while the turbomachine pressure ratio has decreased. We would like to remind that at setting the optimization task these parameters (see(2)) were not constrained, which is typical when investigating MAC under isolated task setting. These parameters are determined directly as included in an engine system to provide for optimum matching of the components included in CTE, that minimizes engine fuel efficiency in the mode differing from the design one. In so doing there is a necessity to assure the engine thrust in the design operation mode (see(2)). The obtaining of the given result seems to be possible only when investigating the turbomachine included in an engine.

It is conceivable that these results clearly demonstrate the advantage of the proposed approach when a possibility of improving engine integrated characteristics at the expense of not only optimum recontouring of turbomachine rows, but optimum optimization of components included in an engine is realized. It is probable that in requirement to assure the best engine characteristics, integrated matching of both GTE component parts (in our case these are compressor blade rows) and integrated characteristics of components, included in an engine, is of more importance than assuring the highest efficiency of separate components

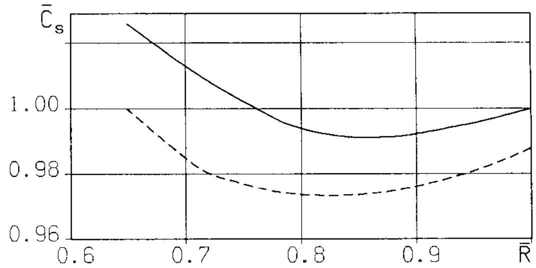

Fig.11 Throttle characteristics

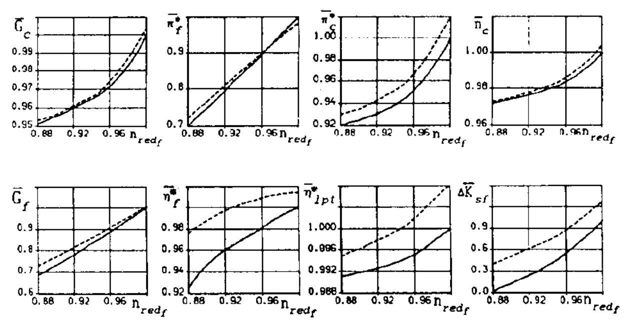

Fig.12 Change of engine parameters while throttling

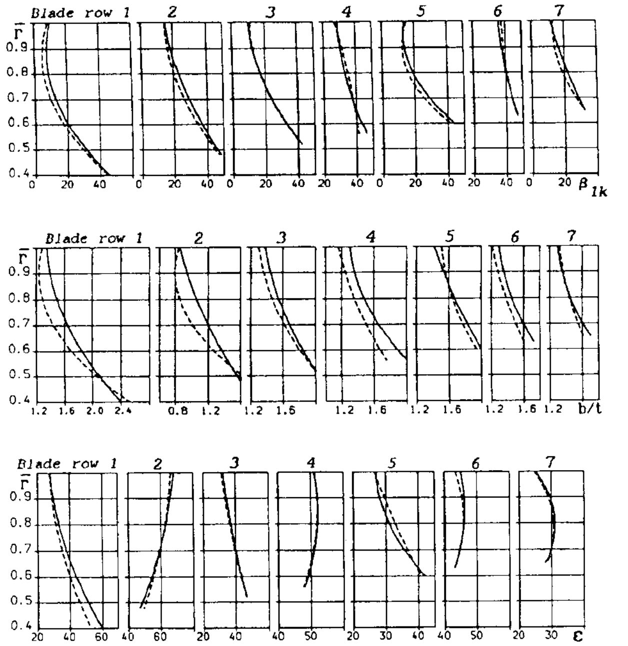

Fig. 13 Change of geometrical angles at the inlet to the blade, grid solidities, curvature angles of initial (———) and optimized (- - - -) fans.

under consideration.

Fig. 13 shows the magnitudes of geometrical parameters of 7 rows in a four-stage fan for both the basic and optimum versions of the task N1. Significant change in these parameters, and, particularly, in the cascade thickness is evident.

Fig. 14, 15 show engine speed characteristics for tasks N2 and N3 respectively. The obtained improvement in fuel efficiency is somewhat lower but, however, exceeds 1% As in the task N1, there is an improvement in s.f.c. within the whole range of Mach number change.

