ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.5604/12314005.1137055

THE INFLUENCE OF MULTI-ROLE AIRCRAFT MISSION TYPE ON THE LOW BYPASS ENGINE PERFORMANCE PARAMETERS

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Abstract

The aim of the article is to find the relationship and dependencies between the mission parameters of the multi-role aircraft (altitude, flight velocity, thrust load) and the parameters that define the flow of the turbofan engine. The conclusions of these studies are relevant at the stage of preliminary engine design. There was built the model of thermal cycle of low bypass. The model of an airplane was simplified to its aerodynamic characteristics. The mission was divided into air tasks (stages) such as a take-off, a climb at a certain velocity, sub and supersonic flight and maneuvers (i.e. turn). Dimensionless energy criteria binding both the engine and aircraft parameters were introduced. There were conducted the simulation studies of the model airplane -engine mission to show the part of the mission that "dimensions" the engine. The results were limited to the presentation of the impact of circuit parameters such as T_3, π, μ *on the defined criteria. The calculations were carried out for a number of selected missions defined in the literature as Loll, HiLoHi and HiHiHi. The comparison of the energy requirements of these missions was done. There were pointed out these criteria of the mission evaluation that may affect making decisions at early design stages. There were designated the areas of design variability in an engine meeting the criteria for energy mission. The advantage of this model is universal character of dimensionless criteria, whereas the disadvantage is the need to build complex models of the engine and the assumption at the outset aerodynamic characteristics of the aircraft. The originality of the presented solution is to show an alternative, unconventional approach to the design process (not as so far) the engine itself but the entire aviation system.*

Keywords: *gas turbine engine design, airplane-engine integration, aircraft mission optimization*

1. Introduction

An analysis of the impact of analytical engine parameters on the characteristics of multi-role maneuvering aircraft is very complex [1–5]. This complexity is a result of the performance of a series of maneuvers in various flight conditions. Each flight stage requires balancing the resistance of movements with engine energy capabilities. At the design, stage there should be predicted these flight stages, which will determine the required thrust to perform a maneuver (e.g. turn on a certain velocity and altitude, loops, etc.). With the end of the flight, the airplane mass changes because of consuming the necessary amount of fuel. A special feature of the mission of a multi-role aircraft is a sudden (even impulsive) weight change and the reduction as a result of the discharge of cargo bomb or missile, or through the use of ammunition during the maneuvering air combat.

These parts of the air task may be more or less likely allocated to the time of performing the task. The reduction of the aircraft weight by the mass of spent fuel and the used weapons changes radically the demand for energy required to overcome the gravity force and aerodynamic forces. Along with the reduction of aircraft, weight the load factor increases, which can lead to the need to throttle the engine for the optimum use of the engine thrust [1, 2]. Knowledge of the tasks performed by the maneuvering aircraft, their order, the flight conditions in which these tasks are carried out – i.e., an analysis of the mission or several different tactically missions is crucial to match the engine to the aircraft.

The overall assessment of the energy efficiency of the engine as an aircraft component consists of a set of indicators by which one can assess the degree to make use of the energy supplied to the engine to perform the entire air mission. An objective assessment of matching the engine to the aircraft on the basis of these criteria can be carried out only by solving a series of coupled equations with many variables relating to both the aircraft and the engine [1, 4, 5].

2. Definition of analytical criteria

Flight operation under certain conditions (altitude, velocity, aircraft weight) is possible only if the engine available thrust balances engine drag forces and the forces of inertia. The value of the required thrust for the flight was determined in [3 ,6–8]. The required value of the load factor V_N is balanced during the flight by the available value of this parameter for the V_R engine.

