Methodical approach to evaluating the effectiveness of electronic counter-countermeasures to airborne interference stations in aerial combat

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Abstract: *Modern active jamming stations reduce the chance of aircraft getting hit by missiles with active and semi-active homing heads during aerial combat by 40-60%. The active development of airborne electronic countermeasures equipment forces to look for ways and means to not only protect against them, but also to actively counter these means, the so-called electronic counter-countermeasures. Nowadays, there are several methods of electronic counter-countermeasures to the enemy airborne active jamming stations, but the sequence and conditions of their application are not defined. Therefore, the paper proposes to determine the features of the application of three methods of electronic counter-countermeasures and to develop an algorithm for electronic counter-countermeasures against the enemy airborne active jamming stations in the conditions of creating polarization jamming of various kinds. The development of the algorithm allows to evaluate the efficiency of the application of electronic counter-countermeasures based on performance indicators of the functioning of an airborne targeting radar.*

Key Words: *polarization jamming, airborne radar, efficiency, fuzzy air combat game*

1. INTRODUCTION

The active development of airborne systems of electronic warfare (EW), the high efficiency of their use and the significant cost of weapons compels experts to look for alternative ways of influencing them to reduce the efficiency of their use and increase the efficiency of their own airborne targeting radars (ATR) during aerial combat.

One of such ways is the tendency to switch from passive protection against jamming that has already reached the input of the receiver, to actively counteract the jamming stations of individual protection (JS IP), so that the jamming that comes to the input of the receiver is least effective.

This direction of the radar technology development was named electronic counter-countermeasures (ECCM) [1], [2], [3], [4], [5].

Nowadays, methods of electronic counter-countermeasures are being actively developed and ways of their introduction on board of a fighter aircraft are being searched for to increase the efficiency of use of airborne targeting systems [3], [6], [7], [8], [9], [10], [11], [12]. One important ways of ECCM is to counteract the enemy JS IP upon operating in the mode of emitting various types of polarization jamming (on a fixed plane of polarization and induced polarization jam), since polarization jamming has one of the highest performance indicators for influencing the ATR.

The polarization jamming (PJ) remains one of the universal and perspective types of ATR jamming (it is created from one point in space, affects radars with various types of direction finding and has a fairly high probability of ATR tracking failure – 0.8-0.95).

We shall investigate the ways of counteracting the enemy JS IP when it is operating in PJ mode on a fixed plane of polarization [3], [10], [12], [13], [14], [15], [16] and PJ, which is caused by the polarization plane [9], [11], [12], [17], [18] as well as ECCM methods for disrupting the regularity selectors of the enemy JS IP based on changing the continuous direction finding of the ATR [9], [10] and a method for changing the parameters of ATR probing signals, that is, on the principle of creating a multifunction signal [3], [12]. The development and possibility of practical implementation of these methods necessitates the development of a new ECCM algorithm based on performance indicators at different stages of flight to determine the order of their application and avoid situations of negative impact of ECCM on ATR characteristics during aerial combat.

Therefore, the purpose of the paper is to develop an algorithm for conducting electronic counter-countermeasures against the enemy jamming stations of individual protection to improve the ATR protection in the conditions of creating polarization jamming of different types with the purpose of determining the order of their application and the expediency of their use at different stages of aerial combat based on the overall and comprehensive performance evaluation of their application.

2. MATERIALS AND METHODS

The analysis of existing papers and publications on the study of the possibility of counteracting JS IP in the developed methods proves that the process of confrontation of ATR and JS IP during aerial combat takes place under conditions of stochastic uncertainty of the jamming environment due to the lack of complete information about the ECCM, enemy JS IP characteristics, unknown warfare conditions, lack of practical evaluation of the radar jamming resistance upon conducting the ECCM at different stages of combat [3], [5].

The main indicator of the effectiveness of the proposed methods for enhancing jamming protection in these papers is the probability of supporting the ATR target in conditions of jamming and conducting ECCM.

