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Mathematical model and algorithm for evaluating the effectiveness of the on-board weapon control radar stations in the conditions of obstacles and countering them in air combat

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Abstract. The development and practical implementation of new methods of active counteraction to enemy interference stations in air combat necessitate considering their impact on the overall efficiency of airborne radar weapons control stations, which requires improving existing mathematical models for describing their functioning in conditions of interference and simultaneous active counteraction. In the article, the author describes an improved mathematical model for assessing the effectiveness of airborne radar weapons control stations in air combat to ensure the survivability of a fighter aircraft and its reliable performance of a combat mission. The analysis of modern airborne radar systems and active interference stations as objects of mathematical modelling, methods of active counteraction to enemy airborne interference stations and existing mathematical models of the functioning of airborne radar weapons control stations is carried out. The initial data on the mathematical modelling of the functioning of airborne radar weapons control stations in conditions of interference with simultaneous counteraction to enemy interference stations are formed and the selected air combat situation is presented, which is subject to mathematical description. Indicators and criteria characterizing the effectiveness of the functioning of airborne weapons control radar stations have been selected, the main of which is the limitation on the range of their use depending on the method of counteraction used. Preliminary calculations have been made regarding the use of these methods of active counteraction. Considering the peculiarities of using methods of counteracting enemy stations, it is proposed to divide the cycle of air combat between aircraft into 5 stages depending on the distance between them. An algorithm for justifying the choice of methods of countering enemy interference stations, considering the range between aircraft for continuous target tracking, is developed and the probability of target tracking is determined, considering the use of various combinations of countermeasures. For a qualitative and complete assessment of the effectiveness of the functioning of airborne radar weapons control stations, it is proposed to use fuzzy sets and game theory, which are used to build a mathematical model for assessing the effectiveness of airborne radar weapons control stations in terms of countering enemy interference stations, which

was used to develop an algorithm and select the most effective combination of countermeasures.

Keywords: efficiency of functioning, weapon control, mathematical modelling, interference station.

Introduction

The experience of local wars and conflicts shows that aircraft without electronic warfare equipment have very low survivability. The use of active interference stations for individual protection (AISIP) on aircraft brings the probability of not hitting an aircraft in an air battle to 45-75%, and the integrated use of electronic warfare (EW) equipment can bring this probability to 80-95%. Thus, due to the importance of the tasks performed by onboard electronic warfare equipment and their effectiveness, the issue of electronic countermeasures to electronic warfare equipment itself - the so-called counter-radio-electronic countermeasures (CREM) - has recently been increasingly studied.

Today, there are several ways to counteract AISIP systems, the use of which is random. However, the analysis of their use shows that most methods of active counteraction have different conditions of use, which are associated with changes in the operation of onboard weapon control radars (WCRs), which imposes restrictions on their range of use.

The development and practical implementation of new methods of active counteraction to enemy interference stations in air combat necessitate considering their impact on the overall efficiency of the WCRs functioning, which in turn necessitates the improvement of existing mathematical models for describing the functioning of WCRs in conditions of interference and simultaneous active counteraction to them.

Therefore, for the further development of electronic countermeasures against enemy interference stations, it is necessary to improve mathematical models for assessing the effectiveness of the WCRs both in conditions of interference and simultaneous countermeasures to form a clearly defined algorithm for applying the developed and practically implemented countermeasures. Given the above, the purpose of the article is to develop an improved mathematical model for assessing the effectiveness of the WCRs in air combat.

Methodological Framework

Recent studies and publications on the subject under consideration (Androsov and Kutakhov, 1996), (Semenenko, 2015), (Semenenko, Vodchyts, Dobrovolskyi, 2011), (Vasilevich, 1989), (Semenenko, Kablukov, Mironenko, Dobrovolskyi, 2019), (Perunov, Matsukevych, Vasilev, 2010), (Semenenko, Kablukov, Chernega, 2019), (Semenenko, Sorokin, Dobrovolskyi, Kablukov, 2019), (Vasilevich, 2000) show that the vast majority of mathematical models describing the processes of interaction between EW and radar means are designed to assess the effectiveness of the functioning of the WCRs in conditions of interference without active counteraction to them (Androsov and Kutakhov, 1996), (Semenenko, 2015), (Semenenko, Vodchyts, Dobrovolsky, 2011).

