Methodical Approach to the Development of a Mathematical Model for Calculating the Combat Potentials of Strike Unmanned Aircraft

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Abstract
The article considers the issue of assessing the combat potential of a strike unmanned aerial vehicle. An analysis of existing methods for assessing the combat potential of manned aircraft and found that they often use methods of expert assessment, which require a significant number of experienced experts and are quite time consuming. The scientific and methodical apparatus for calculations is given: probabilities of unmanned aerial vehicle damage for one departure and for a certain number of departures; mathematical expectation (average number) of combat sorties; mathematical expectation (average value) of the number of single targets hit in one combat flight by an unmanned aerial vehicle; the maximum value of the mathematical expectation (average value) of the relative number of single targets hit in one combat flight by an unmanned aerial vehicle; mathematical expectation of the number of single targets hit by an unmanned aerial vehicle; maximum mathematical value expectations of the number of single targets hit by an unmanned aerial vehicle for the entire period of life; the coefficient of combat potential of the unmanned aerial vehicle; the average combat potential of an unmanned aerial vehicle. The construction of a mathematical model of combat potentials of strike unmanned aerial vehicles based on a block-hierarchical approach is carried out. In this approach, the mathematical model of the modeling object is not represented as a function of many variables, but as a hierarchy of models of much smaller dimension. The basis for building a hierarchy of models is the physical content of the modeling object and the patterns it reflects.

Keywords
group of manned and unmanned aerial vehicles, combat potentials of unmanned aerial vehicles, indicators of combat effectiveness, unmanned aerial vehicle, methods of calculating combat potential.

1. Introduction

In the field of unmanned aerial vehicles, there is a transition from the single use of unmanned aerial vehicles (UAVs) to the group (mass) use in cooperation with manned aircraft. In addition to reconnaissance tasks and individual tasks of combat support of manned aircraft, strike tasks of UAVs are becoming increasingly important [1-6]. This raises the questions of the assessment of the combat potential (CP) of strike UAVs.

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The problem is that the methods of estimating of the CP of UAVs, which are similar to the methods of estimating of the CP of manned aircraft, have not found appropriate distribution. The known methods of estimating of the combat potential of the manned aircraft are based mainly on the methods of expert assessments [7-10,24]. This is a quite time-consuming process and requires the involvement of a significant number of experts with experience in combat use of aircraft. The application of such methods for a large number of existing and perspective UAVs is problematic and practically impossible to implement. Therefore, there is a need to develop approaches to the assessment of the CP of UAVs, which do not require the use of expert assessment methods.

Analysis of the recent researches and publications

In [7] it was noted that in the late 50s of the last century the military authorities had the need for a simple and clear way to compare different types of weapons to solve combat tasks and correctly calculate the balance of forces of the parties in operations. This was due to the fact that with the increase in the variety of weapons and their increasingly narrow specialization, it became almost impossible to determine the ratio of forces by the ratio of individual types of weapons. It was assumed that different types of weapons could be compared in terms of contribution to the end result of hostilities, and therefore each of them could be assigned a weight efficiency factor. Over time, this factor has been defined as the combat potential (CP) of the sample of armaments. CP of the sample of armaments could be considered as a criterion of the totality of samples of armaments for its contribution to the achievement of the objectives of an operation (hostilities).

Initially, the CP of armaments samples were determined either empirically, based on statistics obtained from past wars (armed conflicts) [7], or by methods of expert evaluation.

In the 80s years of the last century the methods of mathematical modeling of hostilities [8] began to be used to determine the CP. The special studies conducted on mathematical models of combat operations have revealed that there is no constant uniform measure of comparison of different types of weapons. CP of a sample of armaments – is a variable value and it is determined not only by its characteristics, but also by its quantity, structure of armaments of confronting groups, type of operation, quality of management, combat and other types of maintenance and by other operational factors.

The construction of mathematical models of aircraft CP, which take into account a fairly complete list of aircraft characteristics and conditions of their use, proved to be quite a problematic task. An alternative solution of this problem remains the methods of expert assessments.

