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METHOD FOR ESTIMATING THE SPATIO-TEMPORAL PERFORMANCE OF AN UNMANNED AERIAL VEHICLE DURING FLIGHT TESTS

Introduction

When conducting flight tests of UAVs, the assessment of individual parameters, such as: range and flight duration (space-time parameters) is associated with the involvement of a significant resource (time, space, material and technical, etc.), which often raises problematic questions regarding their implementation. In addition, obtaining values of a number of indicators, in particular, the flight characteristics of modern UAVs that fly only in an automated mode, is difficult, for example, determining the minimum flight speed, stall speed, controllability, maneuverability, etc.

At the same time, based on the analysis of UAV experience, some of the flight characteristics mentioned above are not fundamental and do not significantly affect the effectiveness of UAVs in performing their tasks (e.g., maximum, minimum speed, maximum flight altitude, etc.). On the other hand, in most cases, the customer usually puts forward fundamental and clear requirements to ensure the required range and duration of the flight. These indicators generally characterize the capabilities of the complexes to perform their intended tasks.

However, in the course of the tests conducted, for a number of UAVs, they were not fully evaluated (confirmed), including due to unfavorable test conditions, as well as space and time constraints, primarily the imperfection of the existing testing facilities.

Analysis of the latest research and publications

It should be noted that a large number of publications and research papers are devoted to the development of the theory of evaluation and synthesis of different classes of UAVs. For example, in works [1-5] the question of the methodological foundations of the synthesis of the development of modern unmanned systems, substantiated methodological approaches to the evaluation of the characteristics of the components of UAVs, proposed criteria and complex indicators for the comparative evaluation of UAVs of various purposes are considered. Works [6, 8] demonstrate the advantages of using a systematic approach to support decision-making in the early stages of development and creation of UAV samples.

Formulation of the problem

However, despite the created scientific basis, a number of problematic scientific issues remain unresolved, including the substantiation of rational methodological approaches to assessing UAV parameters during flight tests, maximum use of the testing base with minimal time and material resources with a sufficient level of reliability of the data obtained.

In view of the above, it is relevant to find ways to optimize the process of obtaining values of individual parameters during flight tests, including with the involvement of new scientific and methodological approaches. Obtaining (applying)

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complex indicators for assessing a number of characteristics (functioning parameters) under these conditions makes it possible to assess the required parameters with greater accuracy and efficiency, as well as to save time and resources during UAV testing.

The purpose of the article is justification, construction and analysis of practical implementation based on the results of a flight experiment, a methodical approach to the operational assessment of individual flight technical characteristics, first of all, the range and duration of flight during flight tests of UAVs. At the same time, an increase in the reliability of the obtained data is achieved due to the use of the proposed comprehensive indicator and saving material and time resources due to the optimization of the program of the corresponding test flights.

Presentation of the main research material

For a comprehensive assessment of the qualities of UAVs, it is proposed to use a comprehensive indicator of technical excellence (CITE) $k_{e,}$ for UAVs with various power plants [2, 3].

This analytically derived coefficient k_e takes into account and shows the interdependence of several determining parameters (range, flight duration, propeller efficiency and the sophistication of the power plant).

Taking into account the most widespread use of UAVs in the Armed Forces of Ukraine and their effective use during the Anti-Terrorist Operation, it is UAVs with electric propulsion systems (EPS) that are most commonly used in the ATO, we propose to consider the Class 1 – tactical – UAVs with EPS.

According to the previously obtained results of theoretical studies [2, 3] for UAVs with EPS k_e due to the maximum aerodynamic quality, $K_{\max}$ is calculated by the expression:

$$k_e = K_{\max} \cdot \eta_{eng}\, \eta_{pp}. \tag{1}$$

where: $K_{\max}$ – the maximum aerodynamic quality of the UAV; H_{eng} – Engine efficiency; η_{pp} – Propeller efficiency.

The dependencies of this coefficient k_e on the values of the maximum flight duration and range in an explicit form, which were obtained during previous studies, have the following form:

$$k_e = \frac{V_{eco} T_{\max}}{0{,}088 \bar{E}_{\max} k_{add} \xi_{etc}}; \tag{2}$$

$$k_e = \frac{9{,}81 L_{\max}}{\bar{E}_{\max} k_{add} \xi_{etc}}, \tag{3}$$

where: V_{eco} – economic flight speed of UAVs; $T_{\max}$ – the maximum duration of the UAV flight; $E_{\max}$ – maximum battery power; $K_{add} = 1 - E_{add}/E_{\max}$ – coefficient that estimates the permissible depth of discharge of the battery; $\Xi_{etc} = (1 - E_{etc}/E_{\max})$ – coefficient that estimates the permissible depth of discharge of the battery; $L_{\max}$ – the maximum flight range of the UAV.