Special cases are models that allow to assess the effectiveness of the use of certain passive means of protection of WCRs against certain types of interference (Vasilevich, 1989), (Semenenko, Kablukov, Mironenko, Dobrovolsky, 2019), (Perunov, Matsukevich, Vasilev, 2010).

The works (Semenenko, Kablukov, Chernega, 2019), (Semenenko, Sorokin, Dobrovolskyi, Kablukov, 2019) are devoted only to methods of active counteraction to CREM, which have different conditions of their application and are associated with changes in the operation of WCRs, which imposes restrictions on their range of use.

In (Vasilevich, 2000), the author notes that the process of confrontation in air combat between WCRs and AISIP occurs under conditions of stochastic uncertainty of the interference situation due to the lack of complete information about the conduct of CREM, the characteristics of enemy AISIP,

unknown conditions of air combat, and the lack of practical assessments of radar interference protection during CREM at certain stages of combat.

In the process of confrontation in the air battle between the WCRs and the AISIP, there are a number of software engineering methods for estimating software costs (Kirsanov, Sahun, 2014), (Potrap, Krivonozhko, 2022), (Andon, Ignatenko, Sinitsyn, Slabospytska, 2016), (Official website of the Center for Systems and Software Engineering at the University of Southern California, 2022), (Information technology - Software measurement - Functional size measurement - Part 1: Definition of concepts ISO, 2022), (Koregin, Chick, 2020).

The authors propose a classification of such methods, according to which they are divided into empirical and analytical. Empirical methods are based on empirical statements, principles, and assumptions formed based on targeted research, observation of software development projects, and measurements of its individual quantitative characteristics related to cost. Analytical methods are based on the use of analytical expressions, analytical models that describe the dependence of quantitative characteristics of software and the cost of its development According to the classification proposed by the authors, empirical methods are classified as follows:

the method of expert evaluation, in which the software cost is estimated by an individual specialist (expert) or a group of experts with relevant experience and data on previous similar projects, the capabilities of development companies, scientific achievements and scope of application in relation to software, the use of several methods of cost calculation;

analogies method, which involves comparing with similar projects in the field of developing software for the process of confrontation in air combat of the WCRs and the AISIP defence system; the result is an adjusted value that is estimated taking into account quantitative and qualitative differences;

Parkinson's estimation, a method based on Parkinson's law - the amount of work increases to the extent necessary to take the time allocated for its completion. According to this law, the effort spent on work is distributed evenly over the time allocated to the project. The criterion for estimating the cost of software for the air combat process of the WCRs and the AISIP air defence system is human resources;

The Price-to-win method is based on the principle that the client is always right. The essence of the method is that regardless of the estimated real costs of project development, the cost of the software depends on the customer's budget, not on the functional characteristics of the software for the air combat process of the WCRs and the AISIP air defence system being developed.

To conduct a comparative analysis of methodological approaches, we have chosen a procedure consisting of the following stages (Surmin, 2006), (Gusak, Kirsanov, Ostrovsky, 2021):

defining the purpose of the comparative analysis;

selection of methodological approaches for comparative analysis;

studying methodological approaches, collecting the necessary information about their advantages and disadvantages, and the differences between them;

defining criteria (indicators) for comparative analysis;

conducting a comparative analysis based on certain criteria (indicators);

formulation of conclusions (recommendations) based on the results of the comparative analysis.

The purpose of the comparative analysis of methodological approaches to estimating software development costs is to develop recommendations for choosing a methodological approach that can be used to justify the costs of software development for the needs of the Armed Forces of Ukraine.

The fourth stage of the methodological approach involves substantiating the procedure for implementing the process of managing C4ISR troops in an air combat confrontation between WCRs and the AISIP air defence systems (Husak, Kirsanov, Ostrovsky, 2021).

