Research and optimization of axial gas forces in turbines of turbojet bypass engines with afterburner combustion chamber

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Abstract. The paper presents the results of research and analysis of the efficiency of the power systems of the rotor of the gas generator of modern bypass engines with an afterburner. It was revealed that the gas axial forces, which are the difference between the axial forces of the rotors of the high-pressure compressor and its turbine, acting on the front angular contact bearing of the gas generator, can be significantly reduced in order to increase their reliability and service life.

1. Introduction
The requirement to ensure high reliability and service life of critical units of aviation turbojet engines, which also include the main bearings of the rotors, are relevant and of great practical importance. It is most difficult to implement these requirements when designing a gas generator rotor, and not a fan rotor, since the axial gas forces applied to it are significantly higher. So, for example, in one of the considered turbofan engines, a critical force of 3700 kgf (kilogram-force), directed along the flight (negative), acts on its thrust bearing, and an applied force equal to 1100 kgf acts on the thrust bearing of the fan. It acts against the direction of flight (in the positive direction), and its value is more than three times less. In addition, the rotational speed of the high-pressure rotor is much higher than that of the low-pressure rotor, therefore, the gas generator has a much higher sensitivity to variable operating modes and the impact on the axial load of production deviations of the area of the nozzle apparatus and the turbine impeller of the gas generator.

Structural and power schemes [1] of rotors of gas generators afterburning turbofan engine, designed with two support rotors, are very diverse, however, the study showed the availability of technical possibilities to reduce the axial gas forces acting on the angular contact ball bearing of these gas generators. The complexity of the solution to this problem lies in the fact that the air system simultaneously provides cooling and temperature reduction of the parts of the hot part of the gas generator, as well as reduction and unloading of axial gas forces acting on the front support of the rotor. This task can be realized both by changing the axial forces in the compressor and in the turbine.
2. Methods and materials
In this work, the actual problem of reducing the axial forces acting on the angular contact bearing of the rotor of the afterburning turbofan engine gas generator was solved. For this purpose, their design schemes and design features were investigated.

At present, there are a large number of methods for calculating the axial gas forces and their unloading, the main provisions of these methods are presented, for example, in [2-4]. However, it is obvious that the calculated results must be compared with experimental data in order to take into account the features of the design solutions of air cavities, labyrinth seals used, changes in the values of pressures and temperatures of air, when they pass from one cavity to another, etc. The thermodynamic parameters of air are also significantly influenced by the values of radial clearances in labyrinth seals, which change under the action of their heating and deformations due to arising stresses.

Experimental measurement of air pressures and temperatures in separate cavities of the air system of the basic design of the investigated turbofan engine was carried out, as well as strain gauging of the angular contact bearing of the gas generator, in ground and flight conditions of their operation, in order to determine the real acting axial loads and the correlation of the calculation method for their determination [5]. As a result of the studies carried out, the available possibilities of reducing the axial loads at critical operating conditions of the base engine have been determined, an effective technique has been proposed for correcting the location of the labyrinth seals in the inter disk cavity of the turbines of the turbine engine. All calculations were carried out in several typical flight modes of an aircraft of this type and purpose [6,7], its flight modes were determined at which the values of the axial gas force are maximal.

Below, in figure 1, the structural diagram of the EJ 200 turbofan engine is presented [8]. Its parameters: in the mode H = 0 and M = 0, the thrust value is 9200 kgf, and the air consumption is G = 76 kg/sec. These data are close to the parameters of the modern Russian afterburning turbofan engine RD 33, therefore, the study of the features of its design and the formation of the configuration of air cavities that determine the value of axial gas forces acting on the rotor of the gas generator is relevant and of great practical interest [9].

As can be seen, brush seals are widely used in the air cavities of this engine, having a minimum amount of air leakage in the seals of the radial clearances between the rotor and stator parts, where they are installed. Brushes are made of cobalt wires with a diameter of 0.025 ... 0.1 mm, when assembling the brushes, they provide contact with the rotor with their elasticity, during the change of operating modes this contact is maintained, which is very important from the point of view of the stability of the acting forces on the rotor. This new type of seals provides a minimum level of air flow in the sealed gaps between the rotor and stator of the turbofan engine, in a wide range of variation in their values in operation.

