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## METHODOLOGICAL APPROACH TO EVALUATING THE COST-EFFECTIVENESS OF UNMANNED AERIAL VEHICLE WITH A TURBOJET ENGINE

### Introduction

Modern unmanned aerial vehicles (UAVs) are complex technical systems that include direct unmanned aerial vehicles (UAVs) with onboard systems, power plant and payload, as well as ground complex for takeoff, landing, control, data transmission and others. Each of these components requires a specific approach to the requirements and requirements of the aircraft. Each of these components requires a specific approach to the specification of the requirements and the search for criteria for their evaluation.

### Relevance of research

The use of multicriteria methods for evaluating complex technical systems, such as UAV, requires the use of large data sets with significant time costs, so the search and application of comprehensive evaluation criteria, as proposed below, is currently considered appropriate and necessary.

### Analysis of works and publications on the topic

It should be noted that a great number of publications and scientific works are devoted to the development of the theory of evaluation and synthesis of

various classes of UAVs. Thus, in [1; 5; 6] the issues of methodological bases of synthesis and development of modern unmanned complexes are considered, methodical approaches to evaluation of characteristics of UAVs components are substantiated, criteria of comparative evaluation of UAVs of different function are offered.

The works [6; 8] demonstrate the advantages of using a systematic approach to support decision making at various stages of UAVs design and creation. In [9] the importance of the scientific and methodological apparatus for assessing technical risks at the early stages of the design of advanced UAVs is outlined.

However, despite the established scientific basis, a number of scientific issues remain unresolved, in particular, on the equation of integrated indicators to assess the performance of UAVs with a turbojet propulsion system with limited initial data.

### Statement of the research task

The above findings indicate that this article provides a methodology for evaluating the economics and a comprehensive indicator of technical excellence of UAV with a turbojet propulsion system.

**Presentation of the main material**

**1. Choice of cost-effectiveness indicator**

In order to ensure high performance on modern large-size UAVs (strategic, operational,) turbojet engines (TREs) can be used. For the flight of the aircraft, they create an active force directly — jet propulsion  $P$ , which is expressed equally often in the Newtons [H] and in kilograms of force [kgf].

It is known from the dynamics of the field that the range  $L$  and flight duration  $T$  are determined by the fuel supply for horizontal flight  $m_n$ , as well as kilometers  $q_k$  and hourly  $q_h$  fuel consumption in accordance with the following formulas [2; 3]:

$$L = \frac{m_n}{q_k}, \quad T = \frac{m_n}{q_h}, \quad (1)$$

where  $m_n = m_{n0} - m_{nn}$ ,  $m_{n0}$  — the maximum amount of fuel in the tanks,  $m_{nn}$  — Non-productive fuel consumption (for power plant testing, system checks, flight and height gain, reduction and landing, as well as fuel surplus that is not produced). Non-productive costs can be taken into account by introducing a special coefficient, e.g.,  $m_n = 0,94m_{n0}$ .

Hourly fuel consumption, in turn, depends on the specific fuel consumption  $C_p$  (amount of fuel consumed per unit of thrust per hour), which is expressed in  $C_p$  [kg/kg force hours] =  $gC_p$  [kg /H hours]. In practice, however, the negative characteristics are often used more often

$$\bar{C}_p = C_p / C_{pmax},$$

where  $C_{pmax}$  — the fuel consumption at maximum engine speed.

This is expressed as a function of the relative thrust  $\bar{P} = P / P_{max}$  and is called the throttle characteristic. An example of such a dependence is shown in Fig. 1. The minimum value  $\bar{C}_p$  is usually achieved at the nominal mode of operation of the engine - the mode of greatest efficiency [4].

