ISSN: 1231-4005
e-ISSN: 2354-0133
ICID: 1133241
DOI: 10.5604/12314005.1133241

CRITERIA FOR THE ASSESSMENT OF THE ENGINE EFFICIENCY OF THE MULTI-PURPOSE AIRCRAFT MISSIONS

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Abstract

The problem of design parameters selection of the turbine engine is the most important task at the preliminary design stage of the multi-purpose aircraft. A special feature of the multi-purpose aircraft mission is a sudden (even pulse) weight change, especially its decrease as a result of discharge of cargo bombing or rockets due to the ammunition consumption during air combat manoeuvring. In this article the attempt to use economic and mass criteria to assess the impact of the type of air missions on the choice of the design parameters of the engine was done. As the design, parameters there were selected the following measures: compression ratio, the turbine temperature and the bypass ratio. A mathematical model of the engine – aircraft – air task system was built (taking into account the flight conditions, the mission elements – the subsonic and supersonic flight, flight time, thermo-gas-dynamic and mass model of the engine). The model enables to conduct the simulation research of the complex flight missions and their assessment on the basis of the constructed criteria. The model includes a parametric description of physical processes in the turbofan engine, thereby allowing a direct assessment of the impact of the selection of engine parameters on the effectiveness of the mission. The paper presents the results of calculations according to the classical criteria (e.g. kilometre fuel consumption, specific fuel consumption of the engine). New criteria for evaluation were presented; they are the energy efficiency of complex mission of an aircraft and the relative total and specific fuel consumption. The values of circuit parameters that need to be taken as design constraints for the engine to allow the implementation of the aviation missions were determined. The results are shown in an illustrative way on the number of graphs.

Keywords: *multi-purpose aircraft, turbine engines, airframe and engine integration, thermal cycle*

1. Introduction

The assessment of the energy efficiency of an engine as a structural element of the aircraft consists of a set of indicators based on which one can assess the energy rate supplied to the engine to perform the entire aviation mission. In order to assess the quality of the selection of the engine to the aircraft and indicate the physical aspects for this selection, an assessment of the overall engine – aircraft – aviation task system needs to be performed. In the paper there were discussed some selected evaluation criteria of matching the engine to the aircraft that runs the specified mission, and then for the selected missions the results of calculations will be presented. The influence of thermo-gas-dynamic parameters of the engine (Total Turbine Temperature (TT_3), compression pressure ratio π, bypass ratio μ) on the appropriate mass and economic criteria were researched [3].

2. Comparative criteria

Mass limitations arising from the mass balance equations aircraft are closely related to the mass of fuel. The basic criterion, which results from mass balance equations of an aircraft [1-3, 5, 10], is the relative mass consumption:

$$m_{Wpal} = \frac{m_{\Sigma pal}}{m_s}, \tag{1}$$

where mass of the consumed fuel during the mission execution:

$$m_{\Sigma pal} = \sum_{n=1}^{k} m_{pal,n}, \tag{2}$$

where:
k – number of stages the mission was divided into, (take off *n=1*, climbing *n=2* etc.),
m_S – take-off weight of an aircraft,
$m_{pal,n}$ – mass of the fuel consumed during a selected stage of the mission,

$$m_{pal,n} = c_{j,n} K_{sil,n} \Delta t_n, \tag{3}$$

where:
$C_{j,n}$ – specific fuel consumption for the *n*-th stage of the mission,
$K_{sil,n}$ – available thrust of the power unit on the *n*-th stage,
Δt_n – time of the *n*-th stage of the mission.

