SUPERSONIC AIRCRAFT ENGINES

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Contents

1. Introduction

According to the theory each type of engine has its highest efficiency in a relatively narrow range of Mach number *M* (flight velocity divided the speed of sound). This characteristic is most essential for air-feed jet engines. The major component of their propulsive mass is atmospheric air, and its parameters p_U and T_U, hence the parameters p^*_I and T^*_I at the air intake entry, depend essentially on the velocity and altitude of the aircraft's motion along the flight trajectory.

As a result of the increase in the air pressure in the air intake, the total pressure ratio in the Brayton cycle also increases, alongside the work done by the engine and its efficiency, so the preliminary compression is beneficial within certain limits. The increase in the temperature T^*_I at higher flight velocities degrades the engine performance.

Figure 1 shows the ranges of flight parameters in which different types of engines are used. The graph demonstrates that boosted by-pass turbojets (4) and boosted turbojets (5) are used at supersonic flight velocities up to $M = 3 - 3.5$. At very high flight velocities ($M \approx 3 - 5$) ramjet engines are used, and at flight velocities higher than $M = 5$ hypersonic ramjets are used.

2. Turbojet Engines for Supersonic Flight Velocities

The most suitable engines for operation under conditions of supersonic flight at $M = 1 - 3.5$ are turbojets, boosted turbojets, by-pass turbojets, and boosted by-pass turbojets. But designs of some units of these engines must be modified considerably so that the engines could operate at supersonic velocities. These units are air intake sections, compressors, and exhaust units. Let us consider in detail modifications in designs of these units.