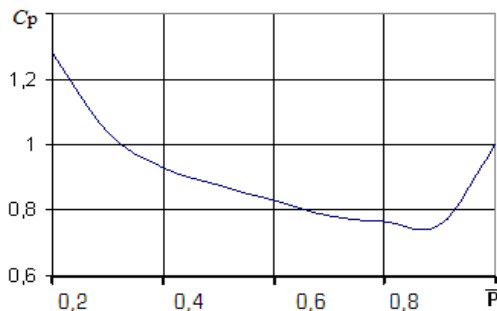


Fig. 1. Throttle characteristics in relative parameters

The main advantage of the relative characteristics is their slight dependence on the speed and altitude of the flight, as it is assumed that when chang-

ing the speed and altitude  $C_p$  and  $C_{pmax}$  change equally. To determine the minimum specific fuel consumption from the graph of the type of Fig. 1 remove the minimum value  $\bar{C}_p$  and its corresponding value  $\bar{P}$ , and then multiply them accordingly by  $C_{pmax}$  and  $(P_H)_{max}$ , corresponding to the maximum speed.

In most advertisements, these specifications are given for starting at maximum engine speed under standard atmospheric conditions  $C_{p0}$  and  $P_0$ . The relationship between these quantities can be determined by the following formulas [3]:

$$P_{Hmax} = P_0 \frac{P_H}{P_0} \left[ \frac{T_0}{T_H} \right]^{k_i}; \quad (2)$$

$$C_{pmax} = C_{p0} \sqrt{T_0 / T_H}, \quad (3)$$

where the indexes «0» correspond to the height  $H = 0$ , and index «H» — the height of the ceiling. Value  $k_i = 2...3$  units.

For these conditions, the formulas for hourly and kilometer fuel consumption will look like:

$$q_h = C_p X_a; \quad q_k = q_h / V = C_p X_a / V. \quad (4)$$

This assumes that the thrust of the propulsion system is equal to the frontal support.

Dependence of the frontal support on speed  $X_a(V)$  (Fig. 2) has a minimum at the highest angle of attack (the highest speed).

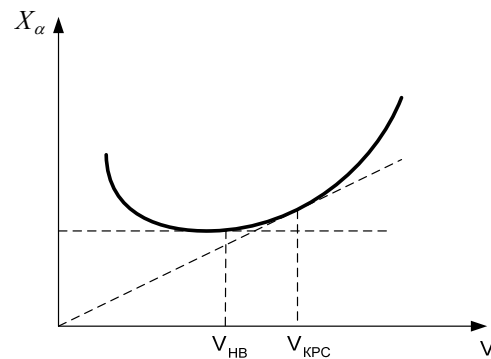


Fig. 2. Dependence of frontal support on speed

Tangent to the curve drawn parallel to the abscissa, determines the most favorable speed  $V_{HB}$ . Flying at this speed provides minimum drag and maximum duration.

The tangent to the curve drawn from the origin determines the cruising speed  $V_{KPC}$ . Flying at this speed provides maximum range [2].

There is a relationship between the two speeds due to the corresponding coefficients [1]

$$C_{y_{KPC}} = \frac{C_{y_{HB}}}{\sqrt{3}} = 0,577C_{y_{HB}}. \quad (5)$$

Given the relationship between the coefficient of lift and speed in a straight horizontal flight, we obtain a relationship between speed and aerodynamic qualities in both flight modes

$$\frac{V_{\text{крс}}}{V_{\text{max}}} = \sqrt[4]{3} = 1,32 \text{ and } \frac{K_{\text{крс}}}{K_{\text{max}}} = \frac{\sqrt{3}}{2} = 0,866. \quad (6)$$

Assuming that the lifting force is equal to the force of gravity  $Y_a = gm[H] = m[\text{kgf}]$ , express frontal drag through the mass of the aircraft and aerodynamic quality  $X_a = m/K [\text{kgf}]$ , and  $C_p$  — y kg/kgf hours. Then the formula for the hourly fuel consumption will be written as

$$q_h = C_p X_a = C_p \frac{m}{K}. \quad (7)$$

As the engine speed increases, the speed increases and also increases  $X_a$ , but also decreases  $C_p$ , and more significantly than the frontal resistance increases. Therefore, at low altitudes it is more profitable to fly at speeds higher than the most profitable. At some height, the engine will reach rated speed,  $C_p$  will reach a minimum (see Fig. 1), and the most favorable speed will provide maximum quality — get the mode of minimum hourly fuel consumption (maximum flight duration)

$$T_{\text{max}} = \frac{m_n}{q_h} = \frac{K_{\text{max}} m_n}{C_{p \text{ min}} m} = k_{ep} \bar{m}_n. \quad (8)$$

In formula (8) the notation is accepted

$$k_{ep} = \frac{K_{\text{max}}}{C_{p \text{ min}}} [\text{kgf h/kg}], \quad (9)$$

where  $\bar{m}_n = m_n / m$ ,  $k_{ep}$  — the coefficient of cost-effectiveness of aircraft with turboprop. It determines the combined efficiency of the glider (due to aerodynamic quality) and the efficiency of the engine  $C_{p \text{ min}}$ .

