Research of the possibility of improving the traction and economic characteristics of a supersonic passenger aircraft engine through minimal modifications to the high-pressure compressor

D Yu Strelets, S A Serebryansky and M V Shkurin
Moscow Aviation Institute (National Research University), 4, Volokolamskoe shosse, Moscow, 125993, Russia

E-mail: m.shkurin@mai.ru

Abstract: In this paper, the possibilities of improving the traction and economic characteristics of a by-pass turbojet engine of a high-speed passenger aircraft due to minimal modifications of the high-pressure compressor. A thermodynamic model of the investigated engine of a new design in a three-dimensional layout was formed using an automated multicriteria optimization process. A computational assessment of the change in the characteristics of compressor modifications is carried out based on a numerical model of gas dynamics.

1. Introduction
At present, all over the world, there is a surge of interest in the creation of supersonic passenger aircraft (SST) of the second generation. Analysis of publications on SST projects shows that there is still no clear understanding of the appearance of such aircraft.

The main thermodynamic parameters of the engine, such as the compressor pressure ratios, the bypass ratio, and the gas temperature in front of the turbine, depend on many conflicting requirements for the aircraft of this class. The most important indicator of technical progress in the field of civil aviation technology is the economic efficiency of a supersonic aircraft. For example, an increase in the cruising number M of the flight requires a decrease in the degree of bypass of the engine and an increase in the degree of increase in fan pressure, and the requirements for noise reduction in takeoff mode led to the need to increase the degree of bypass.

Of all the components of an aircraft (AC), the engine, as an object of modeling, is the most complex. High velocities of gas-dynamic processes, high values of temperature and pressure, as well as the direct influence of the parameters of the gas-dynamic process on the dynamics of a high-speed aircraft, give the problem of modeling gas turbine engines (GTE) great importance from the point of view of flight safety, its efficiency, and also the constructive safety of aircraft and gas turbine engines [1, 2, 3].

When forming the thermodynamic appearance of the engine, it is necessary to take into account the properties of modern materials and the features of the integration of the power plant with the aircraft.

2. Statement of the problem
In such conditions, to the power plants of the ATP, it is expedient to consider technical solutions based on the already created technical groundwork, and, in particular, based on existing gas generators. The
required parameters of gas generators (first of all, the degree of pressure increase in the compressor) to a decisive extent depends on the required value of the cruising number M of flight [4,5].

In this work, the possibility of creating a power plant for an SST with a payload mass of 1000 kg is considered, using the main elements of the gas generator and, in particular, the high-pressure compressor.

To analyze the possibility of improving the traction and economic characteristics of the engine due to the minimum modifications of the HPC, a calculated estimate of the change in the characteristics of the compressor was carried out.

3. Solution method

As part of the research, the characteristics of the HPC of the engine under study were calculated in the range of reduced rotational speeds of 80-100% (100% ≈ 9000 rpm) with a given control program.

This characteristic of the compressor will be used to create a thermodynamic model of the engine gas generator, as part of the study of the technical appearance of a promising power plant for a supersonic passenger (administrative) aircraft. The data obtained are also used to analyze the peculiarities of the flow in the compressor and to assess the possibilities of improving the gas-dynamic parameters of the compressor, as well as to develop its various modifications [6].

To assess the required characteristics of the compressor, geometric models were created for three positions of the inlet guide device (IGD), the guide vane of the first stage (GD1) and the guide vane of the second stage GD2 (figure 1).

\[
\text{Figure 1. Geometric model of a compressor with a changed position of IGD, GD1, and GD2.}
\]

Compressor characteristics were calculated for three positions of controlled devices in the range of rotation frequencies of 80-100%. Such a complex of compressor characteristics is required as input data for the thermodynamic model of the engine, which was used for computational studies [7].

It is shown how the parameters characterizing the operation of the compressor change when the airflow rate changes at a constant rotor speed \( n_r = \text{const} \).

Airflow rate (1) through any cross-section of any channel, i.e., the amount of gas passing through this section per unit of time is equal to:

\[
G_{act} = c \rho F
\]

where: \( c \) – the flow rate, \( \rho \) – its density, and \( F \) – the passage area.

Since each \( n_r = \text{const} \) power supplied to the compressor does not change, an increase in air consumption \( (G_{act}) \) will lead to the fact that the work supplied to one kilogram of the working fluid will decrease, and will lead to a decrease in the degree of pressure increase:
\[ \pi^* = \frac{P_y^*}{P_y} \]  

(2)

This leads to a decrease in the pressure and efficiency of the compressor \( \eta_k \), while the right branches of dependencies (2) tend to the vertical direction [8,9,10].

\[ \pi^* \cdot \eta_k = f \left( G_{\text{inj}} \right) \]  

(3)

Thus, an increase in air consumption, compared to the calculated value, leads to a decrease in both \( \eta_k \) the compressor and \( \pi^* \).