Fig. 16 shows the comparison of optimum parameters of the rows in the tasks under consideration. One can note that different variants of the change in rows parameters by radius correspond to each condition of constructing the fan optimum gasdynamic layout. Thus, turbomachine row optimum geometry is determined exactly prior setting the optimization problem, that is prior stating the design specification. Hence in case of engines installed in multimode flying vehicles the best integrated characteristics could be assured by constructing turbomachine configuration with regard to the multitude of the most important operation modes. The same quality effect could be expected to be reached when considering other engine components as well.

These results conform to a well known proposition that the engine design parameters depend significantly on the flight conditions under consideration. The main goal of solving the tasks N1, N2 and N3 was to determine, what was the direct influence of the flight conditions under consideration upon the design parameters of a fan, when the geometry of other engine components remained the same. Comparison of the data, given in Fig. 13 and 16, shows that optimum designs differ insignificantly as compared to the initial design. This is accounted for by the similarity of engine operation modes in flight conditions corresponding to the tasks N1, N2 and N3. With more considerable difference of the values M and H in these tasks, the optimum solutions are expected to differ more significantly. Hence, one can conclude that the initial version of a fan is not so successful from the point of view of assuring high efficiency of an engine as regards to the terms of the tasks N1, N2 and N3. However, one should hardly expect assuring the highest indices of the initial engine for the terms of the tasks N1, N2 and N3, which were not considered when developing the initial configuration of this CTE.

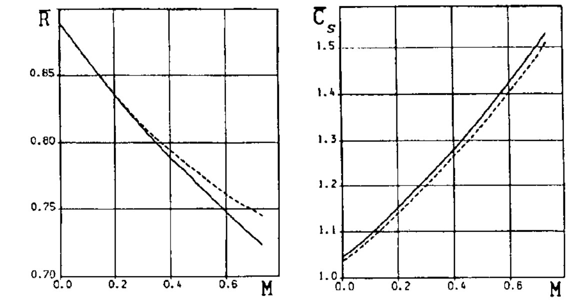

Fig. 14 Speed characteristics of initial engine (———) and of engine with optimized fan (- - - -) for the task N2.

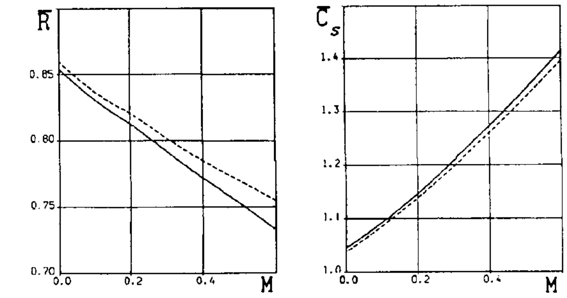

Fig. 15 Speed characteristics of initial engine (———) and of engine with optimized fan (- - - -) for the task N3.

The very aim of the present work was to carry out such version of the fan, that would not deteriorate the engine parameters in a design mode (see (2)), and, second, would assure an improvement of characteristics with reference to the tasks N1, N2 or N3.

Fig. 17 shows an example of selecting the range of the fan competitive parameters considering the requirement to assure the engine highest fuel efficiency in all flight modes considered above. There is an example for two parameters out of 63, for the cases when it is required to assure the maximum fuel efficiency in cruise flight at H=500m (Fig. 14), while from Fig. 15 it is clear that other two flight modes are considered to by more important.

At last, to give a comprehensive answer to the question in what mode the turbomachine configuration should be constructed, one must formulate the requirement to an engine, but this is beyond the investigation into isolated CTE and our paper as well.

In conclusion we shall point out that the tasks were solved using a computer with operating speed of 6 million operations per second. The overall CPU time was approximately 42 hours (the task N1). Fig. 18 demonstrates the dynamics of search for an extremum (the task N1) as relation between the obtained improvement in SFC and the number of the model runs and CPU time required to solve the task. It is evident that approximately 75% of the total number of the model runs and about 56% of CPU time to solve the task was required to obtain 95% improvement relative to the maximum.