The value of the thrust required for the flight changes during a mission in the manner specified by flight conditions. If one assumes that, the engine at each flight stage works at the maximum range, then the physical velocity-altitude characteristics of the engine is conditioned by the design point (altitude H, the relative flight air velocity Ma) and by the variables of the thermodynamic cycle. This means that the value of the available thrust for the selected flight conditions may differ from the required thrust. One can, therefore, introduce a criterion for assessing the degree of energy use in the mission, described with the formula:

$$V_w = \frac{\sum_1^k \frac{V_{R,n}}{V_{N,n}} L_n}{L}, \tag{1}$$

where:
$V_{R,n}$ – required for flight (aerodynamics) thrust load factor, $V_{R,n} = T_{R,n}/(g \cdot m_{A,n})$,
$V_{N,n}$ – available engine (thermodynamics) thrust load factor, $V_{N,n} = T_{N,n}/(g \cdot m_{A,n})$,
$T_{R,n}$ – required (aerodynamics) engine's thrust [N],
$T_{N,n}$ – available (thermodynamics) engine's thrust [N],
$m_{A,n}$ – actual (on flight n-stage) airplane mass,
g – gravitational acceleration, 9.81 [m/s^2],
n – the number of the mission elementary stage,
L_n – length of the elementary flight stage,
L – flight length.

The condition to meet this criterion is that at every (n-th) stage of the mission the value:

$$\frac{V_{R,n}}{V_{N,n}} \geq 1. \tag{2}$$

If this value is less than unity then the task cannot be performed because the engine thrust is lower than the required for the flight. Criterion (1) is a measure of how closely it matches the characteristics of the engine to the aircraft and mission. In the extreme case, i.e. when the engine is optimally matched for the aircraft, the value of this criterion is equal to the number of elementary stages of the mission "k". The reason is that at each stage of the mission, the ratio of (2) can reach a minimum value equal to unity (perfect selection), and the sum of elementary intervals equals L. While selecting the engine to the power mission requirements, it should be selected in such a way that the value of the indicator (1) was as small as possible, while maintaining the condition (2).

The model of specific energy consumption of a mission was presented in [8, 9]. Specific energy consumption of the mission reaches a minimum value when at each flight stage the available trust is equal to the required thrust [3, 6].

Specific (available) energy consumption is determined by the formula [6, 7]:

$$E_{j,N\Sigma} = g \sum_1^k V_{N,n} \lambda_n, \tag{3a}$$

and specific required energy consumption:

$$E_{j,R\Sigma} = g \sum_1^k V_{R,n} \lambda_n , \tag{3b}$$

where $\lambda_n = L_n / L$.

The measure of matching the characteristics of the engine power to the aircraft is ΔE_j – the difference of specific energy consumption calculated for available parameters and energy required in the form of:

$$\Delta E_j = E_{j,R\Sigma} - E_{j,N\Sigma} . \tag{4}$$

Substituting (3a, b) into (4), and making simple transformations one can obtain the relation indicating an excess of energy intensity of the mission, due to the "over-dimensioning" the engine characteristics, in the form of:

$$\Delta E_j = \sum_1^n \lambda_n V_{N,n} \left(\frac{V_{R,n}}{V_{N,n}} - 1 \right) . \tag{5}$$

The expression in (5) makes sense only if the units that are in parenthesis of the expression (5) are negative. In an extreme case, i.e. in the case of perfectly matched engine to the aircraft the value of the expression (5) equals zero. Determined from (5) the excess of specific energy consumption requires an additional energy supply, which was used for maintaining the available, but over-dimensional thrust in relation to the requirements.

3. Description of the selected missions of multi-role aircraft

The variety of flight missions were discussed in detail in [3, 4, 6, 7]. Based on the data contained therein for further analysis there were selected three different as for the performed tasks missions (and their corresponding flight conditions). The first mission of LoLoLo (Low ceiling of approaching, combat maneuvering at low altitude, return at the low altitude) is a typical battlefield support mission. The approach to the combat zone (armament drop) is at small (low return) flight altitude of subsonic flight velocity (ca. $Ma = 0.5–0.8$). The air battle, in this and subsequent missions, is modelled by a series of turns, by a full 360°, made with different overload factor and with different flight velocities. The maneuver velocity is $Ma = 0.8$ and $H = 0$. It is assumed that during the fight the plane gets rid of the weight of the armament load constituting 0.2 aircraft of the take-off weight. Back to the airport is at the same height, with the flight velocity of $Ma = 0.8$.