In the design diagram of the EJ 200 afterburning turbofan engine shown in figure 1, at the outlet of the high-pressure compressor (HPC) there is a diffuser 1 with solid struts. There are no internal channels in these racks, it is obvious that there is no unloader in which the G1 air would have to be directed to the external circuit of the motor. In this case, a decrease in air pressure occurs in the cavity E and the axial force acting in the axial direction on the angular contact bearing of the gas generator decreases. Let us further consider how the reduced pressure in cavity E and the unloading of the HPC rotor are organized in this scheme.

Air pockets C and D have high air pressure. Air enters the swirling lattice and then the existing air leaks are directed upward and released into the flow path, in front of the turbine impeller, and down. There are two three-stage jagged labyrinths, where this air lowers its pressure. With reduced pressure, this air enters the E cavity, the discharge cavity.

Another part of this air increases its pressure in the blade diffuser mounted on the cover disk, and through the channels made in the end of the lock of the turbine rotor blades, it enters their internal cavities.
Figure 1. Structural diagram of the air system of the hot part of the gas generator afterburning turbofan engine EJ 200 [8] with a large number of high-performance brush seals

\[ G_T = (G_1 + G_2) + G_3; G_4 \text{ and } G_5 \text{ - air consumption for cooling of the nozzle and turbine stage rotor}; \]
\[ G_6 \text{ - pressurization of the back cavity of the turbine disk gas generator (cavity N)}; \]
\[ G_1 \text{ - gas generator rotor pressurization (cavity B)}; \]
\[ C, D \text{ - air cavities above}; \]
\[ F \text{ - nozzle turbine}; \]
\[ A \text{ - high pressure cavity}. \]

The pressurized air cavity N in this turbojet engine is installed in the inter-disk cavity of the HPC and low-pressure turbine (LPT), on the back side of the turbine disk of the gas generator. It is closed by upper and lower seals. It is supplied with air from the intermediate stage of the HPC through pipes installed in the external circuit of the turbojet engine. As a result, an axial force is generated which reduces the axial force from the turbine of the gas generator.

The brushes of the seals installed in the high-pressure turbine (HPT) are made of cobalt wires with a diameter of 0.025 ... 0.1 mm; when assembling the brushes, they provide contact with the rotor with their elasticity, during the change of operating modes this contact remains, which is very important from the point of view of the stability of the acting forces on the rotor.

The structural diagram of the 4th generation M-88-2 turbojet gas generator installed on the Rafale aircraft (France) is shown in figure 2. Here, cooling air is supplied to the inter-disk cavity of the HPT and LPT, intrant through the cavities of the nozzle blades to the swirling grids, which also provide socketless entry of cooling air into the channels of cooled HPT and LPT blades. Thus, the entire inter-disc cavity located below the level of the swirling grids is under the pressure of this air. As a result, the unloading effort of the turbine rotor is generated, also directed in the opposite direction from the direction of the forces acting on the blades of this turbine.

In order to optimize the unloading system and search for rational schemes and design solutions, the gas generator afterburning turbofan engine AL-31f is considered below (figure 3). Shown here is a structural diagram of the supply of cooling air to the turbine rotor blade through the inner rear cavity of its nozzle apparatus, at the inlet of which there is a shut-off valve: supplying cooling air to it in the cruising mode of operation of the turbofan engine. This air is supplied due to the intermediate stage of the HPC into its inter-disk cavity of the HPT and LPT turbines.

The design features of this scheme are as follows: a three-stage labyrinth with a reverse tooth is installed on a separate disk behind the HPC of this afterburning turbofan engine (figure 4); the fume air
is bypassed into the external circuit with a heat exchanger integrated there; the air supply to the HPT blade is carried out through a swirling lattice under the cover disk from the front side of the impeller.

**Figure 2.** Design diagram of the turbofan turbine unit of the 4th generation M 88-2F [7]: $G_\Sigma = (G_1 + G_2)$ cooling air supply to the turbine blades.