The criterion (1) acts as a constraint to check for which parameter combinations of the engine thermal cycle during a mission an acceptable value m_{Wpal} can be achieved. According to research carried out in [7] for modern multi-purpose aircrafts the value of m_{Wpal} = 0.2….0.25. To assess the economical efficiency of the aircraft engine a specific fuel consumption of the engine c_j [1, 7] is applied. The value of this ratio is determined for a given value of thrust and flight conditions and usually is given for the most economical operating range of the engine. The smaller the ratio, the engine (or rather the operating range of the engine) is more economical. It is the criterion which only evaluates the engine in economic terms and it does not take into account the characteristics or parameters of the aircraft or an aviation mission. When assessing the mission of the aircraft from an economical point of view, it is usually assessed by indicators such as total fuel consumption, fuel consumption related to range, or the weight of the load (commercial). Each aircraft mission, in order it could be performed, requires the delivery of a specific energy, which is assessed globally: for the entire mission, for several series of missions (in the case of multi-purpose aircraft). The comparison of the selected mission ratios (different in purpose and method) provides an opportunity to assess the mission not only in terms of energy expenditure but also in economical terms. For the purposes of the article it was introduced a new criterion called specific fuel consumption indicator in the mission defined by the formula:

$$c_{j,Ez} = \frac{\frac{m_{\Sigma,pal}}{\sum \Delta t}}{E_Z}, \tag{4}$$

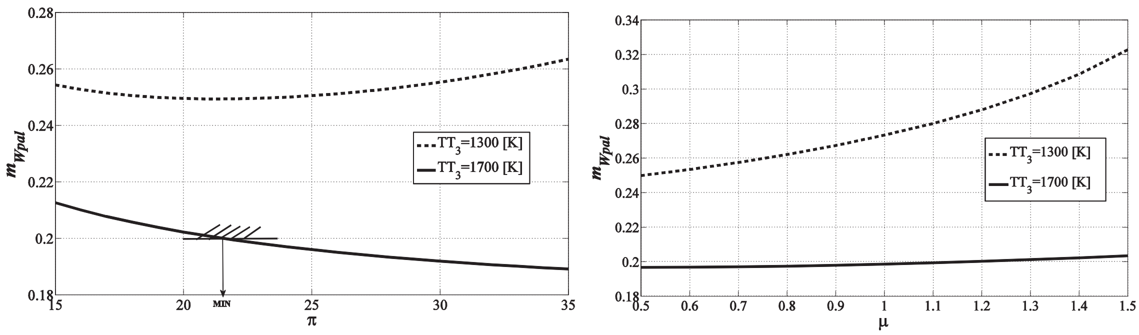
where Ez – range energy-consumption [11],

$$E_Z = \frac{\sum_{n=1}^{k} K_{sil,n} L_n}{\sum_{n=1}^{k} L_n}. \tag{5}$$

In the formula (4) total consumption is divided by the total flight time (total time performing the elementary stages of flight) and related to the so-called [10, 11] range energy-consumption Ez. The indicator (5) determines the amount of work done by thrust force from 1 kg of burned fuel per time to move the mass of the aircraft to the distance unit. An analysis of any of the criteria (1, 4) gives the opportunity to examine the degree of "processing" of the fuel energy into useful work of thrust force. The equations (1-5) are also applied at the elementary stage of the mission, and they enable to show the most and least energy-consumption stage. The smaller the value of $c_{j,Ez}$, the more useful energy created from burning of the mass of fuel unit.

3. Assumptions and analysis

On the basis of [2-6], a model of turbofan engine with a jet mixer and an afterburner was built, as well as the model of aerodynamic characteristics of an aircraft [1, 11], and the mission models [1, 3]. The connection of fuel mass and aircraft take-off weight (1) is a standard criterion to assess the ability of the aircraft to stay in the air. The results of calculations of the impact of the compression pressure ratio π , total turbine temperature TT_3 bypass ratio μ on the m_{Wpal} value was shown in Fig. 1. The results of the calculations relate to the LoLoLo mission (so-called battlefield support missions for which the characteristic is an approaching by air to the combat zone, air combat and return to the airport at subsonic velocity and low altitude flight (Lo)).