Calculations of k_e using formulas (2, 3) should theoretically give the same result, although they are based on different sources of information. At the same time, expressions (2) and (3) allow us to find the value of k_e, and, accordingly, to assess the level of technical sophistication based on the data (characteristics) of UAVs, which are usually declared or specified [5, 6].

Table 1, as an example, shows the results of theoretical calculations of k_e for a group of well-known domestic and foreign UAVs of the first class [9].

It should be noted that the value of k_e can be determined quite closely by the average values of the parameters of formulas (2) and (3) during the test flight of the UAV for the maximum range and duration.

However, more accurate information is provided by the evaluation of individual parts of the flight profile, as was carried out by the authors during a flight experiment (FE) with a tactical UAV – the MARA-2M battlefield.

Table1

Calculation results k_e UAV

UAVs/ Characteristics	$T_{max,}$ hour	$L_{max,}$ km	$M_{toff,}$ kg	$V_{ek,}$ km/h	V_{cru} km/h	$U_{p,\ V}$	$U_{oc,\ V}$	$Q_{n,}$ Amh	$Q_{oc,}$ Amh	$\underline{E}_{n,\ W}$	K_e	K_e
Fly – I	2,3	180	11	68	72	50	36	9,8	2,6	36,0	13,6	13,6
Furia	2	120	7	55	60	12,5	11	32	15	33,6	10,3	9,7
MARA 2M	1,3	72	2,3	54	66	16,4	14	6,3	4	20,6	10,7	9,5
Patriot	1,8	80	3,5	50	60	16,0	14	8,2	3	25,5	11,1	8,6
DeViro	1,2	70	4,5	50	60	16,0	14	8,2	3	19,8	9,5	9,6

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During the tests of the specified UAV, the tasks of the flight experiment were:

- determining the maximum range and duration of the flight;
- assessment of the adequacy of the proposed complex indicator k_e and the methodology for its calculation;
- verification of the reliability of the results of calculation data obtained in the course of theoretical studies;
- verification of the reliability of the stated characteristics of the MARA-2M UAV according to the results of the flight experiment.

In order to obtain the initial information for the flight experiment (tests for maximum range and duration), it was necessary to determine in advance:

- the maximum amount of battery energy (determined during pre-flight training);
- coefficient Ξ_{etc} due to the energy consumption for auxiliary consumption (takeoff, optimal flight altitude, descent, etc. – obtained from onboard measuring devices) during the performance of the respective flight modes;
- coefficient K_{add} due to the residual (permissible) value of the battery energy after the flight (obtained from onboard measuring devices at the end of the flight);
- maximum battery energy reserve;
- efficiency factor based on the parameters of a stable flight section.

The data obtained during the test flight were processed as for the entire flight (Fig. 1 shows the data of measured characteristics by onboard recording devices for the entire evaluation flight), as well as in separate sections of Fig. 2, characterized by the stability of the flight mode and parameters with minimal influence of external factors (wind, change in the flight profile, etc.)

Calculations of the efficiency factor based on average range and flight duration parameters are often associated with incomplete initial data, as well as with distortion of their actual values.

In the presence of real UAVs, these data can be relatively easily obtained without special flight tests, and practically within the framework of regular operation, using standard onboard equipment, as shown in Fig. 2. In addition, the proposed methodology will provide additional information necessary for engineering and navigation calculations.