The purpose of the article is to determine the approach to construction of a mathematical model for calculating the combat potential of a strike UAV without the involvement of expert or other "fuzzy" information.

2. Presentation of the main material

The difficulty of constructing analytical mathematical models for calculating the CP of aircraft functionally related to the characteristics of aircraft, their weapons and parameters of combat conditions, can be attributed to the non-integrability of the vast majority of systems of differential equations [11,23]. Including differential equations that adequately describe the fighting. Regressive mathematical models, which can be built on the basis of mathematical modeling data (numerical experiments) or expert survey data, have significant shortcomings and limitations [12]. They do not provide a full-fledged replacement for analytical models. In this article, the construction of a mathematical model of CP of UAVs is based on a block-hierarchical (decomposition) approach. In this approach, the mathematical model of the modeling object (CP of UAV) is not represented as a function of many variables, but as a hierarchy of models of much smaller dimensions. The basis for building a hierarchy of models, as will be noted below, is the physical content of the modeling object and the patterns it reflects [13].

The concept of "combat potential of a sample of weapons", judging by its various definitions [14,21], still remains controversial. Below, for example, there are two different definitions of "the combat potential of a sample of weapons".

Combat potential of a sample of weapons is an integral indicator that characterizes the maximum set of tasks performed by the sample weapons and military equipment (WME) for the intended purpose in the implementation of the limit tactical and technical characteristics (TTC) for the typical operating time in typical design conditions [15, 16,22].

The combat potential of a sample of weapons is an integral indicator that characterizes the maximum amount of combat tasks that can perform a sample of weapons for its functional purpose in the given (calculated) conditions of use during its existence [17,20].

In the definition [17,20], the most significant difference from the definition [15] is that the key feature is not a vague feature – the characteristic time, but the time of existence of the sample of weapons before its defeat. In particular, if the characteristic time is taken as a time interval that is less than the lifetime of the sample, the combat potential will be determined essentially by the fire performance or firepower of the sample. But the concept of "fire performance" reflects the meaning of a different indicator than "combat potential", because it does not take into account the ability of the weapon to survive in the face of the enemy and continue to function.

As shown in [13,14], the overall purpose of the operation of weapons at the highest level is divided into two partial tasks – the failure of enemy targets and maintaining the functioning of their own means. This follows from the basic law of armed fight. The indicator that describes the first task can be "fire performance" or "firepower" of the weapon. The indicator that describes the second task – "survivability". The other properties of the weapon are the means to achieve the main properties.

It is the indicator "combat potential of the sample of weapons", which combines the indicators of "firepower" and "survivability" should be used in conceptual research on the formation of basic requirements for UAVs on a complex criterion of "combat potential – cost".

The model of combat operations of reusable UAVs can be thought of as a series of repetitive combat sorties in each of which it hits a number of targets. Each subsequent flight can be performed provided that the previous ones were performed.

Suppose that in the process of performing a combat sortie UAV is exposed to fire from the enemy with an intensity of λ, which leads to its defeat in one sortie with probability P_{UAV1} [18,19]. Assuming the Poisson nature of fire effects, this probability is determined by:

$$P_{UAV1} = 1 - e^{-\lambda P_1 t_{cf}} \quad (1)$$

where P_1 – conditional probability of the sample damage under one exposure;

t_{cf} – duration of the combat flight

The number of combat sorties that a UAV can perform before its defeat is a random variable. When performing n combat sorties UAV will be struck with a probability of W_n:

$$W_n = 1 - (1 - P_{UAV1})^n \quad (2)$$

Mathematical expectation (the average number) of combat sorties is determined by the ratio of this probability to the probability of defeat in one combat sortie:

$$\bar{n} = \frac{1 - (1 - P_{UAV1)})^n}{P_{UAV1}} \quad (3)$$

For multiple UAVs n>>1 i $\overline{\mathrm{n}}$ and is reduced to the inverse probability P_{UAV}:

$$\bar{n} = \frac{1}{P_{UAV1}} \quad (4)$$

The mathematical expectation (average value) of the number of single targets hit in one UAV combat flight is determined by the number of successful target attacks during the combat flight. It is limited by the number of means of destruction in combat charge. It is assumed that the ammunition of the aircraft consists of the same type of means of destruction, and launches on one target is carried out by only one means of destruction. This simplification is not fundamental and allows you to reduce the recording of basic expressions in the article. Expression for mathematical expectation (average value) of the relative number of single targets hit in one UAV combat flight:

$$\frac{M\left[N_{PT_{ij}}^k\right]}{N_{T_{ij}}^k} = P_{PT_{ij}} \cdot P_{T_{ij1}} \cdot m_i^k \quad (5)$$

where $N_{PT_{ij}}^k$ – the number of single potential targets of the j-type, hit in the k-combat flight of the UAV by means of the i-type;

$M\left[N_{PT_{ij}}^k\right]$ – mathematical expectation of the number of single targets of the j-type, struck in the k-combat flight of the UAV by means of the i-type;

$P_{PT_{ij}}$ – the probability of fulfilling the conditions preceding the launch (reset, etc.) of the means of defeat of the i-type on the target of the j-type: detection and recognition of the target by external means, long-range guidance, target detection by own means of UAVs, target attack. Depending on the problem to be solved and the method of using the UAV, the composition of the stages of preparation for the launch of the means of destruction may differ from the above. For example, in the case of an autonomous method of UAV application, the stages of external targeting may be absent, and target detection and recognition may be carried out by its own means;

$P_{T_{ij1}}$ – the probability of defeat by one means of defeat of the i-type of the j-type target;

m_i^k – the number of means of defeat of the i-type AV used in the k-combat flight;

The maximum value of the mathematical expectation (average value) of the relative number of single targets hit in one combat flight of UAVs is determined by the expression:

$$max\frac{M\left[N_{PT_{ij}}^k\right]}{N_{T_{ij}}^k} = P_{PT_{ij}} \cdot P_{T_{ij1}} \cdot m_{MD_i}^k \quad (6)$$

where $m_{MD_i}^k$ – the total number of means of defeat of the i-type aircraft, used in the k-combat flight.

For the entire period of the UAV's life, ie during $\bar{n}$ combat sorties, the mathematical expectation of the number of single targets hit by the UAV:

$$M\left[N_{T_{ij}}\right] = \sum_{k=1}^{\bar{n}} M\left[N_{T_{ij}}^k\right] \quad (7)$$

The maximum value of the mathematical expectation of the number of single targets hit during the entire life of the UAV, ie during $\bar{n}$ combat sorties by definition is the UAV CP as to destruction by i-type means of the j-type targets:

$$CP_{UAV_{ij}} = max\sum_{k=1}^{\bar{n}} M\left[N_{PT_{ij}}^k\right] = N_{T_{ij}} \cdot P_{PT_{ij}} \cdot P_{T_{ij1}} \cdot \bar{m}_{MD_i} \cdot \bar{n} \quad (8)$$

or

$$CP_{UAV_{ij}} = max\sum_{k=1}^{\bar{n}} M\left[N_{PT_{ij}}^k\right] = \bar{N}_{T_{ij}} \cdot P_{PT_{ij}} \cdot P_{T_{ij1}} \cdot \frac{P_{T1_{ij}}}{P_{UAV1}} \bar{m}_{MD_i} \quad (9)$$

where $\bar{m}_{MD_i}$ – the average value of the number of means of aircraft destruction (combat kits) of i-type on departures;

$\bar{N}_{T_{ij}}$ – the average number of single potential targets of the j-type, affected by means of the i-type on departures.