The second mission (HiLoHi, high ceiling, low altitude maneuvers, return at the low altitude) is carried out at a higher level (assumed $H = 5000$ m), approaching and return from the mission takes place at velocity of $Ma = 0.8$, air battle is modelled as in the previous mission. Finally, the third mission (HiHiHi) is a mission to capture an enemy in the air, so the approaching is at high altitude ($H = 10000$ m) with a maximum supersonic velocity. Air battle is also a series of turns performed with different overload coefficients in a turn but with supersonic and subsonic velocities. Back to the airport is at big altitude with supersonic speed, lower than the maximum. In addition, for each mission the take-off is considered and in the high-altitude missions, the climbing is analysed as for the energy consumption. Energy analysis of an aircraft is designed to assess the effect of the selected parameters of the engine and the aircraft, which determine the total energy expenditure for the mission performance, including the fuel consumption. Energy analysis in this paper covers only these flight conditions in which the engine runs at maximum ranges (including the afterburner turned on) that is taken into account the driven states. These states included the following stages: take-off, climb, flight maneuvers. Reducing the flight altitude and the landing will not be subjected to energy and economic analysis. During these staged the engine does not run at maximum ranges of the thrust and thus these are not the states of engine dimensioning, and therefore are not included in the calculations.

4. Analysis of calculations results

Assuming further as a prerequisite for the task the relation (2), it is possible to check how the engine cycle variables affect the change of the condition (2). Engine thermodynamics cycle variables are [3]: total turbine inlet temperature T_3 (temperature in engine cross section no. 3, turbine inlet), compressor pressure ratio π (total pressure at the exit of compressor to total pressure in the compressor inlet), and bypass ratio μ (mass flow rate in external contour to internal contour).

Figure 1 shows the course of the curves of V_R/V_N as a function of compression ratio π for two limit values of T_3 – 1300 and 1750 K. For smaller values of T_3 the engine is not able to provide the required thrust excess to perform any stage of the mission. The obtained values of V_R/V_N are lower than unity at all stages of the mission. For maximum temperature T_3 which was adopted for the calculations it is obtained the required value of the relative thrusts $V_R/V_N > 1$ for take-off, in the accepted for the calculations range of compression changes. With the increase of the compression ratio there is a noticeable drop of V_R/V_N particularly for the subsonic flight and the turn, but for the take-off, especially for the T_3 = 1750 K the value of V_R/V_N is almost constant and close to 1. This means that the take-off conditions determine the choice of variables of the thermodynamic cycle. The increase in the by-pass ratio μ reduces the available thrust with respect to the required one (Fig. 2). The range of acceptable values of V_R/V_N together with the change of μ is relatively small in spite of the inclusion in the calculation of the high values of the engine cycle variables. Limitations due to the reduction in the thrusts ratio was shown in Fig. 2 as the vertical line marked on a curve characterizing the flight conditions. Above the limit μ of 0.55 in this example, the execution of take-off at the take-off run of 500 m is not possible. To perform a take-off at higher μ it is necessary either to use afterburner or to lengthen the way of the take-off run. Implementation of the elementary stages of the mission for the engine variant characterized by lower values of cycle variables is virtually impossible. To sum up this piece of research it can be concluded that for the execution of all stages of the aircraft mission with the symbol LoLoLo it is necessary to adopt the engine variant with high values of the thermodynamic cycle parameters and possible low values of by-pass ratio.

