THE INFLUENCE OF ON-DESIGN BYPASS TURBINE ENGINE PARAMETERS ON MULTIPURPOSE AIRCRAFT MISSIONS ENERGY-CONSUMING

Piotr Wygonik

Rzeszow University of Technology, Department of Airplane and Aircraft Engines
W. Pola Street 2, 35-959 Rzeszów, Poland
tel.: +48 17 8651241
e-mail: piowyg@prz.edu.pl

Abstract

In the article there was presented a quality assessment of parameters selection of bypass turbine engine for a multipurpose aircraft. It was assumed that the assessment criterion results from the energy-consumption of a flight. The criteria of energy-consumption range were defined as the relation of sum of energy supplied to the aircraft on the driven stages to the distance during a mission. The second criterion of unitary energy-consumption is defined as the relation of the movement energy-consumption to the product of the aircraft mass and the route during the elementary stage of the flight. With t he use of the already worked out models of the power unit (bypass turbine engine with jet mixer and afterburner) of an aircraft (already k nown mass and aerodynamic characteristics) there were determined the ranges of thrust which are indispensable for a flight and available for the engine at each stage of the mission: take off, climb, subsonic and supersonic flight and turn with different overload factor. On the example of three chosen aircraft missions (Lo-Lo-Lo, Hi-Lo-Hi and Hi-Hi-Hi) the models of mission energy-consumption were developed. For the accepted change ranges of the comparative cycle parameters of the turbine engine the run of energy-consumption was tested. It was stated that for the assumed data the most energy-consuming mission is Lo-Lo-Lo, wherefore the increase of the compression and the rate of bypass reduces the energy-consumption of the mission.

Keywords: *military gas turbine engine, military aircraft mission analysis, multipurpose aircraft, energy consuming*

1. Introduction

Designing of the contemporary aircraft engine is conducted, on the assumption that it is an element of the complex system which is the multipurpose aircraft. During the designing process the big role has the choice of the selection strategy of the aircraft and engine characteristics in order to get the system which is able to perform the aircraft tasks with the lowest energy consumption. It is the problem analyzed usually during the first stage of designing where the characteristics of the engine are initially adjusted to the aircraft. It was assumed that the criteria of the engine adjustment to the aircraft will be based on the energetic criteria. Energy which should be supplied to the aircraft performing the aircraft task (indispensable energy) depends on aerodynamic and mass characteristics of the aircraft. On the other hand the energetic possibilities of the aircraft depend on the parameters and characteristics of the power unit (available energy). Taking into account in the energy balance of the aircraft both the indispensable and available energy and determining the proportion between them for the task performance is the most significant factor which determines the choice of engine parameters.

2. Preliminary assumptions

To build mathematical models of the aircraft, missions and engine the general non-dimensional parameters were applied. Such an approach to modelling in the range of incidents allows cutting down the number of variables and avoid the difficulties connected with the necessity of measuring the variables which are included in the equations describing the models. Parametrical analysis, which is based on the non-dimensional parameters, enables to find the main directions of optimization research of the engine and the aircraft as a whole. Taking into account the engine model in the mathematical model of the aircraft and the model of the performed aircraft task enables for the analysis of the results by the assessment of the chosen criteria, and next enables to measure the physical quantities at the stage where it is necessary for further analyses.

In order to connect the engine and aircraft parameters the non-dimensional coefficient S_{ZN} has been introduced which determines the relative (because related to the surface of the aircraft wings) engine dimension, defined as [6-8]:

$$S_{ZS} = \frac{iF_{sil}}{F_{SK}}, \tag{1}$$

where:
F_{sil} - engine cross-sectional area,
F_{SK} - wing area,
i - number of engines.

Non-dimensional load factor of the aircraft wings is one of the main parameters which describe the aircraft model:

$$\psi_S = \frac{m_S g}{p_H F_{SK}}. \tag{2}$$

Non-dimensional sequence as non-dimensional thrust:

$$\overline{K_{sil}} = \frac{K_{sil}}{p_H F_{sil}}. \tag{3}$$

The thrust load factor, also non-dimensional describes the dependence:

$$\nu = \frac{K_{sil} S_{ZN}}{\psi_S}. \tag{4}$$

Dependences presented by the formulas (1-4) define the aircraft, power unit and parameters of the aircraft mission.

