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INFLUENCE OF BASIC TURBOFAN ENGINE PARAMETERS ON MULTIPURPOSE AIRCRAFT MANEUVERS INDEXES

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Abstract

The problem described in the paper concerns the choice strategy of so-called design point of the flow engine in a multi-role aircraft at the initial stage of aircraft and engine design as the aviation system. The design point is defined by the height and speed of flight and engine parameters of heat flow which allows in particular to determine the mass and dimensions of the engine. The following analysis represents an attempt to seek other than the classic (based on a maximum within unitary thrust, specific fuel consumption) criteria for calculation point for the multi-role aircraft. Multipurpose aircraft, during every mission, very often must perform many tasks and at the same time must use the energy source for the maneuvers. The mathematical model of the chosen tasks of an aircraft has been presented, which due to the energetic requirements do not allow to build the uniform optimization criteria. The models of such flight stages have been presented: take off, climbing with the maximum velocity and the maximum angle of climb, horizontal flight both sub-and supersonic, turn determined. In order to make the considerations easier the engine model was reduced to two parameters: non-dimensional loading coefficient and the coefficient of relative engine measure. During the conducted calculations the values of the non-dimensional coefficients were determined allowing to optimize the tasks performed by the aircraft during the mission. By making comparisons of the determined characteristics the acceptable values of the non-dimensional engine coefficients were shown and the assessment criteria of the aircraft manoeuvre properties vital for the realization of the entirety of its mission were presented.

Keywords: *multipurpose aircraft, airplane engine integration, turbofan engines, engine thrust*

1.Introduction

In the process of aircraft designing the right strategy of the aircraft and engine characteristics is of the great importance in order to get the system capable of performing certain air tasks with the smallest energetic expenditure. The energetic possibilities of an aircraft depend on the parameters and characteristics of the power unit. The power unit should ensure required by an aircraft performance properties at all stages of air task i.e. during the take off, climbing, overshoot and during the complex combat maneuver (turning, pull up, loop). The energetic requirements of an aircraft are fixed limitations for the engine designer. They determine the range of the possible changes in thermo-gas-dynamical parameters of the engine comparative cycle, its size, mass and the way of control. It is assumed that the characteristics of an aircraft for which the power unit is chosen are known. There are no publications in which the problem of the selection of engine parameters and determinations of its optimum characteristics for multi-purpose engine is described. These problems are partially described in [1,3], but the analyses concern the issues connected with the optimization of the constructional scheme of an engine, not the physical aspects of the selection of engine parameters for an aircraft. The statistics of the chosen parameters of the engine comparative cycle [5] in operation, and the analyses results in [3] show that there is not a physical law, quality criterion, rule in an empirical sense, which constructors would take into account while choosing the engine parameters [1,3,5]. Even at the same temperature level T_3^*, some of the values π_s^* and α for the aircraft engines with the same purpose can differ, even twice. It shows that while choosing the engine parameters in many cases backs out of the analytical, optimum for the engine values. It is noticeable that there is no general tendency in the relation between parameters. There are known the following parameters: aircraft aerodynamic characteristics (polar), aircraft mass parameters and performed by an aircraft tasks – determined by the flight parameters such as flight velocity and flight height. The aim is to find the energetic engine parameters which will enable to determine (for the assumed criteria and limitations) the optimum adjustment of engine and aircraft characteristics for the realization of the required air task. For the models building the general non-dimensional parameters [5-7] were used. The parametrical analysis, conducted on the basis of the non-dimensional parameters, enables the main directions of optimum research of an engine and the aircraft as a whole to be found. In order to get to know the physical aspects connected with the choice of optimum thermal-flow parameters of the turbine engine and their influence on the aircraft characteristics we should:

- Show the assessment criterion of the aircraft performance and decide on their relation with the engine parameters,
- choose the design point for an engine (work range, flight conditions),
- choose engine parameters which would be subjected to optimization.