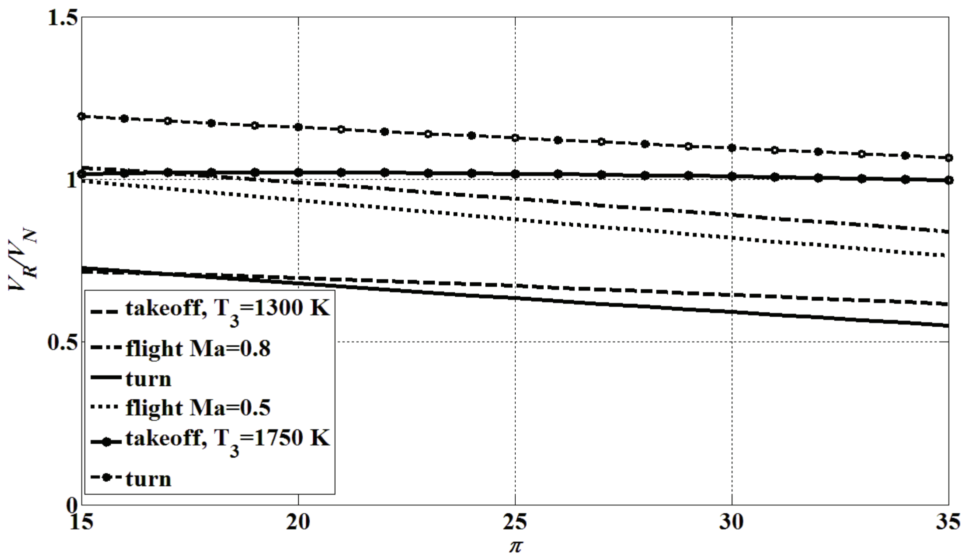

Fig. 1. Influence of the compression ratio π on the value V_R/V_N, for the selected missions stages for two values of T_3 = 1300 K and 1750 K, μ = 0.5

A characteristic feature of the HiLoHi mission is supersonic flight at high altitude (an approaching to the area of the task performance with the maximum armament mass) and return to the airport at the same level but with subsonic velocity. This way one can make a comparison of the requirements for subsonic and supersonic flight (Fig. 3).

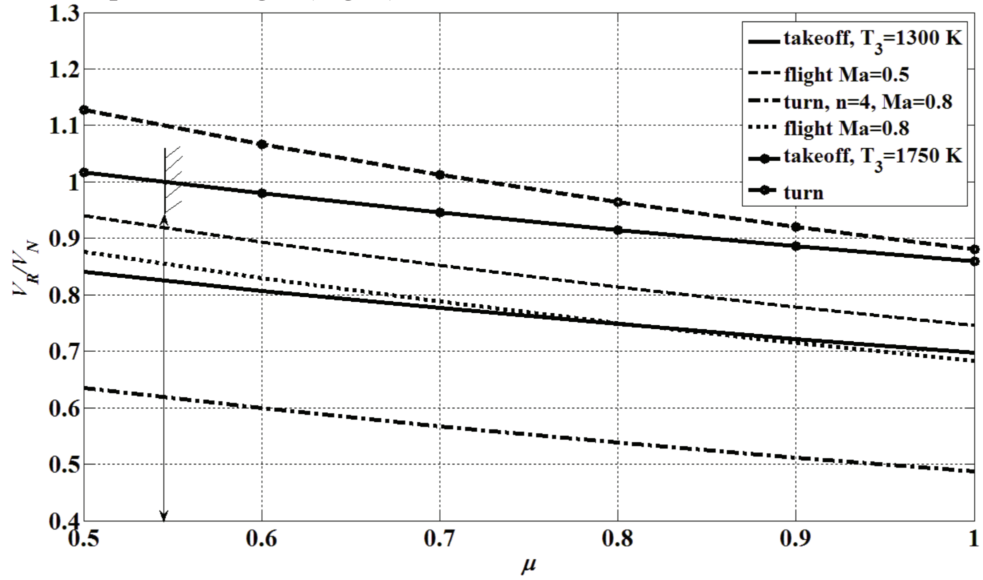

Fig. 2. Influence of by-pass ratio μ on the values V_R/V_N for the selected mission stages for two values of T_3 = 1300 and 1750 K, compression ratio π = 25