At this stage, we consider the peculiarities of building and functioning of the C4ISR type from the cybernetic point of view, namely, regarding:

Ensuring the focus (clear implementation of a specific goal) of management;

use of cause-and-effect and feedback relationships between elements (automated control systems and their complexes);

considering the impact on the elements of the external environment (enemy actions, physical and geographical conditions of the area of operation), which leads to the stochastic nature of the process of commanding troops;

the exchange of information between elements as a prerequisite for its functioning and integrity;

the dynamic nature of the management process carried out in (constant change of state over time in accordance with the intensity of the flow of information that comes out at each stage of the troop management cycle).

To achieve compatibility of the structures of the Armed Forces of Ukraine with the relevant structures of NATO member states, in June this year, the NATO Secretary General signed the updated NATO-Ukraine Partnership Goals 2021 (NATO UNCLASSIFIED, 2021). The goal of G 1000 is the need to train and evaluate units of the Armed Forces of Ukraine that may be assigned to participate in multinational operations, including NATO-led operations, in accordance with NATO concepts, doctrines, standards and procedures.

Thus, a comparative analysis of approaches to assessing the command-and-control bodies (CCB) of the Armed Forces of Ukraine and the NATO Joint Forces is an urgent scientific task.

The analysis of recent studies and publications shows that there are several approaches to assessing the CCB of the Armed Forces of Ukraine and the NATO Allied Forces, as set out in the methods, instructions, guidelines, doctrines, manuals, and standards of the NATO Allied Forces (Handbook “Operational capabilities concept evaluation and feedback (OCC E&F) program”, 2020), (Allied Command Operations Forces Standards Volume VII, 2020). At the same time, each of the approaches to assessing CCB has its own significant differences.

However, there are no studies and publications on assessing the level of compliance of the Ukrainian Armed Forces' guiding documents with the NATO Allied Forces’ guiding documents, on assessing the CCB, or the results of a comparative analysis of the approaches to assessing the CCB of the Ukrainian Armed Forces and the NATO Allied Forces.

On this topic (Komarov, 2019), (Pat. 109226, Komarov, Tkachenko, Galushka, 2016) shows that most of the literature covers statistical methods of analysis and diagnosis of aircraft, but when considering these issues, no attention is paid to cases of aircraft reliability.

Almost no attention is paid to the use of methods and approaches to controlling the frequency of natural oscillations when choosing a method of aircraft restoration, as well as to methods for determining the safety margin of combat aircraft based on the analysis of dynamic characteristics.

Results and Discussions

The structural and logical scheme of the application of the improved mathematical model for evaluating the efficiency of the WCRs consists of five stages.

At the first stage, the initial data on modelling the functioning of the WCRs in conditions of interference and countering enemy AISIP were formed. An air combat situation subject to mathematical description was chosen (Fig. 1), as well as four methods of CREM used to counteract enemy interference stations, namely:

Methods 1 and 2 – “Counteracting the enemy’s active interference station by changing the polarization of the signal at the reception of the WCRs”;

Method 3 – “Counteracting the enemy's active interference station by changing the power of the irradiating signal of the WCRs”;

Method 4 – “Counteracting the enemy's active interference station by disrupting the irradiation regularity”.

At the second stage, we selected indicators and criteria (Table 1) that characterize the efficiency of the WCRs functioning, considering which we made preliminary calculations.