It was assumed that the aerodynamic characteristics of the aircraft are known according to [2]. Moreover, it was stated that the aircraft mass mS, and the wing surface FSK are known thanks to which it is possible to determine the non-dimensional wing load factor ψS. For instance, ψS for F-16, determined for the pressure at the sea level is 0.037, for JAS-39 is ψS=0.028, and for MiG-29 is ψS=0.047.

As variables of bypass engine there are accepted the followings: the rate of the jet division in the engine μ, overall engine compression $\pi^*_{\Sigma S}$, overall temperature before the turbine T_3^*. These are dependent variables, which have a great impact on the engine characteristics [1, 3, 8]. In the designing calculations it is necessary to do research on the influence of other variables, e.g. efficiency, pressure losses in some units on the internal characteristics. It is assumed that the engine works within the range of the maximum thrust and the flight stages which measure it are driven stages. These stages include: take off, climb, flight at high speed, maneuvers. On the other hand the stages which do not require the maximum thrust are: the decrease of the flight height, descent and landing, and that is why in the research the thrust need and the fuel usage will not be taken into account.

3. Energetic balance of aircraft, energy-consumption

Aircraft movement is the result of the energetic changes which result from the kind of energy supplying which is necessary for a flight. The energy can be supplied to the aircraft:
- directly from the power unit (thrust labour),
- by the change of potential energy necessary to overcome the air resistance during speed decrease.

Depending on the enforcement of aircraft movement by means of thrust force one can present the following cases:

- the forced movement by the thrust force which causes that the flight has the constant speed or the accelerated motion,
- height decrease – forced by the action of earthpull component,
- delayed movement caused by the shortage of thrust force in relation to the aerodynamic resistance force,
- braking (during landing) with the use of a parachute, aerodynamic brakes, thrust reverser which cause the scattering of the kinetic energy of an aircraft.

Aircraft mission is realized on a certain distance and comprises a series of a single flight stages which include: take-off run and take off, climb, flight with the constant speed, horizontal acceleration, acceleration with a climb, maneuvers (loop, pull-up, turn). Each of these stages causes that in the movement equations there are some elements which are connected with the force of movement. Aircraft flight which is enforced by the thrust force is the main stage of its movement. The necessary amount of energy which is important to maintain such a movement determines the product of the mass of fuel supplied to the combustion chamber (and to the afterburner) $m_{\Sigma pal}$ and its heating value *Wu,* called the absolute energy-consumption [4]. This energy consumption is counterbalanced with the sum of movement energy-consumption and the power losses in the power unit:

$$W_u m_{\Sigma pal} = E_R + \Delta E_{ZN}, \tag{5}$$

where:

E_R - aircraft movement energy-consumption,

ΔE_{ZN} - power losses in power unit.

ΔE_{ZN} losses are usually considered in a thermal efficiency of an engine [1, 3-5]. At any flight stage there are various forces which differ as for the origin. At the take off stage there will be the friction force of the aircraft wheels against the runway surface and the force of aerodynamic resistance and the inertial force, and during the steady flight just the forces of aerodynamic resistance. The energy-consumption movement concerns only the energy which is spent at such flight stages where the thrust force is at least equal to the sum of forces characteristic for each stage. Such stages still will be called propelled. Hence in the energy-consumption analysis there will not be taken into account the stages of lay down and landing.

Aircraft mission consists of the successive stages which differ as for the speed and height of the flight. It causes the diversity of the energetic balance. By the energy-consumption of the mission one can understand the sum of the energy expenditure at all propelled stages of the mission:

$$E_R = \Sigma_{n=1}^{k} E_{R,n} + \Sigma_{m=1}^{p} E_{k,m}, \tag{6}$$

where $\Sigma_{m=1}^{p} E_{k,m}$ - sum of the acquired velocity energy in m-stages of the aircraft acceleration.

In energy-consuming balance there will not be taken into account the phases of start-up and the engine work within the low thrust.

Range energy-consumption is defined as the relation of sum of energy supplied to the aircraft on the driven stages to the distance during the mission.

$$E_Z = \frac{\Sigma_{n=1}^{k} E_{R,n}}{L}, \tag{7}$$

where $L = \Sigma_{n=1}^{k} L_n$, mission length - is the sum of the length of elementary segments (flight stages).