**Figure 3.** Diagram of the basic gas generator for this study afterburning turbofan engine, with unloading and reduction of axial forces acting on its rotor [1,9]: $B_{LP}$, $B_{HP}$ - angular contact bearings of low and high pressure rotors; $L_1$, $L_2$ - stepped and axial labyrinths at the inlet and outlet of air from the unloading cavity A; $P_1$ - air pressure in the unloading cavity installed behind the compressor; $K_1$ - channel for venting gas pressure in the unloading cavity.
Figure 4. Structural diagram of a dummy cavity with a labyrinth at the entrance to this cavity, which has teeth of seals installed on its upper and lower sides [1]: Δ - the height of the cell labyrinth; δ - the value of the radial clearance; \( G_{lab} \) - air flow through the labyrinth.

Of great importance is the fact that on engines with labyrinth with a reverse tooth [3], the traction characteristics of the engine are significantly improved, especially at variable modes of its operation. In the "cold exit" mode, the thrust losses are approximately halved, and the time to reach the steady state thrust mode is also reduced.

It should be noted that when air is taken from the after compressor air cavity into the outer circuit, the turbine power is lost. Currently, there are many schemes for unloading the HPC rotor without this bypass, as shown in figure 1, where cavity E is the unloading cavity of the HPC rotor.

Figure 3 shows a structural diagram of the supply of cooling air to the turbine rotor blade through the inner rear cavity of their nozzle blades, at the entrance to which there is a shut-off valve for this supply in the cruise mode of operation of the turbofan engine, as well as the supply of air due to the intermediate stage of the HPC into its inter disk cavity turbines of HPT and LPT.

From the front side of the HPT rotor, cooling air is supplied approximately to the middle part of the disk through a swirling grate, which allows it to enter the channel of its supply to the end of the turbine blade without impact, with a static pressure value. The negative side of such a supply system, in comparison with the direct supply of this air, also through a swirling grate, but which is installed at the top, at the level of the blade end, is that this air from the disk is heated and loses part of its cooling capacity.

The following shows the possibility of reducing the axial force applied to the rotor of this HPT. If we leave the design of the front part of the disk unchanged, then the only way to solve this problem is to increase the air pressure acting on the rear part of the HPT disk. This can lead to an increase in the flow rate of air flowing into the flow path of the turbine across the main flow, which reduces its efficiency.
3. Results and discussion

The results of the calculated assessment of the axial loads on the turbine rotors of the gas generator of the basic afterburning turbofan engine and the final version of its modernization are shown in figures 5 (a) and 5 (b). The aim of the work was to reduce the axial force applied to the rotor of the gas generator afterburning turbofan engine AL 31f in critical modes of its operation [5]. The axial load acting on the bearings of the low and high pressure rotors is defined as the difference in the axial forces acting on the rotors of their compressors and turbines, connected by tightening devices or having a common shaft. The methods of such calculations are well known; they are presented, for example, in [1,2,9]. There are obvious problems that affect the reliability of the calculated data, since it is necessary to take into account the change in radial clearances depending on the engine operating modes, the values of air pressures and temperatures, in cavities, etc. The results of these calculations are presented in table 1.

Improving the design of the air system of the gas generator of this afterburning turbofan engine in order to increase the bearing safety margin, can be made, guided by the following considerations:

To reduce the total axial force $R_{HPT}$, it is advisable to reduce the value of the force acting on the compressor rotor $R_{HPC}$, or to increase the force acting on the turbine rotor $R_{HPC}$ so that the total axial force decreases. It is possible to reduce the load on the turbine rotor, as we see from the results of the calculations performed, by increasing the air pressure acting on the turbine disc from behind, or by reducing the force acting on it from the front. It is easiest to reduce the total effect of the axial force on
the HPC by reducing the air pressure in the air cavity located under its diffuser, installed by the compressor.

Table 1. The results of calculating the axial forces applied to the radial thrust bearing of the gas generator in the basic (top of the graph) and modernized (bottom of the graph) afterburning turbofan engine.

| Mode                              | (H=0, M=0) | (H=0, M=0) | (H=13, M=2) | (H=12, M=0.75) |
|-----------------------------------|------------|------------|-------------|-----------------|
| R_{prototype HPC}, kgf            | -989       | -3178      | -3194       | -320            |
| R_{HPC,+}, kgf                    | 25448      | 37639      | 25987       | 6631            |
| R_{HPC,-}, kgf                    | -3553      | -5623      | -4575       | -1127           |
| R_{HPC,kgf}                       | 20878      | 20907      | 28719       | 18077           |
| R_{prototype HPT, kgf}            | -7745      | -11228     | -7693       | -1948           |
| R_{HPT concavity +, kgf}          | 17172      | 25514      | 17937       | 4042            |
| R_{HPT concavity -, kgf}          | -28089     | -42133     | -28877      | -7576           |
| R_{HPT, kgf}                      | -20058     | -31184     | -29905      | -21256          |
| R_{HPT, kgf}                      | 20538      | 20033      | 5851        |                 |
| R_{HPT, kgf}                      | 340        | 849        | -2465       | -1067           |
|                                   | -3173      | -1815      | -665        | -667            |

- the calculated positive direction of action of forces, "in flight".