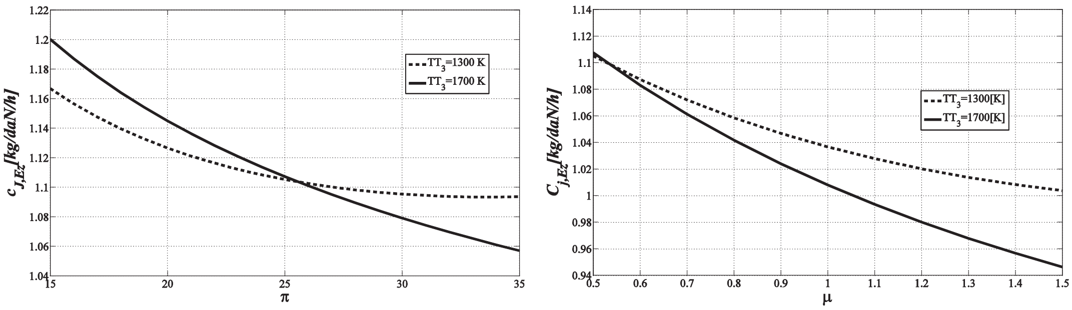


a) *b)*

Fig. 1. Influence of a) compression pressure ratio π (μ=0.5) , and b) bypass ratio μ (π=25)on m_{Wpal}, for two values of TT_3, (LoLoLo mission)

The influence of compressor compression on fuel mass required for the LoLoLo mission depends largely on the total turbine temperature TT_3 (Fig. 1a). For temperatures below 1500 K, the $m_{Wpal} = f(\pi)$ function has a minimum for π, in the range between π_{opt}, due to the maximum specific thrust and π_{ek} due to the minimum of the specific fuel consumption [3]. This value is related to the mission parameters (the range and flight velocity). When one adopts a higher total turbine temperature of ca. 1700 K, the $m_{Wpal} = f(\pi)$ function decreases monotonically. If assume for [3, 7] that the relative fuel weight of modern multi-purpose aircraft is $m_{Wpal} = 0.2$, then to obtain such an indicator of relative mass of fuel is possible at relatively high total turbine temperatures and compressor pressure ratio above the values indicated in Fig. 1a by “MIN” index. The higher the TT_3, the value of π_{MIN} is lower. The effect of bypass ration on m_{Wpal} is opposed to the static compression (Fig. 1b). The increase in the bypass ratio leads to an increase in the relative weight of fuel, the more quickly the lower the total turbine temperature is. When the total turbine temperatures are, lower than 1500 [K], then to obtain $m_{Wpal} = 0.2$ virtually impossible. In addition, for high total turbine temperatures as in the calculation example -1700 K the increase of μ above a certain limit value (μ> 1.1) exceeds the limit value of relative mass. The characteristic is a flat course of the curve $m_{Wpal} = f(\mu)$ in the accepted range of μ changes, for large values of TT_3. If no restrictions for μ because of the mission energy requirements, such a curve course would give the designer of the engine a relatively large range of the selectable values of μ bypass ratios.

The economical criterion, which allows assessing the degree of energy consumption during the mission, is specific fuel consumption during the mission $c_{j,Ez}$ whose courses in the function $f\ (\pi, TT3, \mu)$ are shown in Fig. 2. This parameter (5) should be treated as an average parameter for the entire mission, as a change at every stage of the mission is equivalent to the well-known parameter – the criterion of engine specific fuel consumption c_j [3,10,11]. To comparison, the values of $c_{j,Ez}$ and c_j (only for the engine) in Fig. 2 show the course of the specific fuel consumption for the engine as a function of the same parameters of $f(\pi, TT3, \mu)$, at $c_{j,Ez}$.



a) *b)*

Fig. 2. Influence of a) compression pressure ratio π and b) bypass ratio μ on the specific fuel consumption in LoLoLo mission

The increase in TT has a significant impact on both economical parameters: $c_{j,Ez}$ and c_j. The increase in compression does not cause significant changes $c_{j,Ez}$, and the reason for this is the relatively flat curve of the specific thrust for a selected, the maximum level of temperature change in function of π [3]. The increase in bypass ratio μ has a beneficial effect on the course of $c_{j,Ez}$ (Fig. 2b). Unfortunately, because of the energetic restrictions for the presented mission, the need to choose the engine variant with low μ causes that $c_{j,Ez}$ will be relatively high.