Based on the analysis of mathematical matrix models, the elements of which are the probabilities of supporting the ATR target in conditions of jamming and conducting ECCM, which describe the decision-making process in the conditions of uncertainty of the state of the jamming situation, [3], [5], [9], that the proposed methods of counteracting the enemy JS IP in terms of creating polarization jamming are optimal according to several criteria (Savage, Wald's maximin model, Hurwicz criterion).

Restrictions were also identified as to their applicability, as the principle of their action is based on the change of the ATR characteristics.

The main limiting indicator is the possible range of their creation. For the method of ECCM against the JS IP, when it is operating in the PJ mode on a fixed polarization plane, the range of its possible creation equates to (Eq. 1) [9]:

$$D_{1\,creation} = 0.96 \cdot D_{max} \tag{1}$$

where: D_{max} – maximum detection range.

For the ECCM against the JS IP method when it is operating in the PJ mode, which is directed beyond the polarization plane (Eq. 2):

$$D_{2\,creation} = 0.84 \cdot D_{max} \tag{2}$$

Based on a fuzzy game model (antagonistic game) (Eq. 3):

$$\left|b_{i\,j}\right| = \begin{matrix} A_i/B_j & B_1 & B_2 \\ A_1 & b_{11} & b_{12} \\ A_2 & b_{21} & b_{22} \end{matrix} \Rightarrow \begin{vmatrix} \{0.8; 0.85; 0.9; 0.95\} & \{0.05; 0.1; 0.15; 0.2\} \\ \{0.2; 0.25; 0.3; 0.35\} & \{0.65; 0.7; 0.75; 0.8\} \end{vmatrix} \tag{3}$$

where: the pure strategies of the party A (JS IP) that performs electronic countermeasures (ECM) are: A_1 – creating polarization jamming on orthogonal polarization against the suppressed polarization of the ATR probe signal; A_2 – creation of a polarized sliding obstacle in a defined range with determination of the suppressed ATR reaction, with further narrowing of the range of change of the polarization of the obstacle (induced polarization obstacle); pure strategies of the party B (ATR) are: proposed JS IP countermeasure methods: B_1 – ECCM against the JS IP by means of inconsistency of the receiving plane of the receiving antenna relative to the polarization of the sound signal; B_2 – ECCM against the JS IP by changing the sound signal strength; b_{ij} , $i = \overline{1.2}$, $j = \overline{1.2}$ – fuzzy magnitudes – the probabilities of a target being accompanied by an ATR automatic range tracking system under conditions of polarization jamming of different types and upon simultaneously managed ECCM, which are set by fuzzy numbers with trapezoidal membership functions (Eq. 4):

$$\left(b_{ij}/\mu(b_{ij})\right) = [b_1; b_2; b_3; b_4] \tag{4}$$

where numbers b_1 and b_4 determine the fuzzy number carrier, and b_2 and b_3 – its kernel (Fig. 1).