In the established flight conditions, the work of resistance force is counterbalanced by the thrust force, on the right displacements. We can write that:

$$E_{R,n} = K_{sil,n} L_n. \tag{8}$$

Thus the formula for the range energy-consumption of the mission can be written as:

$$E_Z = \frac{\Sigma_{n=1}^{k} K_{sil,n} L_n}{\Sigma_{n=1}^{k} L_n}. \tag{9}$$

Range energy-consumption in a physical sense means the work which should be performed by the engine thrust force to displace the aircraft on the unitary distance.

Unitary energy-consumption of the $E_{j,n}$ mission is the relation of energy-consumption of the movement $E_{R,n}$ to the product of aircraft mass and the route during the elementary flight stage [5]:

$$E_{j,n} = \frac{E_{R,n}}{m_n L_n}, \tag{10}$$

where m_n - aircraft mass at the beginning of n-stage of the flight.

This criterion defines the work which should be performed by the thrust force to displace the aircraft on the assumed distance.

As the movement energy-consumption equals the work of thrust force $K_{sil,n}$ on the route L_n, so on the elementary stage of the flight the unitary energy-consumption equals:

$$E_{j,n} = \frac{K_{sil}}{m_n}. \tag{11}$$

By using the dependences on the non-dimensional coefficients as (2-4) and by transformation of the equation (11) we get the formula:

$$E_{j,n} = \frac{g K_{sil,n} S_{ZN}}{\psi_{s,n}}. \tag{12}$$

In the formula (12) - $\psi_{s,n}$ - non-dimensional coefficient of wing load is determined for the beginning of the n-stage of the mission from the formula:

$$\psi_{s,n} = \psi_S - g S_{ZN} \Sigma_1^n c_{j,n} \overline{K}_{sil,n} \Delta t_n. \tag{13}$$

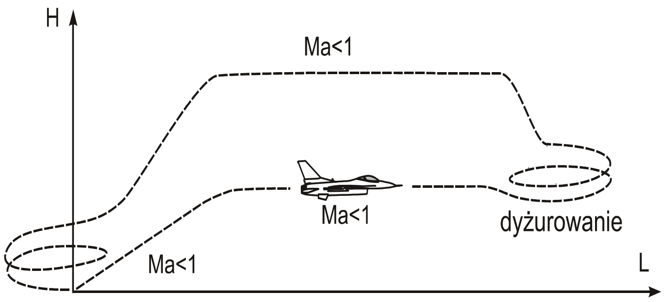
When we know the values of unitary energy-consumption at each stage of the mission, we can determine the total unitary energy-consumption of the mission from:

$$E_{j,\Sigma} = \Sigma_1^k E_{j,n}. \tag{14}$$

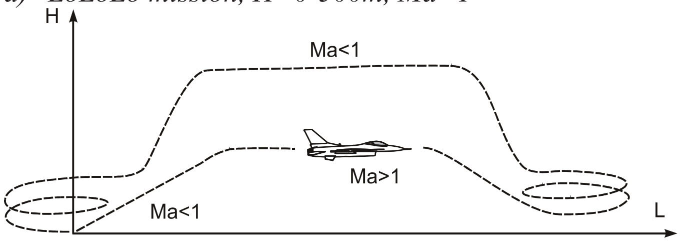
4. Energetic analysis of some missions of multipurpose aircraft

For further analyses there were chosen three different missions (but typical for multipurpose aircrafts) as for the tasks performed (and the right for them flight conditions), which were presented in Fig. 1. The first mission *Lo-Lo-Lo*; the name derives from the first letters of Low ceiling of approaching, maneuver fight on the Low ceiling and come back on the Low height) is a typical mission of the flight battle support. The approaching to the fight zone (armament drop) is on the low height with the supersonic speed (*Ma=0.5…0.8*). The fight, as in the next missions, is modelled by the series of turns, of the full 360°, with the different load factor and at different speeds. In case of the mission in Fig. 1 the speed of the maneuver is *Ma=0.8, H=0*. It is assumed that during the fight the aircraft gets rid of the load-armament, which accounts for the 0.2 of take off mass of the aircraft. The come back to the airport is at the same height but with the bigger flight speed of *Ma=0.8*.