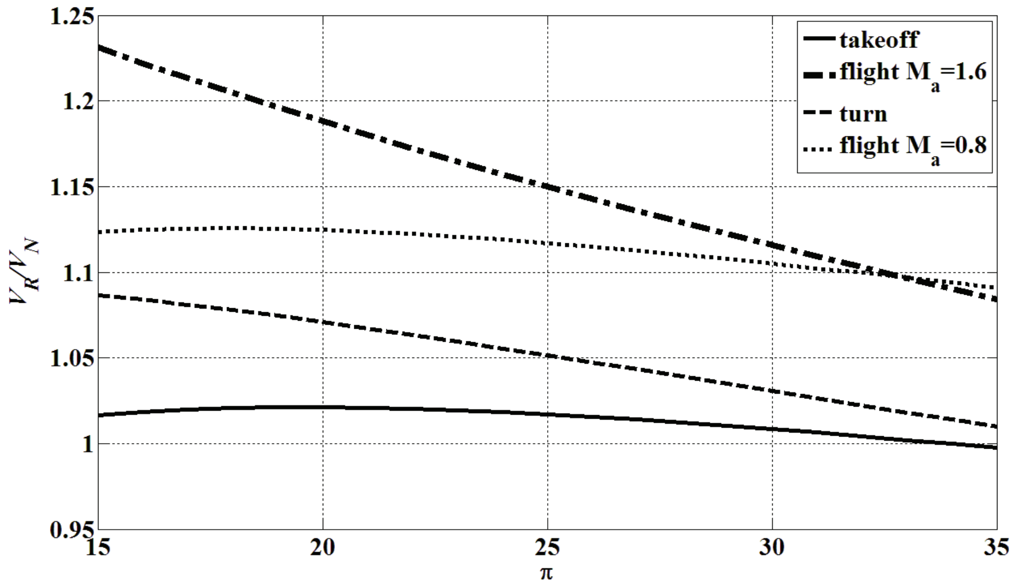

Fig. 3. Influence of compression ratio on the values V_R/V_N for the selected stages of HiLoHi mission (T_3 = 1700 K, μ = 0.5)

The influence of the compression is less important for the take-off stage although it is observed the weak maximum of the function V_R/V_N for smaller values of the compression from the selected calculation interval. An increase in the compression causes a strong decrease in V_R/V_N for supersonic flight stage and for the turn. With the assumed parameters of the engine cycle, and the assumed changes in the compression none of the values of V_R/V_N for the elementary stages of HiLoHi mission is reduced below the limit determined for the take-off. Thus, in broad range of compression ratio these are the take-off conditions, which determine the choice of thermal gas-dynamic cycle parameters (like for the LoLoLo mission).

An increase in the by-pass ratio (Fig. 4) results in an intense decline in the excess of available thrust and the take-off conditions significantly limit the range of values of the by-pass ratio. For the selected data calculations, this value cannot be greater than $\mu < 0.54$.

The last step is to examine the impact of the cycle parameters on the value of the degree of utilization of aircraft energy sources in various missions (5). It is important to choose the parameters of the comparative engine cycle that at all flight stages (assuming that the engine is at the maximum