From formula (8) you can get an explicit dependence  $k_{ep}$  from the flight duration

$$k_{ep} = \frac{T_{\text{max}}}{\bar{m}_n}, \quad (10)$$

which allows to obtain the coefficient of efficiency of aircraft with turbojets for the maximum duration of the flight of the aircraft and the relative fuel supply.

Using the relationship between kilometer and hourly fuel consumption, we express this factor through the maximum flight range

$$q_k = \frac{q_h}{V}; \quad L = \frac{m_n}{q_k} = \frac{m_n V}{q_h} = \frac{m_n V K}{C_p m}. \quad (11)$$

As can be seen from (11), the maximum range is realized at the maximum value  $VK$ .

In [2] it is shown that the condition  $VK = \max$  responds to cruising flight mode when  $V = V_{\text{крс}}$ , and  $K_{\text{крс}} = 0,866K_{\text{max}}$ . Taking into account these relations, we find the value  $k_{ep}$  due to the maximum flight range

$$k_{ep} = \frac{L_{\text{max}}}{0,866 \bar{m}_n V_{\text{крс}}}. \quad (12)$$

It is obvious that the calculations according to formulas (10) and (12) with the same initial data should give the same result. Since the flight time is measured directly and the range is determined by calculation, preference is usually given to the flight for the maximum duration.

## 2. Scale for assessing the technical excellence of UAVs with turbojets

In order to check the validity of the proposed indicators, an assessment was made of their feasibility for determining the performance characteristics of existing and prospective UAVs with turbo-prop. UAVs were used as the main sources of information on flight technical data [7; 8; 10; 11]. The formed group of UAVs with the most complete data are presented in Table 1.

In the Table 1 the results of the calculations are presented for two options for determining these characteristics depending on the available information: regarding the maximum flight duration  $k_e T$  and flight to maximum range  $k_e L$ .

Table 1

The results of the calculation of the coefficient  $k_e$  UAVs with turbojet engines

The name of the UAV	$L_{\text{max}}$	$T_{\text{max}}$	$V_{\text{крс}}$	$m_{\text{зл}}$	$m_n$	$\bar{m}_n$	$H_{\text{ст}}$	$P$	$q_h$	$C_p$	$k_{eT}$	$k_{eL}$	$K_{\text{max}}$
	km	h	$\frac{\text{km}}{\text{h}}$	kg	kg		m	kg	$\frac{\text{kg}}{\text{h}}$	$\frac{\text{kg}}{\text{kgf.h}}$	$\frac{\text{kgf.h}}{\text{kg}}$		
RQ-4N Global Hawk	16 000	34	580	11620	6853	0,67	19 800	3450	171	0,30	51	48	15

The end Table 1

The name of the UAV	$L_{\max}$	$T_{\max}$	$V_{\text{крс}}$	$m_{3л}$	$m_n$	$\bar{m}_n$	$H_{\text{ст}}$	$P$	$q_h$	$C_p$	$k_{eT}$	$k_{eL}$	$K_{\max}$
	km	h	$\frac{\text{km}}{\text{h}}$	kg	kg		m	kg	$\frac{\text{kg}}{\text{h}}$	$\frac{\text{kg}}{\text{kgf}\cdot\text{h}}$	$\frac{\text{kgf}\cdot\text{h}}{\text{kg}}$		
X-47B	6000	9	740	20215	10000	0,53	12190	8074	663	0,35	18	19	6
Predator C Avenger	11000	20	600	7260	4000	0,61	18000	2173	170	0,40	33	30	15
Talarion		20	600	7000	3650	0,57	15240		155		35	30	
HQ-4 Xianglong	8000	14	680	7500	3200	0,44	18		194		32	31	
RQ-170 Sentinel		12		4200	1850	0,46	15500		112		30		
AQM-91 Compass Arrow	3700	6	760	2381	1300	0,60	24000	3700	184	0,29	11	10	4
YQM-94A	11500	24	530	6500	3500	0,59	16500	2370	125	0,30	40	42	12
Barracuda	4500	6	700	3250	1000	0,39	6000	1450	142	0,26	20	22	5
Darkstar	2600	8	463	3900	1000	0,24	13700	862	120	0,35	33	27	11
Skat	4000	6	750	10000	3500	0,34	12000	5000	500	0,30	17	18	6