In the optimization tasks usually the simplified analytical models are used both for the aircraft and the engine. The required degree of simplifications is determined by the necessity and retaining the physical and qualitative compatibility of the analytical model with the researched model. One of the way to solve the task is the use, while model constructing, the general parameters of a non-dimensional form. It enables to decrease the number of variables in the task, and to decrease the dimension of the problem and avoid difficulties connected with recalculating a lot of solutions.

2.Mathematical model of aircraft and power unit

The aircraft movement in co-ordinate system connected with aircraft velocity has been presented in [1,2]. The aircraft movement equations introduced bellow have been written in a form which takes into account the dimensional character of variables. For the needs of the presented article the non-dimensional analysis was presented. The way of movement equations derivation considering the non-dimensional variables has been shown in [4,5]. For further considerations the basic relations have been reminded (presented in [5,6,7]). Non-dimensional coefficient S_{ZN} (called the geometrical parameter of engine adjustment to an aircraft), determining the relative engine dimension [4,5,6]:

$$S_{ZN} = \frac{iF_{Sil}}{F_{sk}}, \tag{1}$$

where:

F_{Sil} - engine cross- sectional area,
F_{SK} – aircraft wing area,
i – number of engines.

Aircraft range is one of the most important criteria of the assessment of aircraft performance properties. The calculations of the aircraft range depending on the flight conditions have been presented in [1,2]. For the needs of the research the model of range determination has been chosen for the constant flight and the constant coefficient of aerodynamic lift (i.e. the height of flight changes). The dependence which describes the range for the above limitations is known as the Breguet formula [3]:

$$x = \frac{EaM_a}{gc_j} ln \frac{1}{1 - \bar{m}_{pal}} \ , \tag{2}$$

where:

E- aircraft lift/drag ratio,
M_a- Mach number,
a- sound speed,
c_j- unitary fuel usage,
m_{pal}- relative mass of the burnt fuel

$$\bar{m}_{pal} = \frac{\Delta m}{m_s} \ ,$$

Δm- mass of the burnt fuel during the flight,
m_s – primary aircraft mass.

In fig. 1 there have been presented the differences in the range of subsonic and supersonic flight and the influence of the geometric parameter of an engine, i.e. the S_{ZN} value on the maximum value of the range [6]. The theoretical range of an aircraft during the subsonic flight achieves its maximum for the low values of S_{ZN} (almost half lower than the required values of parameter for the supersonic flights). During the supersonic flight the range decreases significantly and its extreme, as a S_{ZN} function shifts towards higher values of S_{ZN}. Very important information which results from the conducted calculations is the fact that the range expressed by the equation (2) has its extreme as for S_{ZN}.

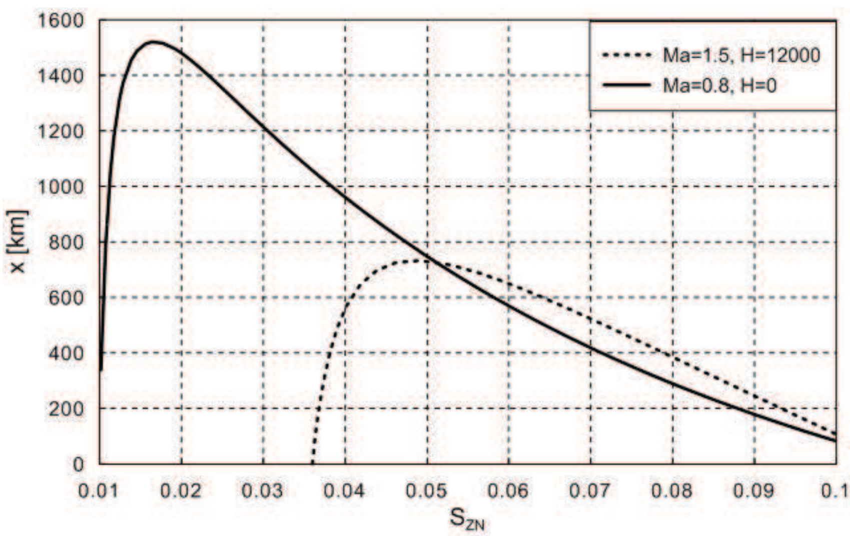

Fig. 1. Influence of the parameter of engine adjustment to the aircraft S_{ZN} on the theoretical range for the subsonic flight (full line) and supersonic flight (dashed line)