If the CP of UAV is already known, which can be taken as a reference, it is more convenient to use the CP coefficient instead of the CP. It is determined by the ratio of the CP of UAV to the reference CP of UAV. It is assumed that UAVs are used in similar conditions. In this case, expression (9) is simplified because the variables $N_{T_{ij}}$ are reduced:

$$K_{CP\,UAV_{ij}} = \frac{P_{PT_{ij}}}{P_{PT_{ij}}^{REF}} \cdot \frac{P_{T1_{ij}}}{P_{T1_{ij}}^{REF}} \cdot \frac{P_{UAV1}}{P_{UAV1}^{REF}} \cdot \frac{\bar{m}_{MD_i}}{P_{MD_i}^{REF}} \quad (10)$$

The CP coefficient has a clear physical meaning. It is reduced to the product of the ratios of the indicators of effectiveness of the destruction means, the number of means in the ammunition and the inverse ratio of survivability.

Model (10) can be applied during researches at the initial stages of UAV creation (external design) when searching for a design compromise between the combat potential and the cost of UAVs.

To optimize (select) the options of technical and design solutions of UAVs, it is necessary to use the dependences of the generalized indicators $< P_{PT_{ij}}, P_{T1_{ij}}, P_{UAV1}, \bar{m}_{MD_i} >$ of the TTC of UAVs. Such dependences should be considered as components of mathematical models of CP.

$K_{CP\,UAV_{ij}}$ in (10) is an element of the matrix, where the types of means by which the UAV will hit the enemy's targets are indicated in the lines, and the types of targets - in the columns.

The matrix (10) is similar to the matrix of efficiency of application of different models of weapons in different conditions. The use of the data contained in the matrix (10) depends on the objectives of research and the method of decision-making based on them.

For example, in comparing $K_{CP\,UAV_{ij}}$ of different UAVs, several different approaches can be used to select the best option.

The simplest approach is to collapse the matrix (10) into a scalar quantity. Then the average CP of UAV is determined:

$$\bar{K}_{CP\,UAV} = \frac{1}{M \cdot N} \cdot \sum_{i=1}^{N}\sum_{j=1}^{M} \alpha_i \cdot \beta_j \cdot K_{CP\,UAV_{ij}} \quad (11)$$

where N – the number of types of UAVs destruction;

M – number of types of targets.

α_i – weight factor that determines the relative frequency (probability) of use of weapons of the i-type, $\sum_{i=1}^{N} \alpha_i = 1$;

β_j – weighting factor that determines the relative part (probability) of the targets of the j-type that will be affected, $\sum_{j=1}^{M} \beta_j = 1$.

Weight multipliers α_i, β_j are determined by the typical composition of enemy targets and weapons of strike UAVs [10].

With a more detailed approach, it is possible to make comparisons when folding the matrix (10) into a vector or without folding. In this case, the problem is reduced to a comparison of a set of criteria [18]. When folded into a vector column, it is assumed that the weapon of the i-type is used for all targets:

$$\overline{K}_{CP\,UAV} = \frac{1}{M} \cdot \sum_{j=1}^{M} \beta_j \cdot K_{CP\,UAV_{ij}} \qquad (12)$$

When folded into a vector-line, it is assumed that the entire weapon is used only for targets of the j-type:

$$K_{CP_{UAV}} = \frac{1}{N} \cdot \sum_{i=1}^{N} \alpha_i \cdot K_{CP\,UAV_{ij}} \qquad (13)$$

Obviously, $K_{CP\,UAV_{ij}}$ reaches its maximum value when using ammunition to hit targets of the same type with maximum efficiency.

3. Conclusions

To select options for technical and design solutions of unmanned aerial vehicles, it is necessary to use the dependences of generalized indicators: the probability of fulfilling the conditions preceding the launch (reset) of a certain type of destruction means for the determined target, ie detection and recognition of targets by external means, long-range guidance, target detection by own means of a UAV, target attack; the probability of defeat by one means of defeat of a certain type of a certain type of a target; the probability of a UAV damage in one flight; the average value of the number of means of destruction of unmanned aerial vehicles (combat kits) of a certain type by departures from the tactical and technical characteristics of the unmanned aerial vehicle. Such dependences should be considered as components of mathematical models of CP.

The considered methodical approach to development of mathematical model of combat potential of strike UAVs allows to build mathematical models for conducting researches of military and economic efficiency of strike unmanned aerial vehicles without involvement of expert or other “fuzzy” information.

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