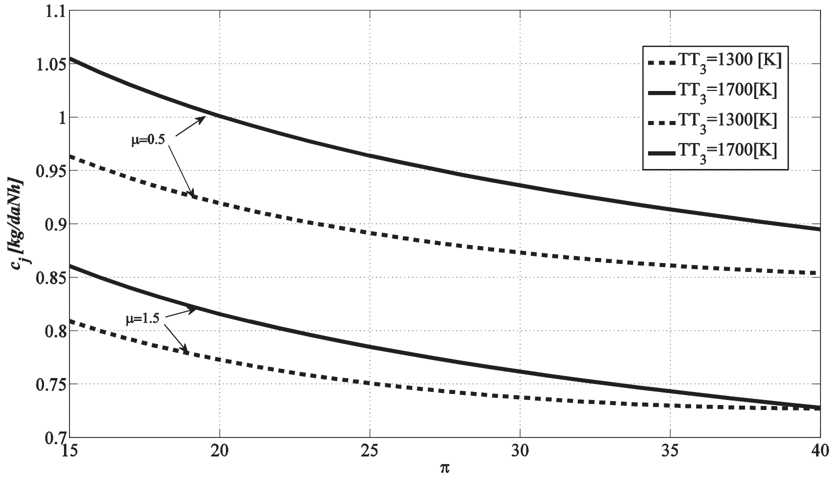
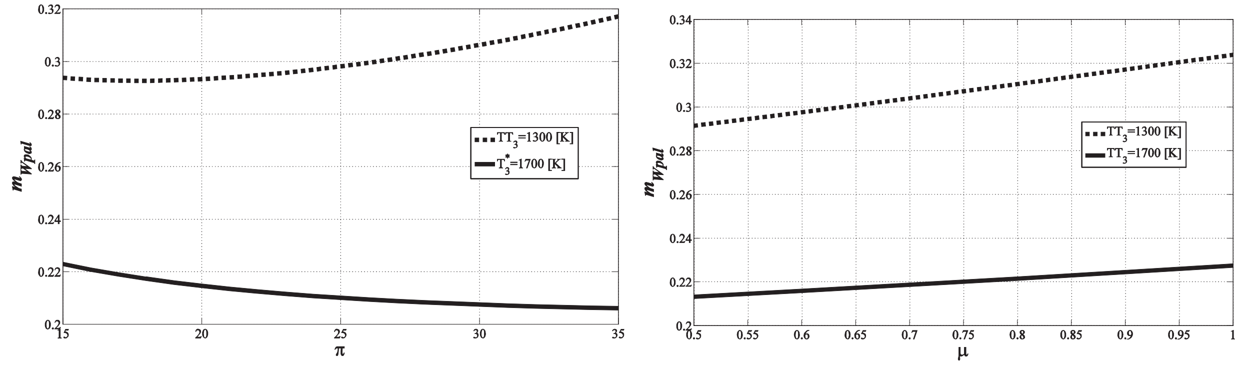