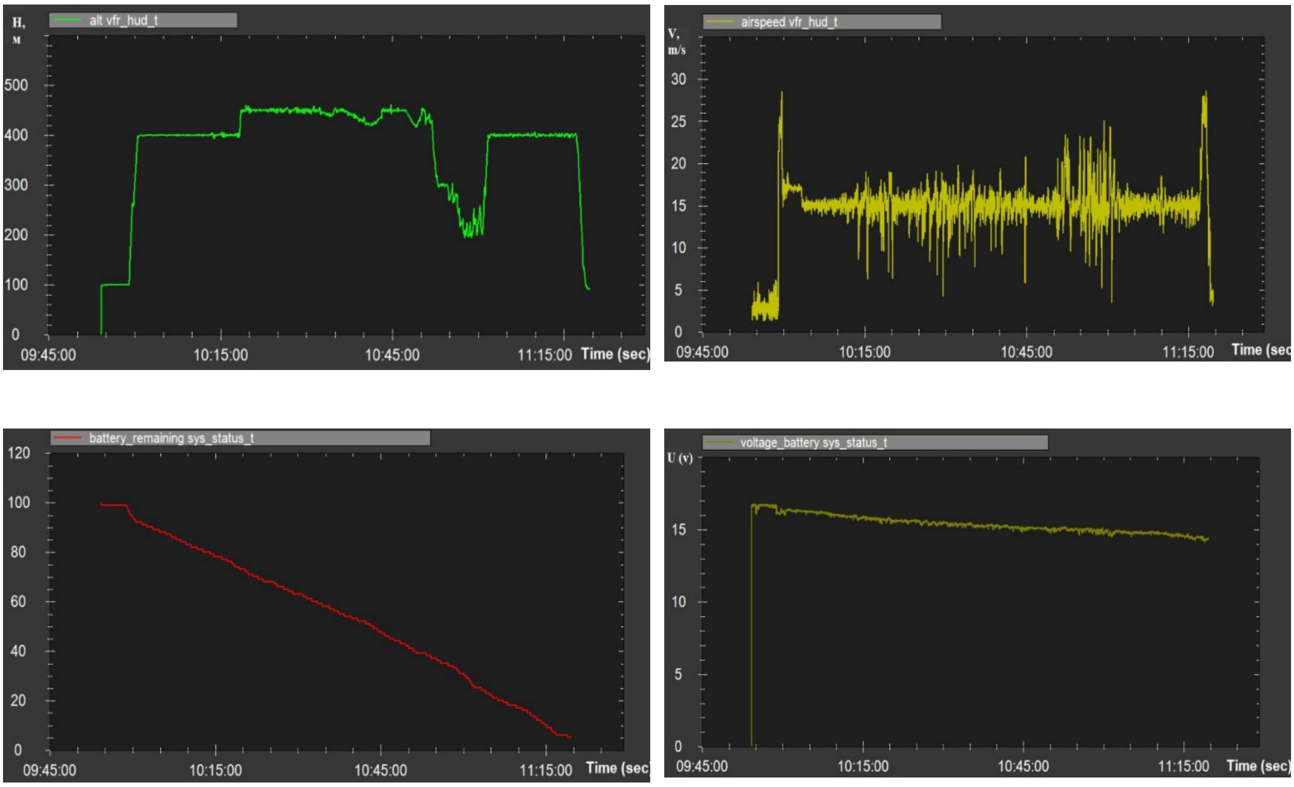

Fig. 1. Flight information (altitude, speed, remaining battery capacity, voltage)

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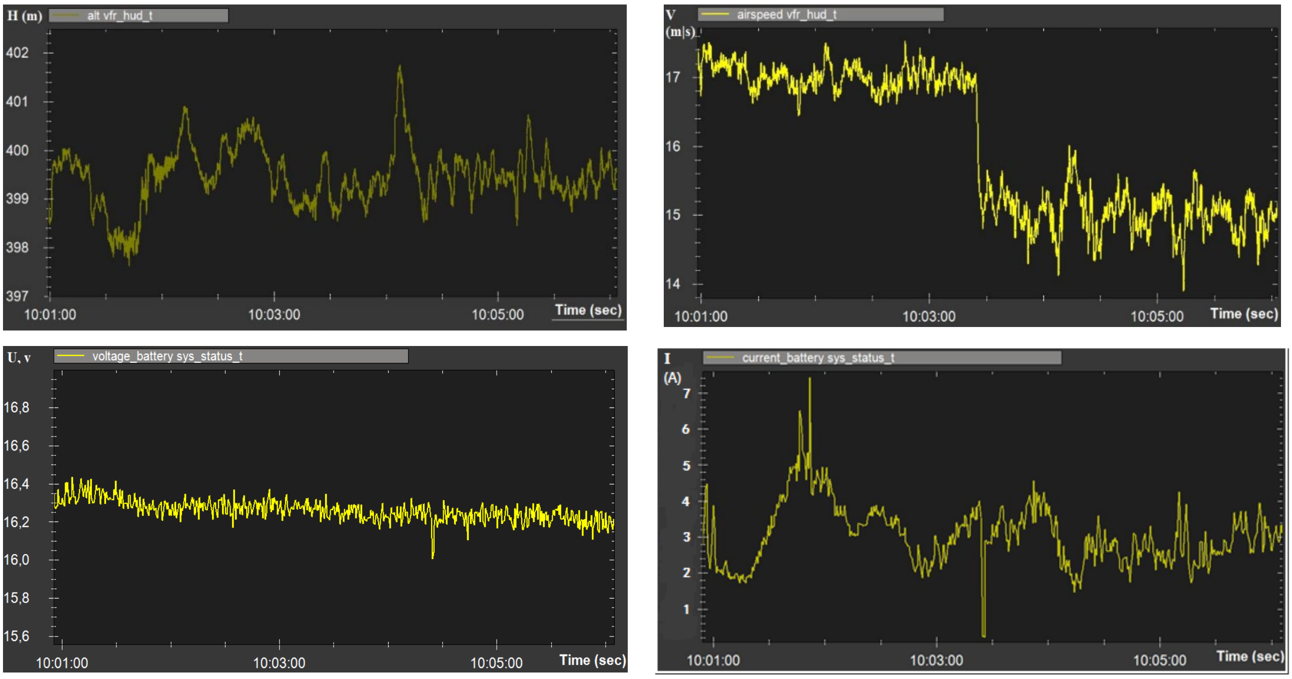