In [5] definition of non-dimensional coefficient of aircraft wings loading was presented:

$$\Psi_S = \frac{m_S g}{p_H F_{SK}} \ , \tag{3}$$

where:

m_s- aircraft mass,
p_H – static pressure,

and non-dimensional coefficient of thrust loading [5]:

$$\nu = \frac{K_{sil} S_{ZN}}{\Psi_S}, \tag{4}$$

In equations(1-4) the parameters of engine K_{sil} (non-dimensional engine thrust [5]) depend on the engine characteristics. The formulas (1,3,5) which present the dimensionless parameters have the same properties as the physical parameters of the form "dimensioned" (related to) for a certain amount and speed of an aircraft. The author carried out statistical analysis (based on available catalogue information) that modern multirole aircraft such as the F-16, Gripen Jas 39 have at the start the coefficient $\nu \approx 1.2$ and ψ_s= (0.028-0.042), while the heavier aircrafts such as the MiG 29, F -14 $\nu \approx$ 1.2-1.4 and ψ_s= (0.038-0.048).

3. Method of selection of engine and aircraft parameters

While selecting the power unit for the multipurpose aircraft it is necessary to show such parameters and criteria of engine assessment which ensure the realization of air tasks at the required energetic expenditure. The selection of engine parameters should be done on the basis of energetic criteria. The use of non-dimensional parameters, which later will be treated as "adjustment" parameters of engine to an aircraft enable to build the analytical model of the energetic system of the power unit-aircraft-air task. It makes possible further assessment of the influence of the accepted parameters of engine on the indexes of aircraft efficiency assessment. Taking into account the non-dimensional parameters as in (1-4), the equation of the aircraft movement (the way of its derivation) has been shown in detail in w [4,5,6]) and has the form of:

$$\nu = \frac{a}{g}\frac{dM_a}{dt} + \left(1 + \frac{a}{g} M_a^2 \frac{da}{dH}\right)\sin\Theta + \frac{1}{2}\frac{kc_x M_a^2}{\Psi_S}, \tag{5}$$

It is the formula, which for the assumed parameters of air task (M_a, H, ψ_S*),* allows to determine indispensable for flight value of ν coefficient. It is then assumed that the ν value determined on the basis of the aircraft flight conditions will be marked by the „N"- ν_N. index. The first term of (5) equation means the value of the thrust loading coefficient for the case of horizontal acceleration, whereas the second one for the climbing with the constant velocity at the angle Θ*,* and the last term in (5) equation means the value of ν_N coefficient for the horizontal flight with constant velocity. On the other hand, the ν value can be determined for the power unit. This value, as a disposable value for the engine is marked by "R" index:

$$\nu_R = \frac{K_{sil} S_{ZN}}{\Psi_S}, \tag{6}$$

The above dependence enables to determine non-dimensional thrust loading coefficient and the relative fuel usage only when it is known the flight plan; that is the height change H and flight velocity Ma during the mission and there are known the engine characteristics.

4. Criteria of aircraft maneuvering

The significant criterion of maneuvering assessment of multipurpose aircraft is climbing. Following [2] and assuming that the total aerodynamic lift is on the aircraft plane and the vectors of thrust force are directed along the flight path of an aircraft, then the angle of the fastest climbing γ_{PWmax} will be determined from the following formula:

$$\sin \gamma_{PW\max} = \frac{\nu E_{PW\max}^2 - \sqrt{1+E_{PW\max}^2\left(1-\nu^2\right)}}{1+E_{PW\max}^2} , \tag{7}$$

where:
Lift/Drag ratio of the fastest climbing

$$E_{PW\max}^2 = \frac{6}{\nu\Gamma\left(1+\frac{36Kc_{D0}}{\nu^2\Gamma^2}\right)}$$

coefficient

$$\Gamma = 1+\sqrt{1+\frac{12Kc_{D0}}{\nu^2}}$$

C_{D0} – parasitic drag,
K – coefficient of aircraft polar.