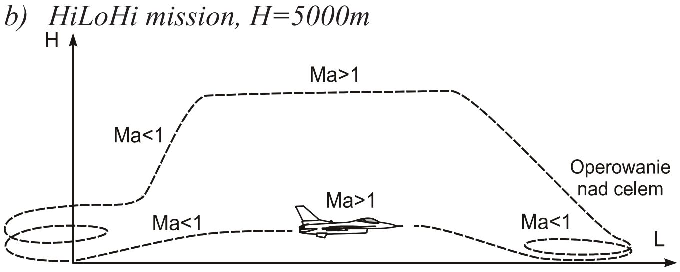
The second mission (Fig. 1b) takes place on the bigger height (of *H=0-500 m*), the approaching and come back from the mission is with the speed of *Ma=0.8*, and the air fight is modelled during the previous mission. The last, the third mission – seizure of the enemy in the air, thus the approaching to the zone takes place on the big height with the maximum supersonic speed (Fig. 1c). The fight is modelled by the series of turns with the different load factors in the turn, but



a) LoLoLo mission, H=0-500m, Ma<1



b) HiLoHi mission, H=5000m



c) HiHiHi mission, H=9000m

Fig. 1. Chosen missions performed by multipurpose aircraft a) LoLoLo mission (approaching the zone, ai r fight, come back on the low height and subsonic flight speeds) b) HiLoHi mission (approaching the zone, come back on the big height, air fight on the low height, supersonic speed range) c) HiHiHi missi on (approaching the zone, air fight, come back on the big height and supersonic speed range)

with the subsonic and supersonic speeds. The come back to the airport is on the big height with the supersonic speed, lower than the maximum one. Moreover, for each mission the take off of the aircraft is taken into account, and in the altitude missions, the climb stage is analyzed. Energetic analysis of the aircraft flight aims at determining the influence of the chosen parameters of the engine and the aircraft which decide about the total energy consumption for the missions, including the fuel usage.

5. Comparative analysis of the mission

Each of the researched missions is characterized by different flight altitude and the speed. Within each mission there were taken into consideration the take off, approaching to the maneuver zone and come back to the airport. The maneuver consisted in the full turn with different speed and different load factor in the turn (in each of the missions). The turn was important from the energetic point of view as it determined the value of the indispensable thrust of an aircraft, and at the same time it determined the thrust requirements for the engine. Moreover, in the calculations there was taken into account the constant change of the aircraft mass which resulted in the fuel usage, paying attention to the amount of fuel necessary for the climb and the acceleration of an aircraft.

An important criterion for the energetic assessment of the mission is the radius of an aircraft operation, which seems to be the smallest for the typical support mission of battlefield (*LoLoLo*), and the biggest for the mission of the seize character (*HiHiHi*). The conducted comparisons aim at showing the most energy-consuming mission.

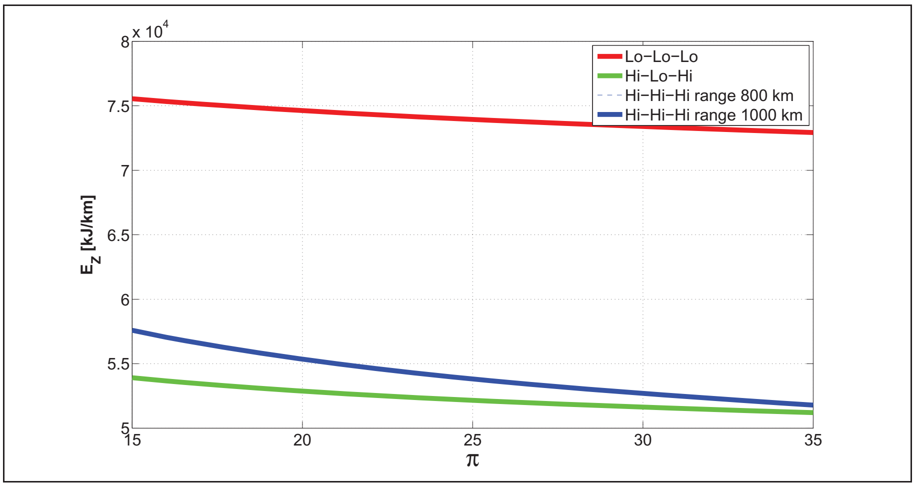


Fig. 2. Influence of compression $\pi^*_{\Sigma S}$ on the range energy-consumption EZ

According to the accepted definition, energy-consumption of the range was defined as the labour quotient of thrust forces on the displacement which reflect the stages of the flight to the length of the aircraft flight. Thus, the energy-consumption of the range is the measure of the average labour done by the power unit on the unit of the flight. The calculations of the range energy-consumption E_Z were conducted for the chosen missions in the function of compression changes and the bypass rate, and the results of the calculations were featured in a form of the graphs in the Fig. 2 and Fig. 3.