CONCLUSION

In part the conclusions pertaining to the work have been stated in the course of the work, but, however, we present them in a brief form herebelow:

- the procedure of constructing turbomachine gasdynamic layout included in CTE, which allows to determine the main parameters by radius, has been proposed;
- the possibility of using the indirect optimization method on the basis of self-organization in the problems of a given class has been shown;
- it is expedient to construct turbomachine gasdynamic layout as included in an engine; this permits to improve CTE integrated indices; at the expense of optimum matching of both turbomachine

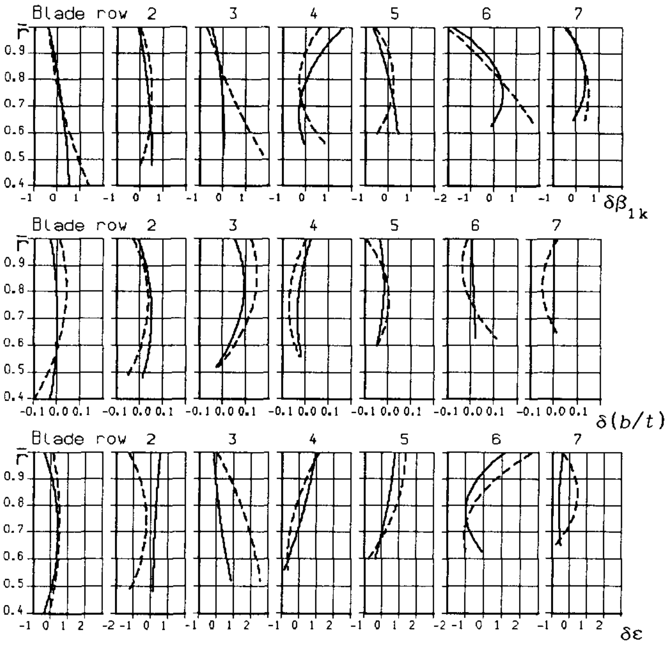

Fig.16 Change of geometrical angles at the inlet to the blade, grid solidities, curvature angles of optimized fan for the task N2 (———), N3 (- - -) as compared the task N1.

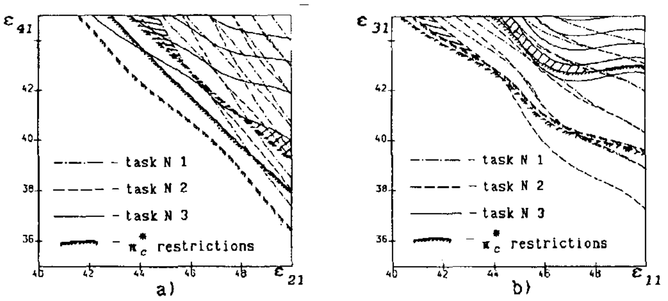

Fig.17 Topology of solution research field while providing the maximum efficiency of engine for the tasks N1 and N2 (\\\\\\), and the tasks N2 and N3 (////).

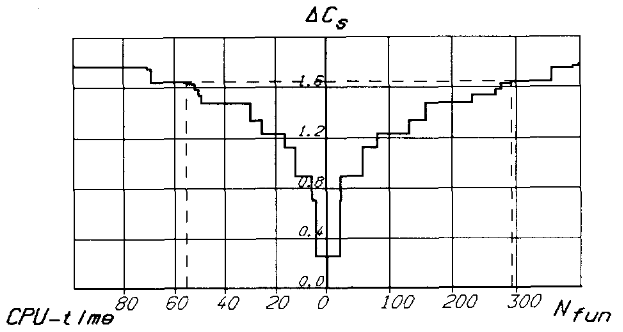

Fig.18 Relation between the obtained SFC improvement and the number of optimization criterion calculations and CPU time

rows and other components included in an engine;

- it is shown, that in requirement to assure the best engine characteristics, integrated matching both GTE component parts (in our case these are compressor blade rows) and integrated characteristics of components included in an engine is of more importance than assuring the highest efficiency of separate components under consideration;
- to assure the highest integrated characteristics of an engine while developing turbomachine design, one should consider the most important, from the service point of view , GTE operation modes.

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