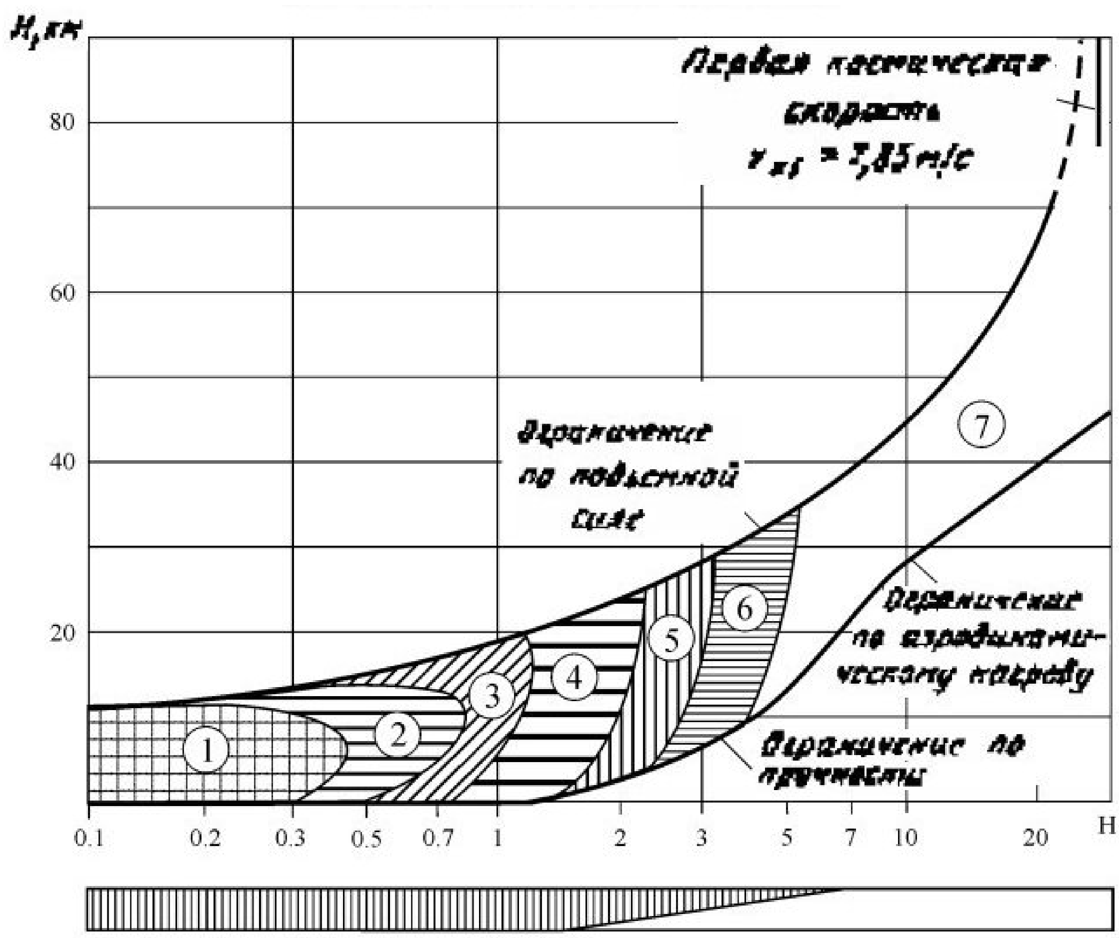

Figure 1. Regions of optimal efficiency for the following engine types: (1) shaft-turbine; (2) turboprop and turbofan; (3) turbojet and by-pass turbojet; (4) boosted by-pass turbojet; (5) boosted turbojet; (6) turbo-ramjet, turbo-rocket, ramjet; (7) supersonic and hypersonic ramjets. Satellite velocity $V_s = 7.85 \text{km/s}$; (8) Limitation due to the lift force; (9) Limitation due to the aerodynamic overheat; (10) Strength limitation.

2.1. Intake Sections of Turbojets for Supersonic Flight Velocities

An important point is that utilization of subsonic intake sections at $M_{fl} > 1.5 - 1.6$ makes no sense because of considerable losses of the total pressure and high external drag. It is advisable to divide intake sections of turbojets into three classes, depending on the position of the zone in which supersonic deceleration takes place with respect to the entry cross section of the cowling in the design conditions.

If the entrant flow is decelerated upstream of the entrance cross section, this is an air intake section with external compression. If the supersonic deceleration processes take place downstream of the entrance cross-section, this is an intake section with internal compression. If the compression process can take place both upstream and downstream of the entrance cross-section, it is termed an intake section with mixed compression. Figure 2 shows diagrams of air intake sections of these three classes. In the intake sections of all classes, compression is possible in principle either on the shock front or in a fan-shaped pattern of compression (i.e., isentropic) waves, and if the compression is of the mixed type, it can take place on both the shock front and in the fan pattern of compression waves**.**

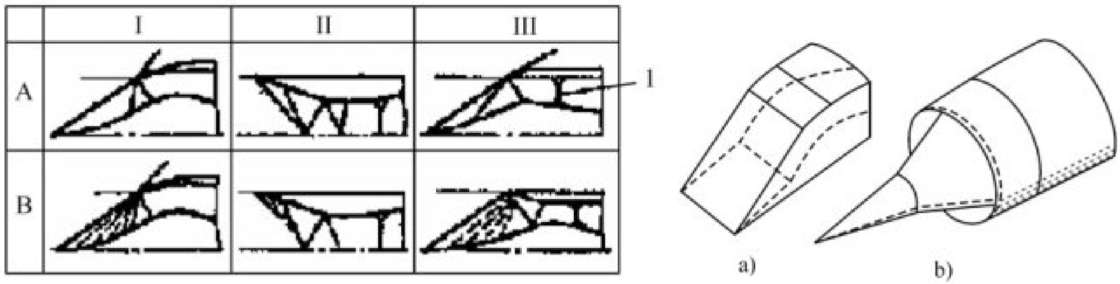

Figure 2. Classification of air intakes: (I) intakes with external compression; (II) intakes with internal compression; (III) intakes with mixed compression; (A) compression on shock fronts; (B) isentropic-jump compression; ------ shock fronts; - - - - small perturbations; (1) ultimate shock front.
(a) Planar and (b) axially symmetrical air intakes

The intake sections should be classified not only on the basis of their compression modes, but also in accordance with the shapes of their deceleration surfaces, namely, as plane and axially symmetrical intake sections**.** Depending on their locations in aircraft, the intake sections can be frontal, lateral, or located near wing roots. When the supersonic flow is compressed on a pattern of oblique shock fronts, the spread of velocities in the flow should be limited. The admissible amplitudes of velocity fluctuations and oscillations are determined by the engine unit downstream of the intake section**.** The configuration of shock fronts at a supersonic velocity of the incoming flow can be defined by the structural elements of the intake section set at a certain angle β with respect to the external flow.