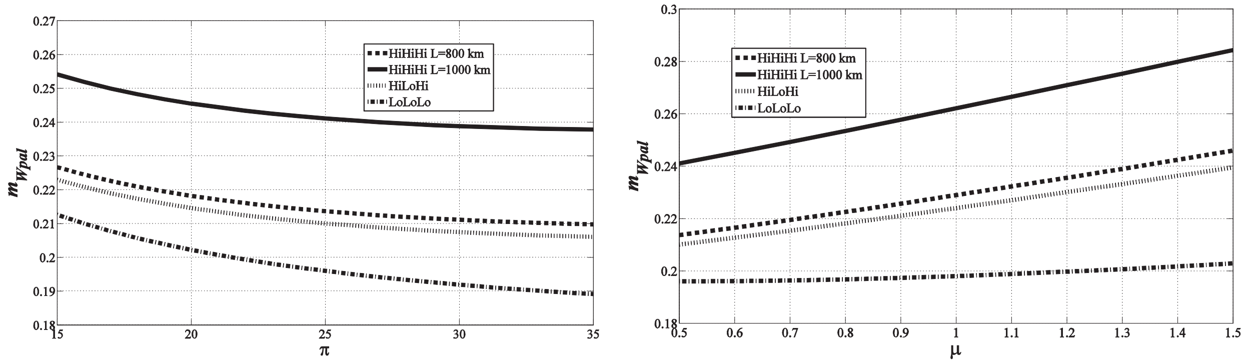
Fig. 3. Dependence of specific fuel consumption cj for the engine in compression π, bypass ratio μ and TT_3 (LoLoLo mission)



a) *b)*

Fig. 4. Influence of a) compression pressure ratio π and b) bypass ration μ on relative fuel mass m_{Wpal} (HiLoHi mission)

The second test mission (HiLoHi mission) consists of two distinctive stages, i.e. supersonic flight of the maximum loaded aircraft to the combat zone and return to the airport at the high (Hi) altitude for with a navigation fuel supply. Air fight takes place at low altitude with subsonic velocity of manoeuvring. It is important to investigate the influence of engine cycle variables on fuel mass. Fig. 4 shows the effect of compressor compression and the degree of bypass on the relative fuel mass. The attention was drawn to the fact that by the relatively high parameter values of the engine circuit (TT3 = 1700 K) the relative fuel mass is not less than 0.2 (as in the LoLoLo mission l). The increase in the compression causes the lowering of the fuel mass and the increase of the bypass ratio causes the opposite effect, i.e. the relative fuel mass increases with the increase of μ. Therefore, to minimize the mass of fuel required to complete a task, it is necessary to use a variant with the lowest possible value of the bypass ratio (from the tested range) and the possibly highest compression pressure ratio selected for calculation point, in this case for the take-off. Calculations have shown that each of the missions, for its implementation requires a different mass of fuel. The third research mission is HiHiHi mission (all stages are supersonic, executed at high altitude (3xHi)) is the most fuel-consuming mission (Fig. 5). Reducing the radius of operation of the aircraft , allows reducing the mass of the fuel, but may be an operation, which diminishes the range of possibilities of modern fighter aircraft. On the other hand, the increase of fuel mass, while maintaining unchanged the take-off mass may reduce the expense of the constituent masses the aircraft including the mass of weapons, which further impairs the tactical abilities of an aircraft. Such engine parameters of the engine cycle cause that it is not possible to reduce the fuel mass during the HiLoHi and HiHiHi missions below $m_{wpal} < 0.2$ (as is the case of the LoLoLo).



a) *b)*

Fig. 5. Change of relative fuel mass m_{Wpal} for various functions of a) compression pressure ration π, (TT3=1700 K, μ=0.5) and b) bypass ratio function μ (TT_3=1700 K, π=25)

4. Conclusions

The use of large compression compressors compensates the effect of an adverse increase of relative fuel mass for each mission selected for calculations and improves the mass efficiency of the aircraft. The rise in the engine bypass ratio μ increases the relative fuel mass (Fig. 5 and 6), wherein the increase is the greater, the greater the share of the range of subsonic to supersonic flight. Fuel mass required to achieve LoLoLo mission (entirely subsonic) depends slightly on the bypass ratio, but it results from the fact of mission execution in a narrow range of flight velocities changes (from Ma=0.5 to Ma=0.8), at a constant height. The presence of supersonic flight velocities during the mission forces to reduce the degree of bypass ratio μ, which helps minimize the relative fuel mass.