Fig. 2 Flight information of the selected section of the UAV test flight MARA-2M (altitude, speed, voltage, load)

Fig. 2 shows the data of measured characteristics by onboard recording devices for the flight stage selected for calculations. At this stage, the maximum values were obtained in the following areas $k_{e\ \max}$.

For example, to determine the efficiency factor, it is necessary to perform several tasks with the maintenance of modes, the so-called "platforms". Maintaining a certain speed and altitude in straight-line horizontal flight mode, the operator must keep them unchanged for 3–5 minutes, while also monitoring the normal overload at level 1 and the absence of roll (Fig. 2).

At the same time, the following is recorded over time

– flight parameters (altitude, speed, normal overload, roll angles);

– energy data (current I, voltage U) of the battery.

Since part of the electric energy is consumed not only to drive the propeller, but also to operate other onboard consumers (control systems, information transmission, camera operation, etc.), the effective current (load current) consumed by the engine to move the UAV in the air can be calculated as $I_{eng} = I\xi_{\text{etc}}$, where $\xi_{\text{etc}} = 1 - I_{\text{etc}}/I$, I_{etc} – current consumption of all UAV systems, except for the propeller drive, I – the total current of the battery, as measured by the on-board ammeter.

The value of the coefficient ξ_{etc} is determined experimentally for a specific UAV, taking into account the option of consumers of other types of energy.

On a number of devices, it is possible to directly measure and record the power of the current consumed by the engine I_{eng}, and power supply voltages U_{eng}, (Fig. 2), as in this case, which simplifies calculations and increases the accuracy of determining the final results. According to the records, "fields" are selected, on which the specified parameters are close to constant values (Fig. 2).

In the case of small short-term changes in the parameters, their averaging is carried out, which is used to calculate the power of the electric current $N_{eng1} = I_{eng}\,U_{eng}$ $[W]$ for a given speed V_1.

Next, the next "platform" is built (for the speed $V2$) (Fig. 2), and the following is calculated in the same way N_{eng2}. Etc. Based on the received data, a dependency graph is built $N_{eng}(V)$, which should have a minimum at economic speed $N_{eng\ \min}$., as shown in Fig. 3

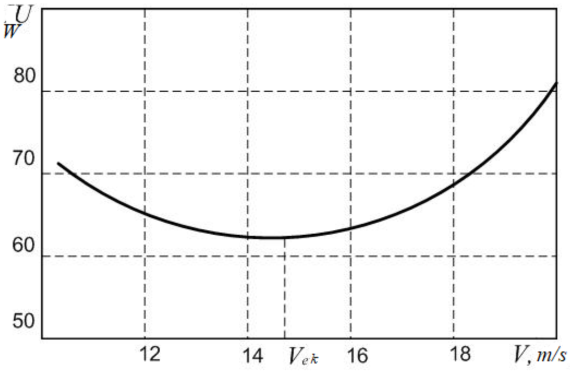

Fig. 3. Change in power consumption depending on the UAV flight speed

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The next step is to determine the minimum required power to move the UAV, taking into account energy losses in the engine and propeller

$$N_n = \frac{X_a V_k \left[\frac{m}{s}\right]}{\eta_{eng}\eta_{pp}} = \frac{gmV_k}{0{,}086 k_{\max}\eta_{eng}\eta_b} = \frac{mV_k \left[\frac{m}{s}\right]}{0{,}088 k_b}. \quad (4)$$

In stable flight, the required power must be equal to the minimum available power $N_{eng.\min} = I_{eng}U_{eng}$. From their equality, we find:

$$k_e = \frac{mV_k}{0{,}088(I_{eng}U_{eng})_{\min}}., \quad (5)$$

If an instrument is used for calculations (more precisely, an indicator V_i) speed, the resulting dependence will be the same for all altitudes to a first approximation. However, if the indicator speed is constant and the altitude increases, the actual airspeed will increase, which will cause a change in the propeller efficiency [10]. Therefore, for more accurate calculations, it is necessary to use the actual speeds $V = V_i(\rho_0/\rho)^{0.5}$.