The velocity downstream of an oblique shock front is usually supersonic, and it is the higher (at a fixed β), the higher M_{fl}. If the velocity downstream of the first shock front corresponds to $M_1 < 1.3 - 1.35$, further compression should be performed on a normally oriented shock front because it results in a smaller loss of energy. But if the velocity downstream of the first shock front corresponds to $M_1 > 1.35$, an additional shock front is needed to reduce the flow velocity upstream of the ultimate normal shock front**.** In the general case, the configuration should include a set of oblique shock fronts and the ultimate normal front. There is an optimal configuration of shock fronts which provides a maximal value of the ratio of the total pressure (at a fixed number of oblique shock fronts and number M of the entrant flow). The general theory of optimization of shock-front configuration suggests that the factor $\sigma_{\mathrm{v,fr}}$ is maximal when the pressure jumps on all oblique shock fronts are equal, and the jump on the ultimate normal front is somewhat lower. A diagram of the intake section of external compression is given in Fig. 3.

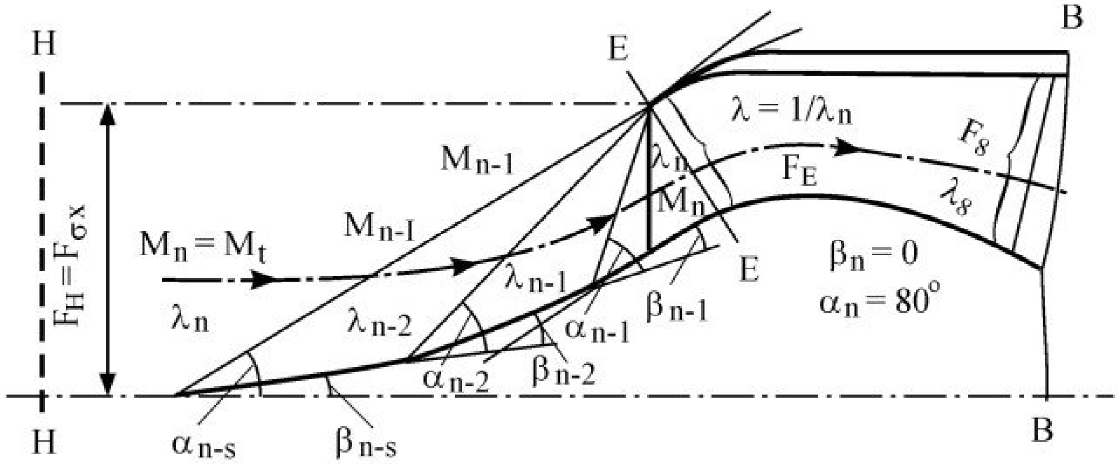

Figure 3. Diagram of the duct of the air intake with external compression (the number of shock fronts $n = 4$; the internal channel has no critical cross section)

The velocity downstream of the last oblique shock front is supersonic, and the flow is decelerated further on the normal shock front. In order to generate the normal front, the duct downstream of the normal front should have a certain configuration. The normal front is located in the entrance cross section if the flow downstream of this section is organized according to two schemes**.**

In the first case, the entrance cross section is designed for a certain gas flow with due account of the desired degree of the total pressure ratio in the system. Since the velocity downstream of the normal front is subsonic, the flow is further decelerated to the value required in the exit cross section of the intake section as it moves through the duct with the monotonically increasing cross section area. This intake section outputs a gas flow with a subsonic velocity. The cross section areas of the intake entrance, F_{I}, and of its exit, F_{IE}, are determined by the flow continuity condition.

The loss of the total pressure in the duct of this intake section includes losses at turning points of the flow and in the subsonic diffuser. The homogeneity of the velocity field, alongside the amplitude and frequency spectrum of its fluctuations in the exit cross section of the intake (section B—B in Fig. 3), depends on the flow turning angle and the length of the subsonic diffuser. If the distance between the intake entrance (section E—E in Fig. 3) and the compressor (section B—B) is large, the homogeneity of the velocity field can be improved (in the design regime) by reducing the duct curvature, but at the expense of the total pressure.

If this distance is small (of order of D_{in}), additional gadgets may be needed (for example, a special cascade) in order to obtain the desired uniformity of the velocity field parameters. An important point is that the intakes with external compression are susceptible to changes in the flight velocity, incidence angle, and regime of engine operation. Therefore, the tilt angles of decelerating surfaces should be tuned when M_{fl} is varied to obtain the highest ratio of the total pressure due to the sequence of shock fronts**.**

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