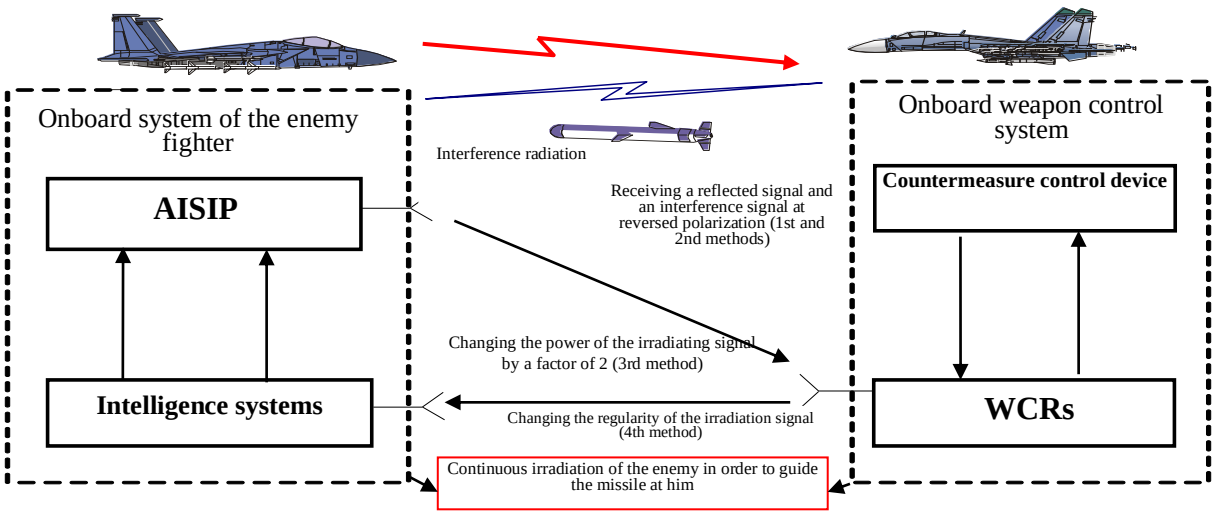


Figure 1. Air combat situation

Table 1: Performance indicators of WCRs in conditions of interference

Indicators and criteria	Without considering the enemy's countermeasures	Considering the enemy's counteraction to the AISIP
Target detection range	$D_{\max} = \sqrt[4]{\frac{N_c G_c G_n \sigma_ц \lambda^2}{64 \pi^3 N_{c\,вх}}}$,	$D = \sqrt[4]{\frac{N_c G_c \lambda^2 G_n \sigma_ц}{64 \pi^3 N_{c\,вх}} \cdot \cos^2 \Delta\beta}$
Range of application of the continuous direction-finding mode	$D_{РБП} = \beta \cdot D_{\max}$, $\beta = f\begin{pmatrix} W_{XT} = 0{,}5\left[1-\Phi(q_0)\right], \\ W_{ПВ} = \left[1+\Phi(q-q_0)\right] \end{pmatrix}$	does not change
Signal-to-noise ratio at the input of the ultrasonic radar receiver	$\frac{N_{c\,вх}}{N_{n\,вх}} = \frac{N_{c\,вх} G}{\left(N_{n\,вх} + N_ш\right) G^k}$	$\frac{N_{c\,вх}}{N_{n\,вх}} = \frac{N_{c\,вх} \cdot G + N_n \cdot G \sin^2 \Delta\beta}{\left(N_{n\,вх} + N_ш\right) \cdot G^k \cos^2 \Delta\beta}$
The power of the useful signal at the input of the receiver of the ultrasonic radar	$N_{c\,вх} = \frac{N_c G_c}{4\pi D^2} \frac{\sigma_ц}{4\pi D^2} \frac{\lambda^2 G_n}{4\pi}$	$N_{c\,вх} = \frac{N_c G_c}{4\pi D^2} \cdot \frac{\lambda^2 G_n}{4\pi} \cdot \frac{\sigma_ц}{4\pi D^2} \cdot \cos \Delta\beta \pm$ $\pm \frac{N_n G_c}{4\pi D^2} \cdot \frac{\lambda^2 G_n}{4\pi} \cdot \frac{\Delta f_{прм}}{\Delta F_n} \cdot \alpha \cdot \sin \Delta\beta$
Radar suppression coefficient	$\frac{N_n G_n}{N_c G_c} \frac{\Delta f_{ПРМ} 4\pi \alpha F_c(\theta_ц, \beta_ц)}{\Delta F} \cdot D^2 \geq K_n$	$K_n \geq \frac{N_{n\,вх} G^k \cos \Delta\beta}{N_{c\,вх} G \cos \Delta\beta + \alpha N_{n\,вх} G \sin \Delta\beta}$
Probabilities of target tracking	$P_{зриву} = 1 - \prod_{i=1}^{4}(1-P_i)$;	$P'_{зриву} = 1 - \prod_{i=1}^{4}\left(1-k_i^{пр} P_i\right)$
	$P_{супр} = 1 - P_{зриву}$ - is chosen as a criterion for the efficiency of radar operation	