Below are considered the main methods of improving the air system turbojet engine and their calculation analysis. As it was revealed when analyzing the results of calculations of the initial layout of the labyrinths in the inter disk cavity, increasing the service life of the high pressure rotor (HPR) bearing requires constructive interventions in this air system. A possible measure is to strengthen the HPC support, which is not the best option, since it is much easier to change the power circuit of the HPC, in particular, by increasing the pressure at the exit from the labyrinth and obtaining a gain in the total load on the HPR support. This design of the labyrinth, according to the results of tests of the serial engine, turned out to be the most successful in transient conditions, providing a much shorter time for changing the thrust.

Another way to optimize the acting axial forces, in engines of this type, is to change the configuration of the air cavities of the turbine engine. On the front side of the HPT, the main influence on the level of axial load is exerted by the air flowing out from the gap between the stator and the rotor into the axial gap, across the gas flow moving in the flow path of the turbine. Calculations were carried out with an increase in the number of labyrinth teeth separating the cavity above the swirling apparatus from the air flow moving in its flow path. However, a positive effect was not obtained, the available pressure was insufficient to prevent gas inflow from the flow path. Therefore, the labyrinths in the cavity under the pressure ring had to be abandoned.

Another option was considered for changing the balance of axial gas forces by adjusting the change in the geometry of the inter disk cavity. To increase the pressure in this cavity, labyrinth seals are installed in the axial clearances in the front (1) and behind (2) of the nozzle of the injection pump. In order to obtain a greater value of the axial HPT acting on the disk from behind, the hole (4) between the cavity behind the transit channel (3) and the labyrinth (5) is doubled in diameter. For the same purpose, the diametrical dimensions of labyrinths positions 1 and 2 in figure 5b have been changed. This new arrangement of labyrinths allows air to be distributed with greater pressure and over a larger surface area.

This makes it possible, without a significant increase in pressure, to obtain a significant, about 30% increase in the force acting on the rear part of the high-pressure turbine disk, necessary to reduce the resulting load on the high-pressure rotor bearing.

At limiting modes, the new system for installing labyrinth seals in the inter disk cavity of the HPT and LPT turbines makes it possible to increase the air pressure in this cavity by approximately one
atmosphere, which is essential for reducing the axial force of the HPR by several hundred kgf at maximum rotor speed.

The problem of reducing the axial forces acting on radial thrust bearings in aircraft gas turbine engines considered in the article is extremely important for ensuring the reliability and service life of the power plants of modern and future maneuverable aircraft, manned and unmanned, where they are critical, for example, when leaving from the peak and in the modes of supersonic flight at low altitude. Obviously, this task is complex and should be solved in two directions: on the one hand, by increasing the efficiency of labyrinth seals in order to ensure the possibility of increasing the gas pressure in these cavities [10-14], on the other hand, it is necessary to optimize the scheme of interaction of individual forces, for example, so that their value acting on the thrust bearings is reduced. Both of these tasks have been discussed above.

4. Conclusion and recommendations
The performed analysis and comparison of the design diagrams of the air systems of modern turbofan engines and the level of axial forces acting on the rotor of the gas generator allows us to make the following conclusion:

When optimizing the axial gas forces acting on the rotor of the turbojet engine, the maximum efficiency of both the front and rear unloading cavity should be considered in all modes of operation of the turbojet engine, in particular, in transient modes and flights at high speed near the ground, at a minimum height;

The performed calculations showed that optimization of the diametrical dimensions of the installation of labyrinth seals in the interdisk cavity, which leads to an increase in the area exposed to high air pressure, can reduce the total load on the HPR by almost 35% - in this example, by 1400 kgf, which has a significant value for increasing the service life of the radial thrust bearing of this rotor.

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