The parameter of specific fuel consumption in the mission $c_{j,Ez}$, accepted for economical analyses of the engine, should be treated as an average parameter which characterizes not a selected flight stage (as is the case of determining the specific fuel consumption of the engine), but the whole mission. Fig. 6 and 7 show the courses of criteria parameter $c_{j,Ez}$ in a function of thermodynamic parameter of engine cycle. It is characteristic that the curves of change $c_{j,Ez}$ are

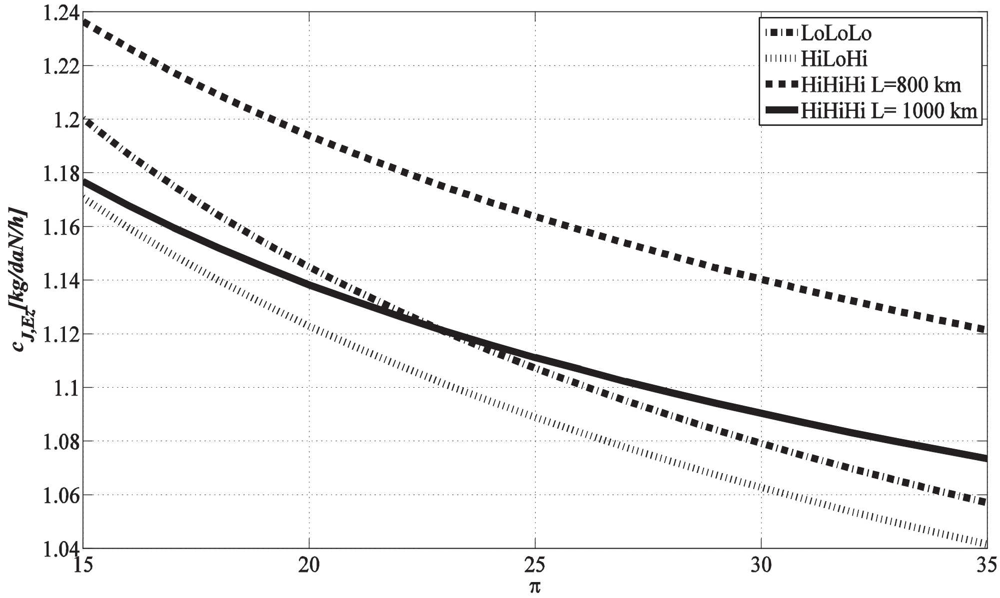


Fig. 6. Influence of compression pressure ratio π on $c_{j,Ez}$

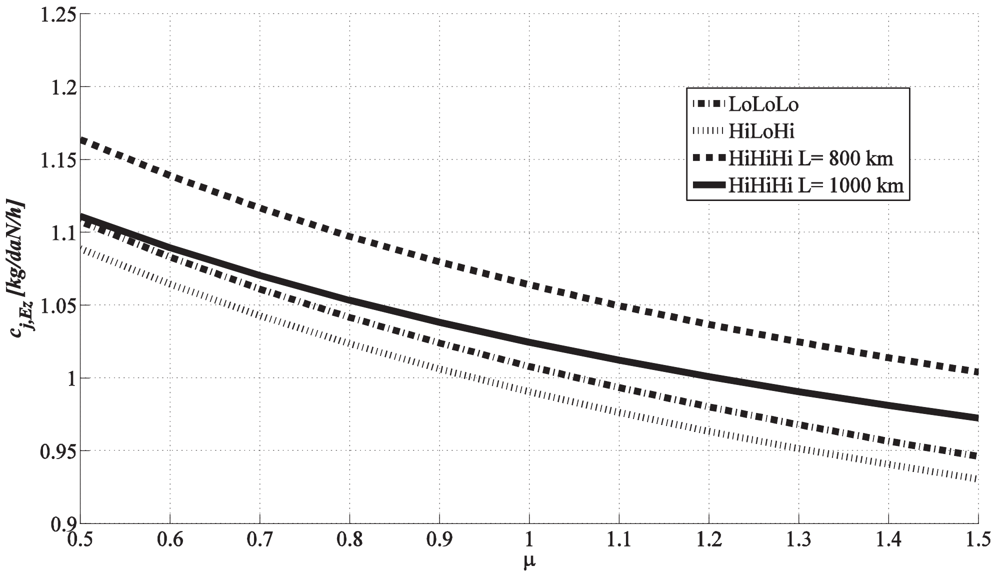


Fig. 7. Influence of bypass ratio μ on $c_{j,Ez}$

monotonically decreasing functions of compression and bypass ratio, and the differences between the values of $c_{j,Ez}$ for the analysed missions are relatively small. The increase in compressor compression (TT3 = 1700 K) is beneficial for reducing the specific fuel consumption during the mission. The parameter $c_{j,Ez}$ (Fig. 6 and 7), clearly depends on the range, while a small reduction in range calculation results in a relatively large increase in $c_{j,Ez}$. LoLoLo mission is characterized by the lowest value of $c_{j,Ez}$, which makes it attractive from an economic point of view. However, it is important to note that the multi-purpose aircraft must perform a number of different missions, often performing different parts of the mission in the next, combined missions, which makes the problem of engine parameters selection even more complicated. Significant in this case is the fact that the economic characteristics of the mission, such as $c_{j,Ez}$, can be significantly improved by increasing the compression of the compressor. If there were no restrictions with regard to the bypass ratio, which had been mentioned before, also, it would be advantageous to use higher degrees of bypass, but it would result in a deterioration of the dynamic properties of the engine. The obtained results also show why the aircraft designers increase them m_{Wpal} value even by 0.5.