where N_c ($N_{c\,вх}$) is the power of the transmitter signal and the signal at the antenna input; G_c (G_n) is the maximum gain of the WCRs and the AISIP antennas; λ *is the* operating wavelength; $\sigma_ц$ is the effective scattering plane of the target; $\Delta\beta$ *is the* angle of change of the polarization plane; W_B is the detection probability; W_{XT} is the false alarm probability; $\Delta f_{прм}$ is the radar receiver bandwidth; ΔF_n is the emission band of the interfering signal; F_c ($\theta_ц$,$\beta_ц$) is the normalized radiation pattern of the antenna by the radar power; α is a coefficient that takes into account the polarization mismatch between the antenna of the WCRs and the AISIP to be suppressed; K_n is the suppression coefficient; $P_{зриву}$ is the probability of disruption; $P_{супр}$ is the probability of target tracking; $k_i^{пр}$ is the countermeasure effectiveness coefficient.

Source: developed by the author based on (Semenenko, Vodchyts, Dobrovolsky, 2011), (Semenenko, Kablukov, Myronenko, Dobrovolsky, 2019), (Semenenko, Kablukov, Chernega, 2019), (Semenenko, Sorokin, Dobrovolsky, Kablukov, 2019).

Limitations on the use of the selected methods of active counteraction were calculated, the main criterion for limitation being the range of their use depending on the method of CREM used.

The calculations show that when using the 1st and 4th methods, the maximum range is reduced by 4%; when using the 2nd or 3rd methods, by 16%; and when using all four methods, by 20%.

The criterion for the effectiveness of radar operation in conditions of interference and simultaneous counteraction to them is the probability of tracking the target (Table 1).

To improve the efficiency of the functioning of airborne radars, it is necessary to revise the sequence of air combat, considering the peculiarities of the use of methods of electronic countermeasures against enemy interference stations. Therefore, it is proposed to divide the air combat cycle between aircraft into 5 stages depending on the range (Fig. 2).

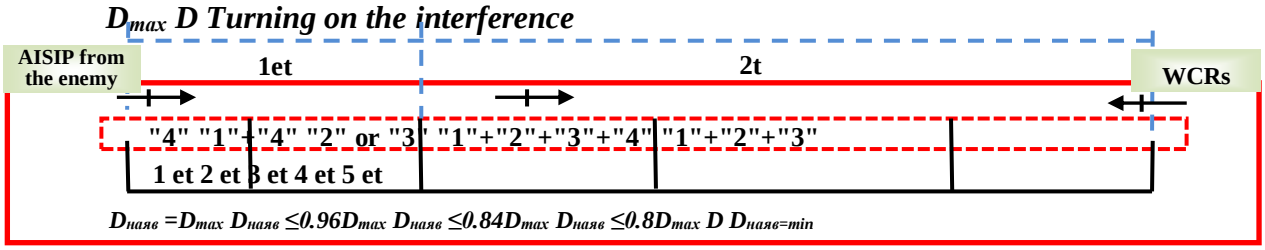


Figure 2. Stages of air combat

Next, an algorithm was developed to justify the choice of methods for countering enemy interference stations for continuous target tracking, considering the range between aircraft. The probabilities of tracking the target are also determined, considering the use of various combinations of countermeasures and the corresponding countermeasure coefficients (Fig. 3).

The developed algorithm improves the existing approach to the functioning of the onboard WCRs in terms of the probability of tracking the target in the conditions of application of the proposed methods of counteracting enemy interference stations and considering the limitations of their use.

For a qualitative and complete assessment of the effectiveness of the WCRs, it is proposed to use fuzzy sets and game theory. The use of fuzzy scales is caused by the lack of clear assessments of the effectiveness of the use of various types of interference and ways to counter them, as well as the natural uncertainty of air combat [9]. In an air battle, there are situations in which possible strategies for the use of enemy AISIP are known, but it is not known which of the known strategies is currently in place, that is, data on the types of fighter aircraft and countermeasures installed on these aircraft, as well as options for their use, may be known, but it is not known at this time what types of interference it is currently creating, whether the AISIP is turned on at all and further options for continuing the battle.