The data for calculating the aircraft polar was taken from [1] for F-16 airplane. In fig. 2 there has been presented the dependence of the angle γ_{PWmax} from ν coefficient in the borders (ν_{min},ν_{max}).
The next characteristic flight stage is the right turn of an aircraft (without the sideslip). The right turning can be performed only when the bank angle of an aircraft Φ is bigger than zero [2]. The bank angle is determined by the G-load coefficient *n* :

$$n = \frac{1}{\cos\Theta} , \tag{8}$$

Substituting into equation (5) the expression (8), and assuming that the speed of the turn is constant, after the simple transformation (5) it was determined non-dimensional thrust loading coefficient ν for the right turn:

$$\nu = \frac{kM_a^2}{2}\left(\frac{c_{D0}}{\Psi_S} + \frac{4\Psi_S Kn^2}{\left(kM_a^2\right)^2}\right) , \tag{9}$$

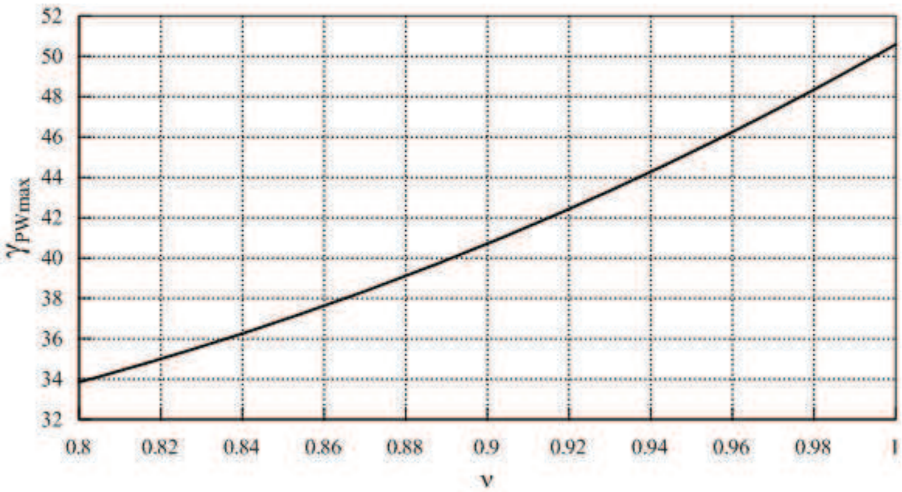

Fig. 2 Dependence of angle of fastest climbing γ_{PWmax} from ν parameter

Formula (9) allows to determine the indispensable value of the ν coefficient depending on the *n* G-load coefficient and non-dimensional wing loading coefficient ψ_S, in which is “hidden” the aircraft mass. On the G-load coefficient in turn there are imposed limitations which concern the situation when the aircraft mass is partially decreased by the mass of the used during the flight fuel and armament (so-called combat mass) and it is assumed that the coefficient n=9. On the other hand for the maximum take off mass the assumed value of the n G-load coefficient in turn is smaller and is n=7 [2].

The most important part of the aircraft mission is its take off. In the procedure calculations of aircraft take off it is better to assume the length of the take-off run L_S and determine for it the indispensable value of the thrust loading coefficient at the take off [5]:

$$\nu_S = \mu_S + \frac{\frac{k_S \zeta_S}{c_{Z\max}}}{1 - e^{-\tau L_S}} \quad , \tag{10}$$

where:

coefficients: $k_S = \frac{M_0}{M_S}$, $\tau = \frac{g k \zeta_S}{a^2 \psi_S}$,

M_S – stalling speed,

ζ_S - reduced coefficient of aircraft total resistance during takeoff [3,5,6],

$C_{Z\max}$ – value of coefficient of aerodynamic lift in the conditions of take off.