To determine the relative mass of fuel  $\bar{m}_n$  the corresponding devices were taken into account unproductive fuel consumption for takeoff, and the altitude set by introducing the appropriate coefficient of performance  $m_{nn}$ , and the calculated average flight mass of the aircraft according to the formula  $m_{\text{пол}} = m_{3л} - m_n/2$ .

The calculations and analysis were based on the Tactical and Technical Characteristics of the current strategic, operational and operational-tactical classes, as well as the promising and experimental ones having non-traditional UAV shapes and configurations.

For the purpose of this definition  $k_e$  these devices can give an idea of their technical level in terms of efficiency.

It varies in a fairly wide range:

– in great value ( $k_e = 51...48$ ) UAV RQ-4N Global Hawk, due to its optimal aerodynamic layout with high aerodynamic quality, extensive use of composites in structural elements and the use of modern economic turbojet engines;

– to a low value  $k_e$ , which is equal to 10 and 13 for devices AQM-91 Compass Arrow та Neuron, respectively, which is explained: in the first case by

suboptimal aerodynamic layout and engine of outdated design. In the second case, there are doubts about the reliability of the used Tactical Technical Characteristics of the Neuron device as a result of finding it at the stage of creation and testing.

As follows from the analysis of formula (9), the coefficient  $k_e$  should vary within relatively narrow limits. Thus, the maximum aerodynamic quality for traditional aircraft schemes is usually no more than 20, and for most real UAVs — no more than 15; the minimum specific fuel consumption of the turbojet engine is within 0,3...0,4 kg/kgf hours. Therefore, theoretically the maximum value  $k_e$  should not exceed 70 kgf · h / kg, and practically — 50 kgf h/kg.

In order to build a 5-point scale of comparative evaluation of the obtained indicator, you can determine a sample close to the best UAVs with the following characteristics:

$$K_{\max} = 15, C_{P\min} = 0,3 \text{ kg} / \text{kgf} \cdot \text{h}$$

and consider it as a reference.

Then we get a reference value for comparison  $k_e = 50$  kgf hours/kg which includes the calculated characteristics of real devices (Table 2).

Table 2

**Normative scale for assessing the technical excellence of UAVs with turbojets**

Scores	Value $k_e$ , kgf hours/kg	Characteristic
1	10 and less	Unsuccessful aerodynamic scheme, inconsistent engine with the characteristics of the glider, uneconomical engine
2	11...20	The aerodynamic scheme is not optimal in terms of fuel economy, significant fuel consumption
3	21...30	Significant aerodynamic quality, moderate fuel consumption
4	31...40	Optimal aerodynamic scheme, to ensure high fuel economy. Significant range and duration of operation, new technologies implemented
5	41...50	Innovative materials, production technologies, advanced achievements in aerodynamics and engine construction have been implemented

**Conclusions**

1. The paper suggests a comprehensive indicator  $k_{ep}$  — the cost-effectiveness coefficient of UAV with turbojet engine, which determines the efficiency of the glider (due to aerodynamic quality) and the efficiency of the engine (due to  $C_{Pmin}$ ).

2. Unlike the current ones, the resulting figure is  $k_{ep}$ , allows the evaluation of the UAV with the minimum necessary information on its performance data, which allows the use of the requested methodological apparatus for the evaluation of the UAV already at the stages of its design, including the specification of the tactical and technical requirements.

3. The feasibility of the practical application of the indicator has been demonstrated on a group UAVs with turbojet engine, with the results indicating the validity of the proposed methodology.