The biggest need for the energy to perform the entire mission is in *LoLoLo* mission. The work which the thrust forces perform during this mission results from the assumption that each flight stage is realized within the maximum thrust range. In this mission the flight to the area of the task performance and the come back flight are realized at very high values of the coefficient of available thrust in relation to the indispensable thrust (it results from the analysis of the obtained results which are not placed in the article), and additionally the radius of the aircraft operation (300 km) increases the disproportion of the calculations result E_z in relation to other missions. This result means that the chosen stages of the *LoLoLo* mission can be realized by the partially engine spluttering (bypass with a jet mixer). If an aircraft did only *LoLoLo* mission it would be necessary to apply another construction scheme of an engine, e.g. bypass with two separate flow ducts and a relatively high rate of quantity of flow. The increase of the compression of the compressor and the rate of quantity of flow in the bypass engine with the flux mixer allows to decrease the energy-consumption of the range of the analyzed missions. Lower value of the *Ez* parameter for two other missions shows better energy usage by the aircraft power unit during these missions, and for better adjustment of the power unit to these missions. The change of the radius of operation of the *HiHiHi* mission does not influence significantly on the change in energy-consumption (dashed and solid line in blue overlap in Fig. 2 and Fig. 3). It results from the accepted definition of energy-consumption of the range (in spite of the range change the proportions of the participation of the flight stages to the range route did not change as well as the engine thrust). In reality there are the changes but in case of the assumed scale of the drawing they are omitted. But this is the proof that from the energy-consumption point of view such flight stages as take off or the turn are relatively low in the energy-consuming balance in relation to the approaching or come back to the airport.

Referring the range energy-consumption to the current aircraft mass (which is decreased at each stage by the mass of the fuel and the mass of the used armament) there is a possibility to assess the energy-consumption in a unitary form (14). The biggest values of unitary energy-consumption concern the *HiHiHi* mission, and not as in case of range energy-consumption *LoLoLo* mission (Fig. 4 and Fig. 5). *HiLoHi* mission is an intermediate mission between *HiHiHi* and *LoLoLo* and requires the lowest energy consumption. It means that in order to displace the unitary mass of the aircraft for the distance of one kilometre during the *HiHiHi* mission there will

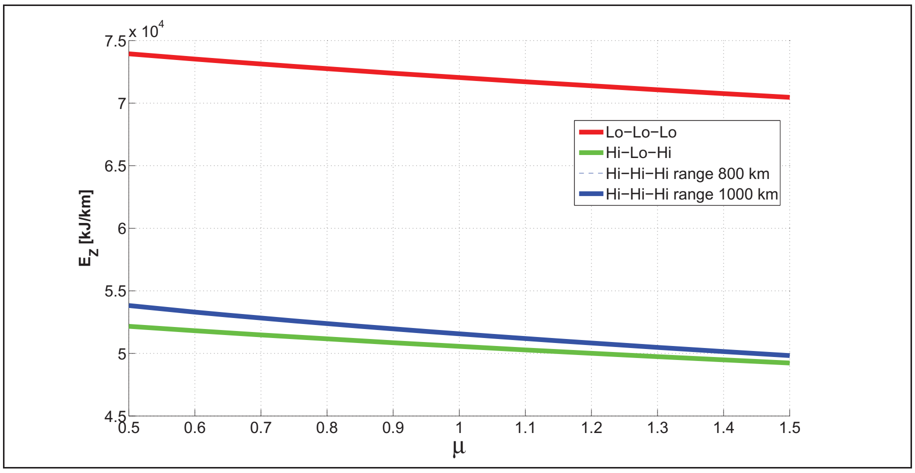


Fig. 3. Influence of the bypass rate μ on range energy-consumption EZ

be done the biggest work of the thrust (among all the researched missions). *HiLoHi* mission is characterized by the lowest value of unitary energy-consumption and range. Thus, from the energetic point of view, the flight schedule characteristic for *HiLoHi* mission can be judged as the most rational one. The influence of the compression and the bypass rate on the unitary energy-consumption is analogous as on the energy-consumption of the range.