However, UAVs with electric propulsion systems fly at low altitudes, when the indicator and actual speeds do not differ significantly, which simplifies calculations.

Results of calculating the coefficient k_e of the UAV under study based on the results of flight tests (results of direct measurements of flight parameters) according to expression (2) are shown in Table 2.

Table 2

The experimental values k_e

m_{toff}, kg	V, m/s	U, V	I, A	k_e
2,3	17	16,3	3	9,1
2,3	15	15	2,7	9,7
2,3	13	14,8	2,8	8,2

Conclusions

The presented calculations k_e of UAVs with electric propulsion using different approaches (theoretical calculation according to the appropriate methodology and experimental study) demonstrate the possibility of using this indicator to assess some flight characteristics of UAVs with electric propulsion during their flight tests.

The data obtained in this way (quantitative values of the indicators) allow to increase the reliability and efficiency, taking into account the limitations of the available testing facilities, of obtaining certain flight characteristics of UAVs during their flight tests.

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МЕТОД ОЦІНКИ ПРОСТОРОВО-ЧАСОВИХ ПОКАЗНИКІВ БЕЗПІЛОТНОГО ЛІТАЛЬНОГО АПАРАТУ ПРИ ПРОВЕДЕННІ ЛЬОТНИХ ВИПРОБУВАНЬ

В ході проведення льотних випробувань безпілотних літальних апаратів (БпЛА), оцінка окремих параметрів, таких як: дальність та тривалість польоту (просторово-часові параметри) пов'язана із залученням значного ресурсу (часового, просторового, матеріально-технічного, тощо), що часто викликає проблемні питання щодо їх реалізації. При цьому, у більшості випадків замовником, як правило висуваються принципові та чіткі вимоги щодо забезпеченням необхідних дальності та тривалості польоту.

Дані показники загалом характеризують можливості комплексів щодо виконання завдань за призначенням. Проте, в ході проведених випробувань, для ряду комплексів, вони не були повністю оцінені (підтверджені), у тому числі внаслідок несприятливих умов проведення випробувань, а також наявності просторово-часових обмежень, перш за все – недосконалості наявної полігонно-випробувальної бази.

Враховуючи зазначене, у статті обґрунтовано, побудовано та проведено аналіз практичної реалізації, на підставі результатів льотного експерименту, методичного підходу до оперативної оцінки окремих льотно-технічних характеристик, в першу чергу, дальності та тривалості польоту під час льотних випробувань БпЛА. При цьому, досягається підвищення достовірності отриманих даних за рахунок застосування запропонованого комплексного показника та економія матеріально часового ресурсу завдяки оптимізації програми відповідних тестових польотів.

Раніш запропонований комплексний показник - коефіцієнт технічної досконалості БпЛА, що одночасно враховує досконалість конструкції, аеродинамічної компоновки та економічності силової установки дозволяє здійснити перевірку достовірності отриманих, в ході льотних випробувань, значень параметрів максимальної дальності та тривалості польоту БпЛА

Наведено та порівняно теоретичний та практичний розрахунок (в ході льотного експерименту) коефіцієнту технічної досконалості БпЛА з електричною силовою установкою за експериментально отриманими характеристиками максимальних дальності та тривалості польоту.

Ключові слова: безпілотний літальний апарат, режим польоту, оцінка характеристик

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These indicators generally characterize the capabilities of complexes to perform tasks as intended. However, during the conducted tests, for a number of complexes, they were not fully evaluated (confirmed), including due to unfavorable conditions for conducting tests, as well as the presence of space and time limitations, first of all, the imperfection of the existing testing facilities.

Given the above, the article substantiates, builds and analyzes the practical implementation, based on the results of a flight experiment, of a methodological approach to the operational assessment of certain flight characteristics, primarily the range and duration of flight during UAV flight tests. At the same time, an increase in the reliability of the data obtained is achieved through the use of the proposed complex indicator and savings in material and time resources due to the optimization of the program of the relevant test flights.

The previously proposed complex indicator - the coefficient of technical perfection of the UAV, which simultaneously takes into account the perfection of the design, aerodynamic layout and efficiency of the power plant, allows to verify the reliability of the values of the parameters of the maximum range and duration of the UAV flight obtained during flight tests

The theoretical and practical calculation (during a flight experiment) of the coefficient of technical perfection of a UAV with an electric propulsion system based on the experimentally obtained characteristics of the maximum range and duration of flight is presented and compared.

Keywords: unmanned aerial vehicle, flight mode, performance evaluation.

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