References

[1] Goraj, Z., *Dynamika i aerodynamika samolotów manewrowych z elementami obliczeń*, Biblioteka Naukowa Instytutu Lotnictwa, Warszawa 2001.
[2] Herteman, J. P., Goutines, M., *Design principles and methods for military turbojet engines.* RTO-MP, AC/323(AVT)TP/9 Design Principles and Methods for Aircraft Gas Turbine Engines, 1999.
[3] Orkisz, M., et al., *Podstawy doboru turbinowych silników odrzutowych do płatowca*, Biblioteka Naukowa Instytutu Lotnictwa, Warszawa 2002.
[4] Oates, G., *Aerothermodynamics of gas turbines and rocket propulsion*, AIAA, New York 1985.
[5] *Performance prediction and simulation of gas turbine engine operations*, RTO-TR-044 AC/323(AVT-018)TP/29, RTO Technical Report 44, RTO/NATO, 2002.
[6] 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.
[7] Smykla, M., *Efektywność taktyczna samolotów w aspektach masowo-geometrycznych*, Rozprawa doktorska, Akademia Obrony Narodowej, Warszawa 2000.
[8] Stricker, J. M., *The gas turbine engine conceptual design process – an integrated approach*, RTO-MP, AC/323(AVT)TP/9, Design Principles and Methods for Aircraft Gas Turbine Engines, 1999.
[9] Wygonik, P., *Kryteria doboru parametrów silnika turbinowego do samolotu wielozadaniowego*, Silniki Spalinowe, 4, 2006.
[10] Wygonik, P., *The influence of Multi-role aircraft mission type on the low bypass engine performance parameters*, Journal of KONES Powertrain and Transport, Vol. 20, No. 3, pp. 435-442, Warsaw 2013.
[11] Wygonik, P., *Engine and multitask airplane integration criteria of engine parameters selection*, An International Journal, Aircraft Engineering and Aerospace Industry, Vol. 85, No. 6, pp. 460-466, 2013.