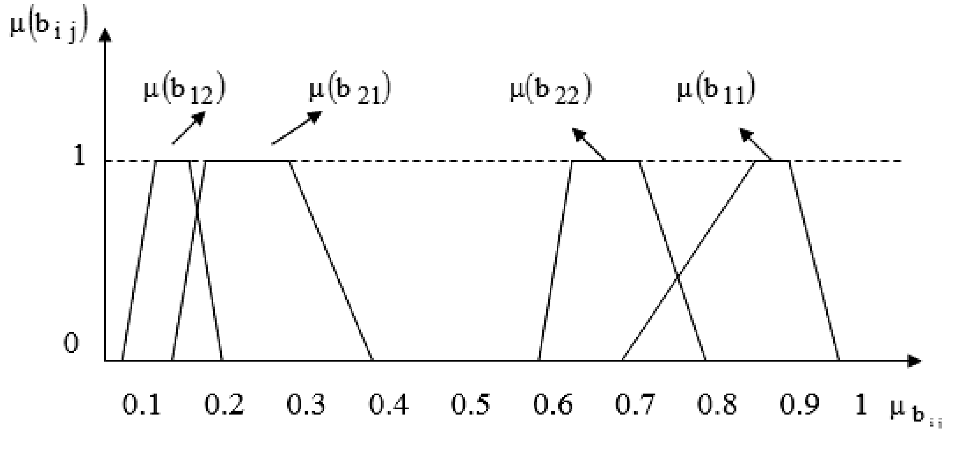

Fig. 1 - Membership function of fuzzy estimates $b_{i\,j}$

3. RESULTS AND DISCUSSIONS

The solution of the fuzzy matrix game according to the Brown-Robinson iterative method determined approximate estimates of optimal mixed interference strategies and proposed ECCM methods [12]: $S_A \approx |0.5; 0.5|$, $S_B \approx |0.37; 0.63|$ and the obtained game value $\nu_A \approx \{0.42; 0.47; 0.52; 0.57\}$. The results of the evaluation prove that even upon using ECCM methods in mixed strategies, the evaluation of the effectiveness of counteraction of the enemy station of active jamming in the conditions of creating polarization jamming of different types has increased [12]. An analysis of the developed method of ECCM against the enemy JS IP [11], which is based on the disruption of its regularity selectors by changing the time modes of continuous tracking of the ATR target shows that it can be used in conjunction with the two previous to improve the efficiency of ECCM, but it also has limitations on minimum range of its use.

Thus, the need to use the developed methods of ECCM against the enemy JS IP during aerial combat necessitates the development of an algorithm for their use, which would factor in: the peculiarities of creating these methods (restrictions on the range of creation); ATR principles and modes, to avoid situations of characteristics deterioration during ATR operation; information from radio intelligence devices. It is also necessary to determine the approach to assess the effectiveness of conducting ECCM against the enemy JS IP at different stages of aerial combat in case of using multiple ECCM methods and the enemy JS IP operation. Conventionally, the period of execution of the combat task assigned to the fighter aircraft in the absence of practical implementation of the proposed methods of ECCM aboard the fighter aircraft can be divided into two stages (Fig. 2), where the first is the stage from maximum range to range at which the opponent's JS IP starts forming a defined set of jams; the second is the stage of opposing ATR and the enemy JS IP. The probability of following the ATR of an enemy aircraft at the first stage equates to $P_{tracking\ without\ jamming} \approx 0.9$, it can be set for the highest sensitivity of fuzzy estimation: $P_{tracking\ without\ jamming} = \{0.85; 0.9; 0.95; 1\}$.

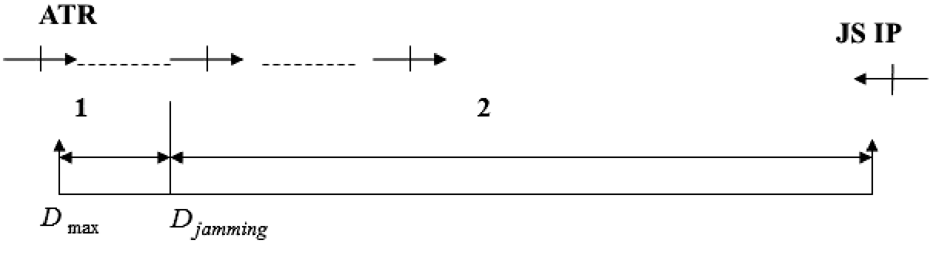

Fig. 2 - Stages of completing a task set without implementing ECCM

At the second stage, if one of the types of polarization jamming is created, it can equate to $P_{tr.\,1} = \{0.05; 0.1; 0.15; 0.2\}$ – when the enemy JS IP creates PJ on a fixed polarization plane and $P_{tr.\,2} = \{0.15; 0.2; 0.25; 0.3\}$ – when JS IP operates in PJ creation mode, which is targeted by the ATR reaction.