Figure 4 shows a mathematical model for assessing the effectiveness of the WCRs in air combat, which was used to develop the algorithm and select the most effective combination of countermeasures. In our opinion, it is advisable to present the mathematical model for assessing the effectiveness of the operation of the WCRs in the conditions of interference and simultaneous counteraction to the AISIP in the form of a fuzzy matrix game, which is the most adequate to describe such a situation with regard to the WCRs of a fighter aircraft and the enemy's AISIP in the conditions of their active counteraction. The proposed mathematical model makes it possible to assess the effectiveness of the WCRs in the conditions of interference and simultaneous counteraction to them and has the form of an effectiveness matrix $|a_{ij}|$, where the elements of the matrix are a_{ij} - fuzzy estimates of the effectiveness of the WCRs, namely, indicators of the probability of tracking the target for each of its decisions to apply countermeasures A_i and each state of the environment B_j regarding the emission of interference by the AISIP.

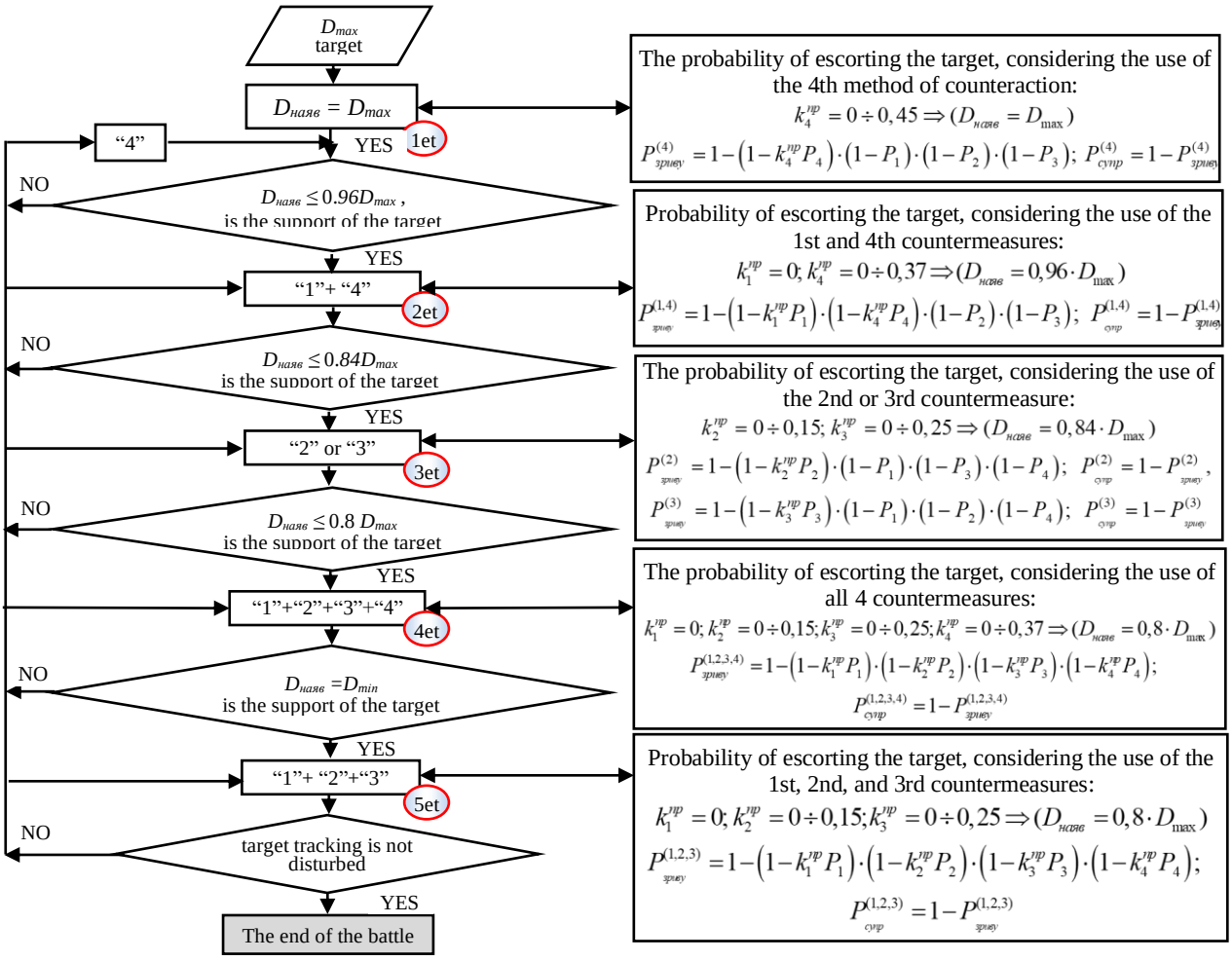


Figure 3. Algorithm for justifying the choice of countermeasures

$$A = \left\| a_{ij} \right\| = \begin{matrix} & B_1 & B_2 \\ A_1 & a_{11} & a_{12} \\ A_2 & a_{21} & a_{22} \end{matrix} = \begin{vmatrix} \{0,65;0,7;0,75;0,8\} & \{0,15;0,2;0,25;0,3\} \\ \{0,05;0,1;0,15;0,2\} & \{0,8;0,85;0,9;0,95\} \end{vmatrix}$$

solution by the approximate (iterative) method

$$S_A \approx \left|\frac{15}{30};\frac{15}{30}\right|,\quad p_1 = \frac{m^*_i}{n_\Sigma} = 0,5;\quad p_2 = \frac{m^*_i}{n_\Sigma} = 0,5,\ S_B \approx \left|\frac{11}{30};\frac{19}{30}\right|,\quad q_1 = \frac{n^*_i}{n_\Sigma} = 0,37;\quad q_2 = \frac{n^*_i}{n_\Sigma} = 0,63.$$

$$\nu_A = \frac{\alpha+\beta}{2} \approx \frac{\alpha \sum_{\min} + \beta \sum_{\max}}{2 \cdot k} \approx \{0,42;0,47;0,52;0,57\}$$

Figure 4. Mathematical model for assessing the efficiency of radar operation

The proposed mathematical model makes it possible to assess the effectiveness of the WCRs in the conditions of interference and simultaneous counteraction to them and has the form of an effectiveness matrix $|a_{ij}|$, where the elements of the matrix are a_{ij} - fuzzy estimates of the effectiveness of the WCRs, namely, indicators of the probability of tracking the target for each of its decisions to apply countermeasures A_i and each state of the environment B_j regarding the emission of interference