The engine under study is a two-circuit two-shaft turbojet with flow mixing without an afterburner. The throat area of the nozzle is non-adjustable and the nozzle exit area is adjustable to ensure full expansion at the nozzle.

For engines of this type at maximum modes, a set of control programs (limitation) of such parameters as the rotational speed of the high and low-pressure rotors and the gas temperature behind the turbine is usually formed.

The choice of the modification option for the engine gas generator for its use as part of the power plant of a supersonic passenger aircraft should be carried out not only from the point of view of the achieved indicators of technical efficiency but also from the point of view of labor costs for modification and technical risk.

4. Research results
A comparison of the calculated characteristics of the high-pressure compressor of the engine under study at different positions of the adjustable guide vanes is shown in figure 2.

![Figure 2. Comparison of the calculated characteristics of the high-pressure compressor of the engine under study at different positions of the adjustable guide vanes.](image)

Modification options for the gas generator of the engine under study.

“Variant No. 1” is a variant with an unchanged high-pressure turbine and a high-pressure compressor with the last stage removed.
When carrying out the first version of “linking”, the calculated characteristics of the high-pressure compressor of the engine under study with the last stage removed were used. The high-pressure turbine was considered unchanged, and the variable parameters were:

- the calculated degree of pressure increases of the LPC (the value of the efficiency at the calculated point is 0.86, the inlet diameter is 1100 mm.);
- the estimated value of the LPT throughput (LPT efficiency at the calculated point - 0.91);
- the area of the mixer along the outer and inner contours;
- nozzle throat area.

The values of the hydraulic losses of the total pressure in different sections of the gas-air duct were set corresponding to the average values for engines with a small bypass ratio.

“Variant No. 2” is a variant with an unchanged high-pressure turbine and a high-pressure compressor with the last two stages removed.

When carrying out the second variant of “linking”, the calculated characteristics of the high-pressure compressor of the engine with the last two stages removed were used. The variable parameters were:

- the calculated degree of pressure increases of the LPC (the value of the efficiency at the calculated point is 0.86, the inlet diameter is 1100 mm.);
- the calculated value of the TPE throughput (without changing its efficiency and maximum gas temperature);
- the estimated value of the LPT throughput (LPT efficiency at the calculated point - 0.91);
- the area of the mixer along the outer and inner contours;
- the nozzle throat area.

The values of the hydraulic losses of the total pressure in different sections of the gas-air duct were set similarly to other coupling options.

“Variant No. 3” represents a “classic” option for increasing the efficiency of engines, which consists of increasing the total degree of pressure increase and bypass. In this case, the HPC remains unchanged, and the high-pressure turbine with the maximum gas temperature increased by 100 degrees is optimized according to the criterion of specific fuel consumption.

Specific fuel consumption (4) characterizes the efficiency of the engine and shows how much fuel is required to perform the flight under the given conditions.

\[ C_{sp} = \frac{C_{\tau,\theta}}{P} \]  

where: \( C_{\tau,\theta} \) – fuel flow rate; \( P \) – engine thrust.

The variable parameters were:

- the calculated degree of pressure increases of the LPC (the efficiency value at the calculated point is 0.86, the inlet diameter is 1100 mm.);
- the estimated value of the throughput of the TPE (maximum gas temperature in the throat of the SA - 1700 K);
- the estimated value of the LPT throughput (LPT efficiency at the calculated point - 0.91);
- the area of the mixer along the outer and inner contours;
- the nozzle throat area.

The values of the hydraulic losses of the total pressure in different sections of the gas-air duct were set similarly to the previous options.
It should be noted that the similarity of the regimes in all considered cases is carried out only approximately. The main assumptions that determine the approximation of the similarity theory for gas turbine engines and their power plants are:

- self-similarity of operating modes of all elements in terms of Reynolds numbers, i.e., availability of a condition (5):

\[
Re > Re_{\text{us}}
\]  

- the absence of heat exchange with the external environment and the independence of the physical constants of the compressible gas (adiabatic exponent \( k \), gas constant \( R \)) and the conditional heat capacity of the combustion chambers from changes in the temperature of the gas flow, air humidity, as well as the composition of combustion products on similar operating modes;
- the similarity of the fields of velocities, pressures, and temperatures in the incoming flow and its stationarity in similar operating modes of the considered group of elements.