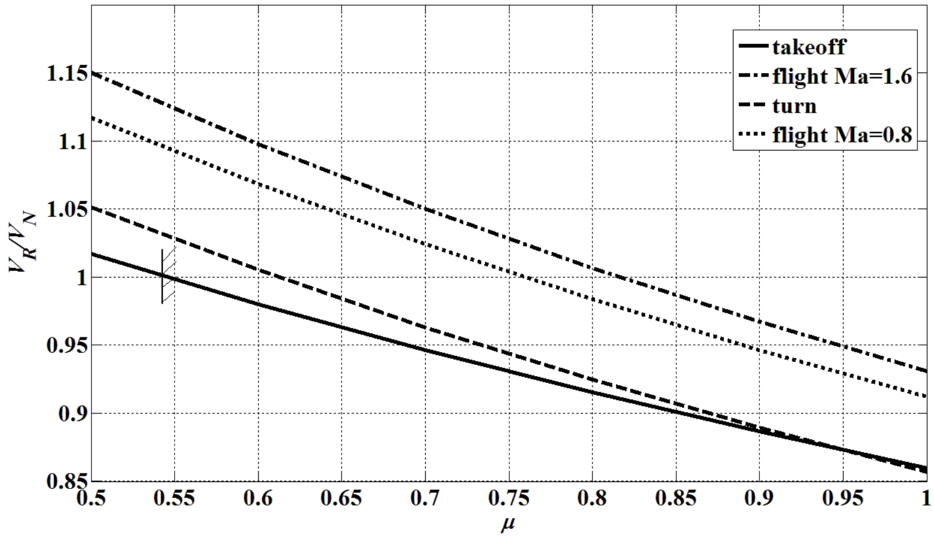

Fig. 4. The influence of by-pass ratio μ on the value V_R/V_N, for the selected stages of HiLoHi mission (T_3 = 1700 K, π = 25)

thrust range) satisfy the condition of the available ad required thrust (2). The essence of the criterion ΔE_j is to examine the "deviation" in the direction of positive values of ΔE_j. Ideally matched engine (actually engine parameters) is the one for which the value of $\Delta E_j = 0$. The higher the "deviation" of ΔE_j, the degree of "over-dimensioning" of the engine is bigger and the engine is energetically unmatched.

The value of ΔE_j criterion cannot be negative because it means that at one stage or stages of the flight the engine does not produce the necessary value. Fig. 5 and 6 show the influence of the compression ratio π and the degree of by-pass ratio μ on the ΔE_j criterion for the tested mission types.

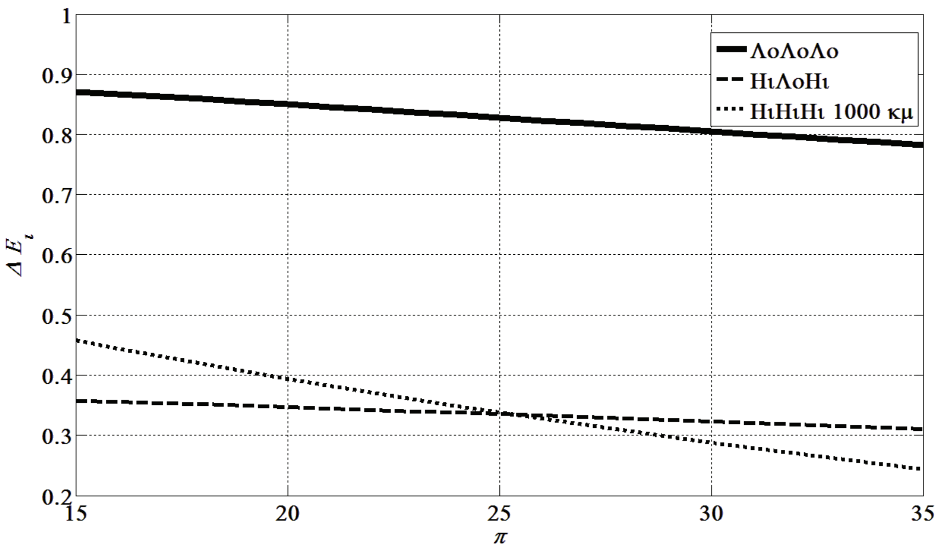

Fig. 5. The influence of compression ratio π on ΔE_j for various missions

As the graph in Fig. 6 shows, the highest value of ΔE_j is characteristic for the LoLoLo mission. By proper selection of compression ratio, i.ee the adoption of a relatively large values (Fig. 5), it is possible to decrease the value of ΔE_j approaching $\Delta E_j = 0$. The fact for the performing of the subsonic flight at very high coefficient of thrust excess is decisive in this case. This task could be done by partial throttling of the engine at such velocity range, which will reduce the value of ΔE_j. However, for other missions the criterion value of ΔE_j is much lower, which means that the parameters of the engine thermodynamic cycle for these missions are matched in a more rational way.