5. Calculation example

To find limitations the calculations for exemplary aircraft data have been conducted. It was assumed that the take off mass of aircraft m_s=10500 [kg], the atmosphere parameters are according to the standards of International Standard Atmosphere [1]. At this stage of calculations there are not known the characteristics of engine that is why to simplify the considerations the calculations have been conducted for some values of ψ_S coefficient. It was assumed that this coefficient is the function of wing loading coefficient at the start ψ_{S0} according to the formula:

$$\Psi_S = k_m \Psi_{S0} \quad , \tag{11}$$

Coefficient k_m determines the change of aircraft mass during the air mission, caused by the fuel usage ad armament (k_m=1 – for takeoff mass, k_m=0.55 – aircraft without fuel and armament).

The change in value of coefficient ψ_S in function of H height has been presented in fig.3.

The decline in pressure connected with the growth in flight height causes the increase in the value of ψ_S coefficient. The lines which limit the graph show the border of the changes in values of the coefficient ψ_S for an aircraft depending on the flight height. During the take off the value of the coefficient in the accepted example is ψ_{S0}=0.04. In fig. 4 it has been presented the influence of values of ψ_S coefficient and the length of the run on the indispensable value of ν coefficient.

Multipurpose aircraft can perform a number of tasks at various subsonic and supersonic velocities. The calculations on the influence of the ψ_S coefficient and flight velocity on the ν coefficient during the horizontal flight with constant velocity were conducted and the results have been presented as graphs in fig. 5. The fulfillment of the requirement, obtaining the minimum value of the thrust indispensable during the turn performed at the given value of *n* G-load coefficient is important from the point of view of aircraft maneuvering has been presented in fig.6.

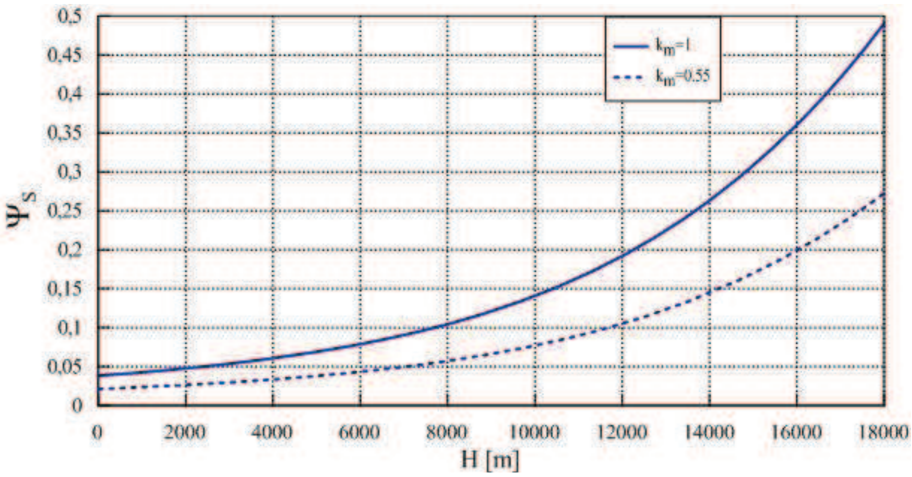

Fig.3 Change of values of coefficient ψ_S together with the growth of flight height for two values of coefficient k_m. (k_m=1 – for takeoff mass, k_m=0.55 –aircraft without fuel and armament)