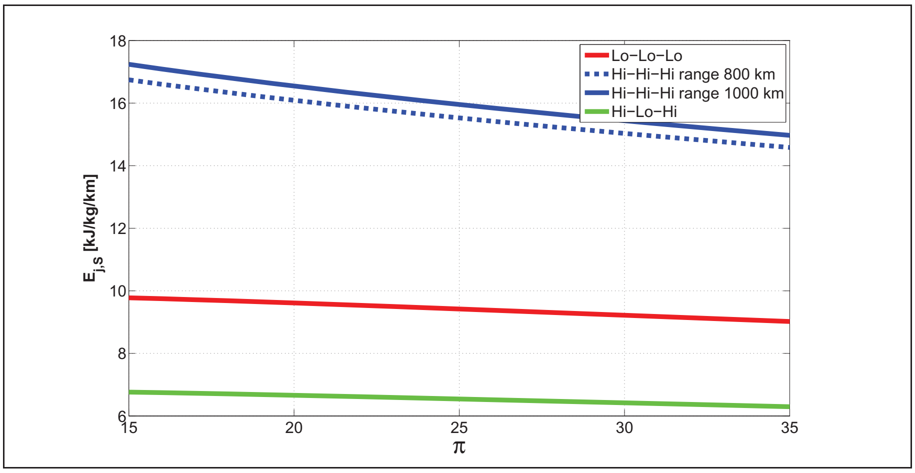


Fig. 4. Influence of compression $\pi^{*}_{\Sigma S}$ *on unitary energy-consumption Ej,Σ*

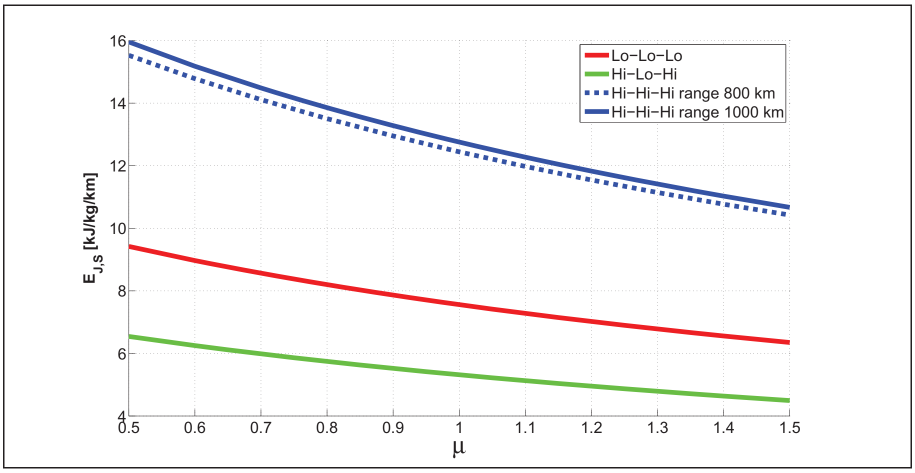


Fig. 5. Influence of bypass rate μ on unitary energy-consumption $E_{j,\Sigma}$

References

[1] Dzierżanowski, P., Kordziński, W., Łyżwiński, M., Otyś, J., Szczeciński, S., Wiatrek, R., *Turbinowe silniki odrzutowe. Seria Napędy Lotnicze*, WKiŁ, Warszawa 1993.

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

[3] Orkisz, M. (red), *Podstawy doboru turbinowych silników odrzutowych do p łatowca*, Biblioteka Naukowa Instytutu Lotnictwa, Warszawa 2002.

[4] Siłka, W., *Energochłonność ruchu samochodu*, WNT, Warszawa 1997.

[5] Schaffer, A., Lauer, W., *Design of a new fighter engine – the dream in an engine man's life,* RTO-MP-*, AC/323(AVT)TP/9 Design Principles and Methods for Aircraft Gas Turbine Engines, 1999.

[6] Wygonik, P., *Kryteria doboru parametrów silnika turbinowego do sa molotu wielozadaniowego*, Silniki Spalinowe, Nr 4, 2006.

[7] Wygonik, P., *Masowe kryteria doboru parametrów dwuprzep ływowego silnika odrzutowego do samolotu wielozadaniowego, dla wybranych zada ń lotniczych*, Polskie Towarzystwo Naukowe Silników Spalinowych, Silniki Spalinowe, T. 1, 2007.

[8] Wygonik, P., *Criteria of aircraft engine parameters evaluation for multi-purpo se aircraft*, Journal of KONES Powertrain and Transport, Vol. 14, No. 2, 2007.