by the AISIP.

The results of solving the matrix game at each stage of the proposed algorithm are estimates of the effectiveness of the WCRs at certain stages of air combat under different conditions of its use - both in conditions of interference and in conditions of simultaneous counteraction to them. The overall assessment under different conditions of the air combat environment is calculated using the full probability formula. Formula (1) calculates the assessment of the effectiveness of the WCRs in conditions of interference without counteraction of the enemy's air defence system, and formula (2) - considering the counteraction.

$$E_{супр}^{\text{без КРЕП}} = \sum_{i=1}^{2} P_{супр.i} \cdot P(П_i) = P_{супр.1}(a_{12}) \cdot P(П_1) + P_{супр.2}(a_{21}) \cdot P(П_2) \ , \qquad (1)$$

$$E_{супр}^{\text{КРЕП}} = \sum_{j=1}^{2} P_j \cdot P(П_j) = P_{супр.1}(a_{11}) \cdot P(П_1) + P_{супр.2}(a_{22}) \cdot P(П_2) . \qquad (2)$$

where $P_{1,2}$ - the state of the I&C system (on and off)

Conclusion

Thus, the improved mathematical model for assessing the effectiveness of the WCRs allows for its reasonable description in conditions of interference and simultaneous active counteraction to enemy interference stations, which, according to preliminary calculations, will increase the effectiveness of the WCRs by 14-33 percent, as well as consider the uncertainty of the situation during air combat. The developed algorithm improves the existing approach to the functioning of the WCRs in terms of the probability of tracking the target in the conditions of using an effective combination of the proposed methods of counteracting interference stations.

Recommendations

Further research should be aimed at improving the method of mathematical modelling of the functioning of the WCRs in the conditions of active counteraction to enemy interference stations, as well as providing recommendations for the implementation of an improved mathematical model during the modernization of fighters of the Air Force of Ukraine, considering various types of interference and the emergence of new ways of counteraction.

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