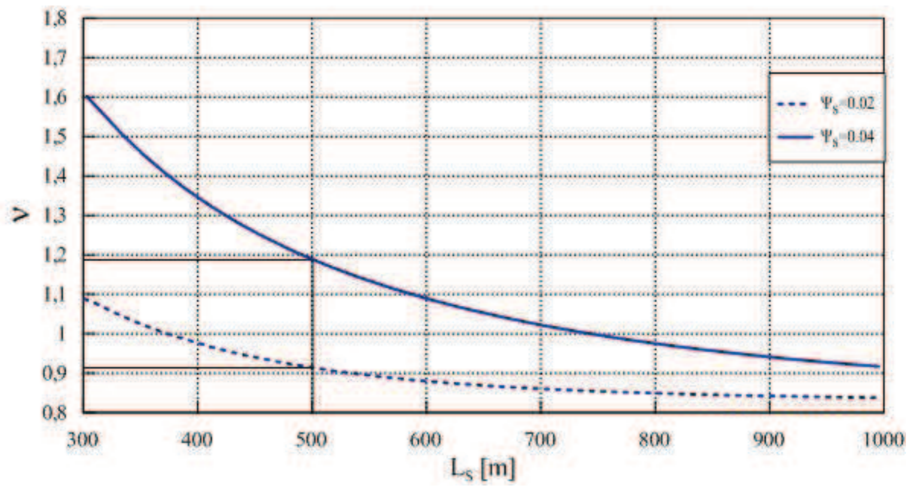

Fig. 4 Influence of run way L_S and ψ_S coefficient on the value during the take off. The calculations for two values ψ_S=ψ_{S0}= 0.04 , and ψ_S=0.02 (for k_m=0.55)

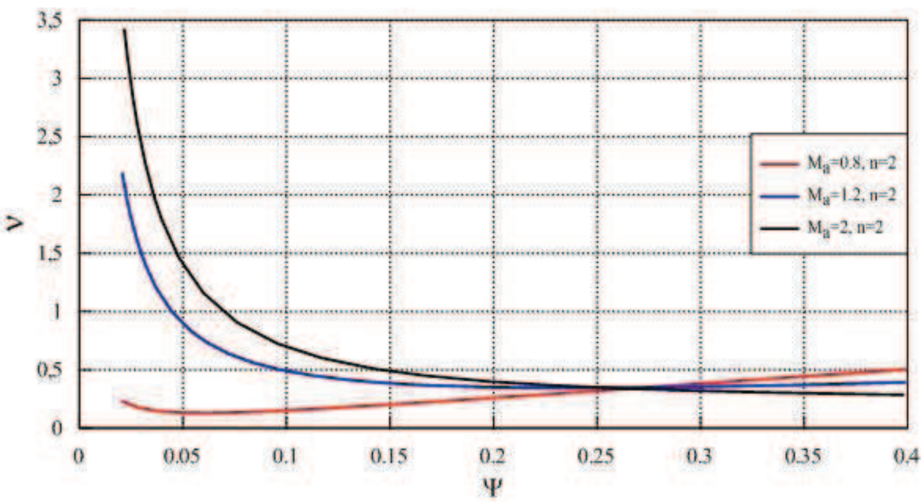

Fig.5 The influence of flight velocity and changes of ψ_S coefficient on the value coefficient ν during the steady horizontal flight