These assumptions usually do not lead to significant errors; therefore, the similarity theory is successfully used in practice.

In figure 3 … 6 show the results of calculating fragments of throttle lines obtained in the course of modeling for the modifications “Variant No. 1”, “Variant No. 2” and “Variant No. 3” in the flight mode of a high-speed passenger aircraft, corresponding to:

- flight altitude, \( H = 12 \) km;
- flight speed \( M = 1.8 \);
- coefficient of thrust losses:

\[
\bar{P} = \frac{P_{\text{reqi}}}{P_{\text{avail}}},
\]

where: \( P_{\text{reqi}} \) – required engine thrust; \( P_{\text{avail}} \) – available thrust of the engine.

It can be seen that the specific fuel consumption \( (C_{sp}) \) of the variant “2” is lower than variant “1” by about 1% but higher by 2 … 2.5% compared to option “3” (figure 3).

![Figure 3. Change specific fuel consumption (C_{sp}).](image)

In this case, the gas temperature \( (T_{p^{*}}, K) \) for variant “3” is 80 degrees higher on average (figure 4).
Figure 4. Change gas temperature ($T_r$).

The decrease in the specific fuel consumption of variant “2” is explained by the higher values of the efficiency ($\eta_v$) of the modified compressor (figure 5) due to the reduction to the required level $\Delta K_u$ of the reserves of gas-dynamic stability (figure 6).

Figure 5. Change efficiency HPC ($\eta_{HPC}$).
5. Conclusion
The research results showed that a decrease in the number of HPC stages by two leads to a further increase in efficiency with a decrease in the available stability margins.

An attempt to carry out thermodynamic coupling without changing the high-pressure turbine was not crowned with success, since the reserves of gas-dynamic stability of the HPC turned out to be insufficient. Therefore, in variant “2”, the minimum degree of increase in the throughput of the TPE was determined to ensure the reserves of the gas-dynamic stability of the HPC of at least 22%.

According to preliminary estimates, the best performance indicators of a supersonic passenger aircraft can be achieved using option No. 3. This option involves the creation of a new high-pressure turbine with an allowable gas temperature increased by 100 degrees.

It should be emphasized that resource requirements will be imposed on the power plants of the SST, comparable to those for the power plants of conventional passenger aircraft. Under these conditions, an increase in gas temperature creates serious technical risks. At the same time, the power plant based on the first variant of the gas generator modification assumes only a slight change in the high-pressure compressor.

References
[1] 2020 Digital technologies in the life cycle of Russian competitive aviation technology Monograph Under the editorship of Pogosyan M A (Moscow: MAI Publishing House) 448 ISBN 978-5-4316-0694-6
[2] 2009 More Intelligent Gas Turbine Engines RTO TECHNICAL REPORT TR-AVT-128 NASA
[3] Pripadchev A D, Sultanov N Z, Shatalova T N and Tikhonov O A 2009 Methods for the Economic Assessment of Passenger Aircraft: textbook (Orenburg: GOU SU) 121
[4] 2004 The Work of the Leading Aircraft Engine-Building Companies on the Creation of Advanced Aircraft Engines (analytical review) Under total. ed. Skibina V A and Corned V I (Moscow: TSIAM) 424
[5] Babkin V I and Solonin V I 2015 The role and place of experimental research in creating advanced aircraft engines Engine 4(100)
[6] 2003 Theory, Calculation and Design of Power Plants Ed. Sosunova V A and Chepkin V M (Moscow: Publishing house MAI) 688
[7] Krivosheev I A, Rozhkov K E, Simonov NB and Yalalov R F 2019 Choice of attack angles in the
design of rotor blades in GTE compressors [Text] Bulletin of Ufa State Aviation Technical University 23(3) 85 62-71

[8] Marchukov E Y, Egorov I, Popov G, Salnikov A, Goriachkin E and Kolmakova D 2017 Multi-disciplinary optimization of the working process of uncooled axial turbine according to efficiency and strength criteria Proc. of the ASME Turbo Expo. GT2017-64843 (Charlotte, United States) DOI 10.1115/GT2017-64843

[9] Marchukov E, Egorov I, Popov G, Baturin O, Goriachkin E, Novikova Y and Kolmakova D 2017 Improving of the working process of axial compressors of gas turbine engines by using an optimization method IOP Conference Series: Materials Science and Engineering 232(1) Article number 012041 DOI 10.1088/1757-899X/232/1/012041

[10] Popov G M, Goryachkin E S and Novikova Y D 2017 Multicriteria optimization of axial compressor operating process of gas turbine engine taking into account multi-mode operation [Text] Izvestiya Samara Scientific Center RAN 19(1) 98-106