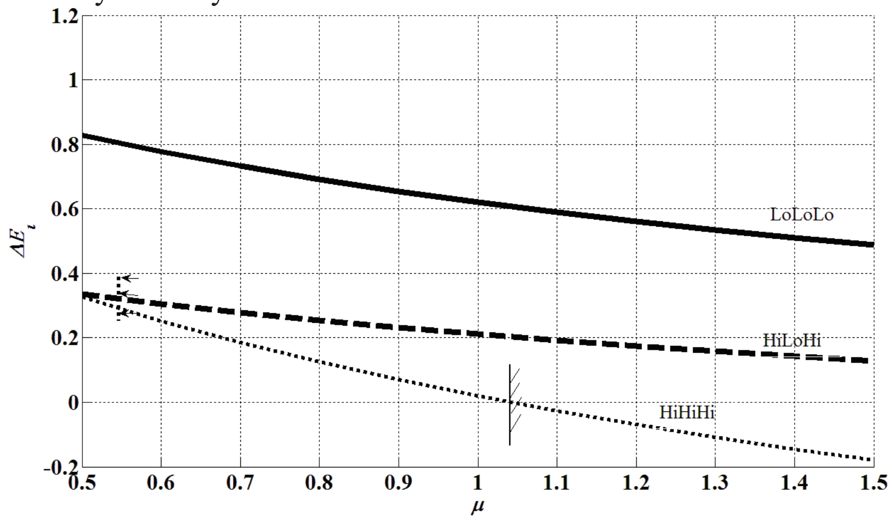

Fig. 6. The influence of by-pass ratio μ on ΔEj for various missions

5. Summary

The fact for the performing of the subsonic flight at very high coefficient of thrust excess is decisive in this case. This task could be done by partial throttling of the engine at such velocity range, which will reduce the value of ΔEj. However, for other missions the criterion value of ΔE_j is much lower, which means that the parameters of the engine thermodynamic cycle for these missions are matched in a more rational way. The effect of the compression is more visible for supersonic mission (which is the HiHiHi mission) than for mixed mission (HiLoHi) and subsonic one (LoLoLo). The study on the influence of the degree of by-pass ratio μ on ΔE_j is very limited due to the fact that a significant influence of this parameter on the characteristics of high altitude and velocity of turbofan engine. For the adopted calculations of variables it was obtained the maximum, limit the degree of by-pass ratio $\mu_{gr} = 0.55$. For larger values of $\mu > \mu_{gr}$ the airplane will have a thrust that will allow for the take-off on the take-off run of 500 m (regardless of the type of mission, because for each mission start is described with the same characteristics). In Fig. 6, this restriction is indicated by arrows. If, however, one accepts that the take-off can be extended (so that it was not a constraint), then the critical mission because of the value of ΔE_j is the supersonic HiHiHi mission. With a value μ close 1.05 the value of $\Delta E_j = 0$. This means that by the adopted parameters of the engine cycle (in this case $\pi = 25$, $T_3 = 1700$ K) and $\mu = 1.05$ it was obtained the engine matched for the HiHiHi mission. Other missions will be able to achieve by partly ”choking” the engine characteristics. Such a large value of the degree of by-pass ratio of the engine enables to improve energy and economical characteristics of the aircraft seen as a technical system (engine, aircraft, airline tasks). If the aircraft during the operation has to perform a variety of missions such as those presented in the article, then the supersonic HiHiHi mission at high velocity, being an intercept mission, with the assumed aerodynamic characteristics is a mission dimensioning the aircraft engine and determining its thermal gas-dynamic parameters. The aircraft will be able to perform other missions using the appropriate power unit control programs to ensure energy requirements of the mission.

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