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## МЕТОДИЧНИЙ ПІДХІД ДО ОЦІНКИ ЕКОНОМІЧНОСТІ БЕЗПІЛОТНОГО ЛІТАЛЬНОГО АПАРАТА З ТУРБОРЕАКТИВНИМ ДВИГУНОМ

При розробці та створенні нових зразків виникає необхідність оцінки їх ефективності та технічної досконалості вже на етапі попереднього проектування. Для безпілотних авіаційних комплексів (далі – БпАК) одним із напрямків такої оцінки може бути співвідношення обґрунтованих тактико-технічних вимог та очікуваних льотно-технічних властивостей перспективного зразка із характеристиками кращих аналогів. Проте, такі оцінки пов'язані із високим ступенем невизначеності на ранніх стадіях проектування безпілотних літальних апаратів БпЛА. Виникає питання апріорних оцінок із використанням багатокритеріальних підходів. При цьому, застосування багатокритеріальних методів оцінки складних технічних систем, як БпАК вимагає застосування великих масивів даних із суттєвими витратами часу, тому пошук та застосування комплексних показників оцінки, як пропонується у статті, вважається актуальним. У статті розглянуто питання комплексної оцінки технічної досконалості безпілотних літальних апаратів, що оснащені турбореактивною силовою установкою (далі – ТРД). Для цього обґрунтовано склад та зміст відповідного методичного апарату з оцінки економічності та комплексний показник технічної досконалості БпЛА із ТРД. На відміну від існуючих підходів, отриманий комплексний показник  $k_{ep}$ , дозволяє здійснювати оцінку БпЛА за мінімально необхідною інформацією про його льотно-технічні данні, що дозволяє застосовувати запропонований методичний апарат для оцінки БпАК вже на етапах його проектування.

Відповідно до запропонованого методичного апарату проведено фактичну порівняльну оцінку групи БпЛА з ТРД. Побудовано диференційну шкалу оцінки технічної досконалості БпЛА. Такий підхід, на думку авторів, дозволить підвищити достовірність порівняльних оцінок БпЛА з ТРД за мінімально необхідним масивом вихідних даних.

**Ключові слова:** безпілотний авіаційний комплекс, безпілотний літальний апарат, оцінка технічної досконалості, турбореактивна силова установка, льотно-технічні характеристики, дальність та тривалість польоту.

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## METHODOLOGICAL APPROACH TO EVALUATING THE COST-EFFECTIVENESS OF UNMANNED AERIAL VEHICLE WITH A TURBOJET ENGINE

During the design and construction of new products, it is necessary to evaluate their effectiveness and technical thoroughness already at the preliminary design stage. For unmanned aerial vehicle systems (hereinafter referred to as UAVs), one of the areas of such assessment can be the ratio of the overall tactical and technical requirements to the estimated flight and technical properties of the prospective model to the characteristics of the best analogues. However, such estimates are associated with a high degree of uncertainty in the early stages of UAV design. There is a question of a priori evaluations with the use of multicriteria approaches arises. At the same time, the use of multicriteria methods of evaluation of complex technical systems, such as UAVs requires the use of large amounts of data with significant time consumption, so the search for comprehensive evaluation indicators, as proposed in this article, is considered to be relevant. This article deals with the complex evaluation of the technical efficiency of unmanned aerial vehicles equipped with turbojet propulsion system (hereinafter — turbojet).

For this purpose, the composition and content of the relevant methodological apparatus for assessing efficiency and a comprehensive indicator of technical excellence of unmanned aerial vehicles with turbojet engines are substantiated. In contrast to existing approaches, the obtained comprehensive indicator allows to evaluate UAVs on the minimum necessary information about its flight data, which allows to use the proposed methodological apparatus for assessing UAVs already at the design stages. In accordance with the proposed methodological apparatus, the actual comparative assessment of the UAV group with turbojets was carried out. A differential scale for evaluating the technical perfection of UAVs has been constructed. This approach, in the opinion of the authors, will allow to increase the reliability of comparative evaluations of UAVs with turbojets for the minimum required amount of output data.

**Keywords:** airplane, unmanned aerial vehicle, technical excellence assessment, turbojet propulsion system, flight range and duration.

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