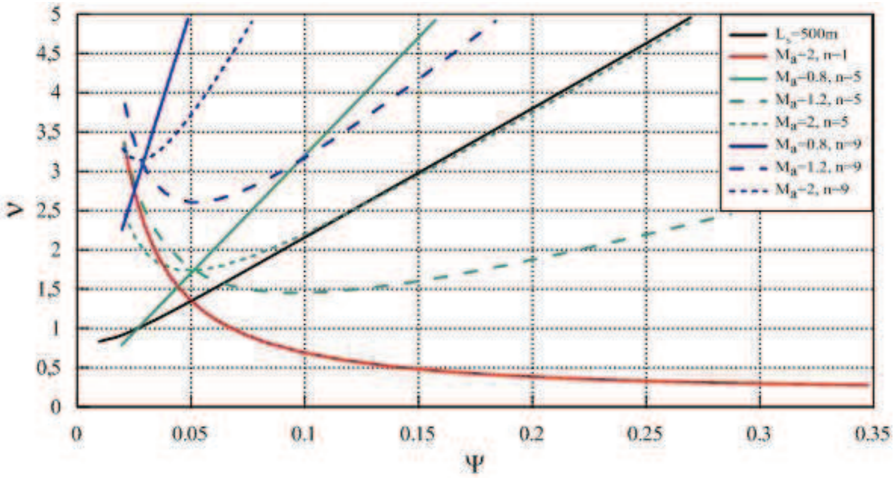

Fig.6 Influence of some chosen aircraft flight conditions and changes of wing loading coefficient ψ_S on indispensable for flying value of wing loading coefficient ν

In fig. 6 there have been presented the requirements for the ν coefficient, critical with regard to ν stages of flight. From the graph in fig. 6 one can assume that in order to perform the turn with the high values of *n* G-load coefficient the flights with high wing loading (big aircraft mass) require the big values of the indispensable thrust, which exceeds the requirements for the take off.
In fig. 6 there have been presented the requirements for the ν coefficient, critical with regard to ν stages of flight.

6. Conclusions

Each curve presented in fig. 5, 6 is the borderline value for ν, at the given flight velocity and ψ_S (aircraft mass). The biggest requirements because of the ν value concern the turn (in figures n=1) at small flight velocities as the growth gradient ν together with the growth of the flight height (grows ψ_S) is the biggest among all the presented curves. The requirement of the horizontal flight with the constant supersonic velocity is not a limitation at big heights. The consequence of the maneuver choice which determines the loading ν during the aircraft flight is to determine the values of the indispensable coefficient, non-dimensional thrust loading which must be counterbalanced by the power unit and the thrust depended on the thermo-gas-dynamical parameters. An analysis of the graphs of Figure (1-6) provides information about the limitations for the propelling set (by ν parameter)of the plane depending on the mission (subsonic, supersonic, mixed). The study shows that supersonic, maneuvering flight is a criterion for the selection of the engine (not even the take off of the airplane). The application of dimensionless parameters to the analysis of the aircraft powerplant can significantly simplify the analysis, and allows the testing of the influence of the engine characteristics directly on the mission done. This results directly from the definition adopted by the parameters in their current form because they involve the engine, aircraft and mission. They are therefore a higher level parameters of performance compared to a conventionally used in the literature of the unitary and specific fuel consumption. All the presented in the analysis dimensionless parameters are sensitive to changes in flight conditions and characteristics of the engine and can be considered as criteria for assessing the quality and quantity of air engine system - airplane - air mission. There are conducted further simulations to examine the influence of engine thermal-gas parameters (static pressure, temperature before the turbine, the by-pass degree) on the value of the parameter ν, Szn, ψ.

References

[1] Filippone A., *Flight performance of fixe and rotary wing aircraft*; Elsevier Ltd. 1998

[2] Goraj Z., *Dynamika i aerodynamika samolotów manewrowych z elementami obliczeń*. Biblioteka Naukowa Instytutu Lotnictwa, Warszawa 2001.

[3] Orkisz M., *Podstawy doboru turbinowych silników odrzutowych do płatowca*. Biblioteka Naukowa Instytutu Lotnictwa, Warszawa 2002.

[4] Rumiancev S.W., Sgilevskij W.A., *Sistemnoe projektirovanie awiacionnovo dwigatela*., Izidatelstwo MAI, Moskva 1991 (in russian)

[5] Wygonik P., *Kryteria doboru parametrów silnika turbinowego do samolotu wielozadaniowego*. Silniki Spalinowe, 4/2006.

[6] Wygonik P., *The influence of on-design bypass turbine engine parameters on multipurpose aircraft mission energy-consuming*, Journal of KONES Powertrain and Transport,Vol.17,No.1/2010.

[7] Wygonik P., *Determining of the optimum size of turbo fan engine for obtaining the maximum range of multipurpose-airplane*, Journal of KONES Powertrain and Transport, Vol.17, No. 2/2010.