That is, in the second flight phase, the enemy JS IP can take two states: to create PJ on a fixed polarization plane, or PJ that is driven by the reaction. We shall assume that both states equate to $P(E_1) = 0.5$ and $P(E_2) = 1 - P(E_1) = 0.5$ and form a complete group of incompatible events between each other. Then, according to the formula of full probability, the efficiency of the ATR automatic range tracking system in terms of creating diverse types of PJ is determined as follows (Eq. 5):

$$P_{tr\cdot gen.without\ ECCM} = \sum_{i,j=1}^{2} P_{tr.1,2} \cdot P(E_{1,2}) = P_{tr.1} \cdot P(E_1) + P_{tr.2} \cdot P(E_2)$$
$$= 0.5 \cdot \{0.05; 0.1; 0.15; 0.2\} + 0.5 \cdot \{0.15; 0.2; 0.25; 0.3\}$$
$$\approx \{0.1; 0.15; 0.2; 0.25\} \quad (5)$$

The result shows that the effectiveness of the ATR automatic range tracking system of a fighter aircraft in conditions of creating two possible types of polarization jamming is sufficiently low – this emphasizes the need for the ECCM against the enemy JS IP to increase the possibility of completing their assigned combat task.

During the implementation of the proposed ECCM methods onboard the aircraft, the following stages of application of the developed methods during the performance of the fighter aircraft combat task (they are conditioned upon limitations regarding their creation (distance-wise) and ATR transition to continuous direction finding mode (CDF)) are possible (Fig. 3): 1 – the stage from maximum range to the range of possible creation of the first ECCM method against the enemy JS IP ($D_1 \approx 0.96D_{max}$), when it operates in PJ mode on a fixed polarization plane.

At this stage, the third method of ECCM against the enemy JS IP can be applied, provided that the ATR is transferred to the target CDF; 2 – the stage of possible creation of the first ECCM method and simultaneously the third; 3 – the stage of beginning the possibility of creating the 2nd ECCM method against the enemy JS IP when it emits a PJ induced by the ATR reaction.

This stage is characterized by the inability to simultaneously create two developed methods due to the deterioration of the distance-wise detection characteristics of the radar $D_{1,2} \approx Dmax - 0.04D_{max} - 0.16Dmax \approx 0.8Dmax$.

At this stage, the third method is used simultaneously with any of the selected; 4 – a stage of possible use of three methods at once; 5 – the stage of simultaneous use of ECCM methods against the enemy JS IP, when it operates in PJ emission mode of different types, but without the third, since it has a minimum range limit.

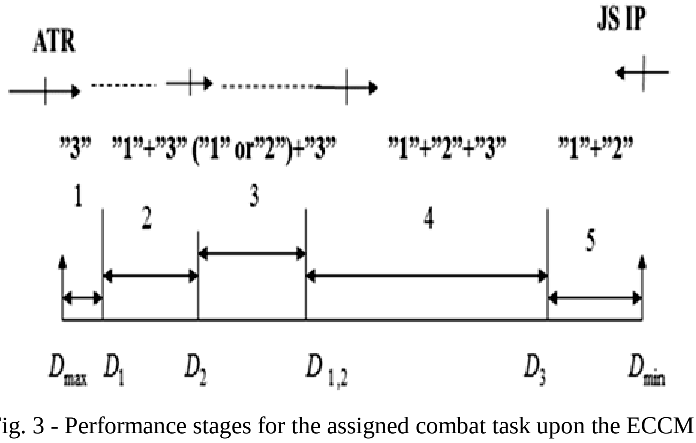

Fig. 3 - Performance stages for the assigned combat task upon the ECCM

The sequence of application of the developed methods at each stage can be described by the algorithm of their combat use by the main operands, which will be the transition of the ATR to the CDF mode and the range to the target (Fig. 4). The input data of this algorithm are the value of the maximum target detection range (D_{max}) which will be used to compare with the (current) distance (D_{curr}), to decide which ECCM method should be used or whether to combine them. At distances when it is unknown which method to use, the decision will be made at random based on calculated mixed strategies for their use [8].

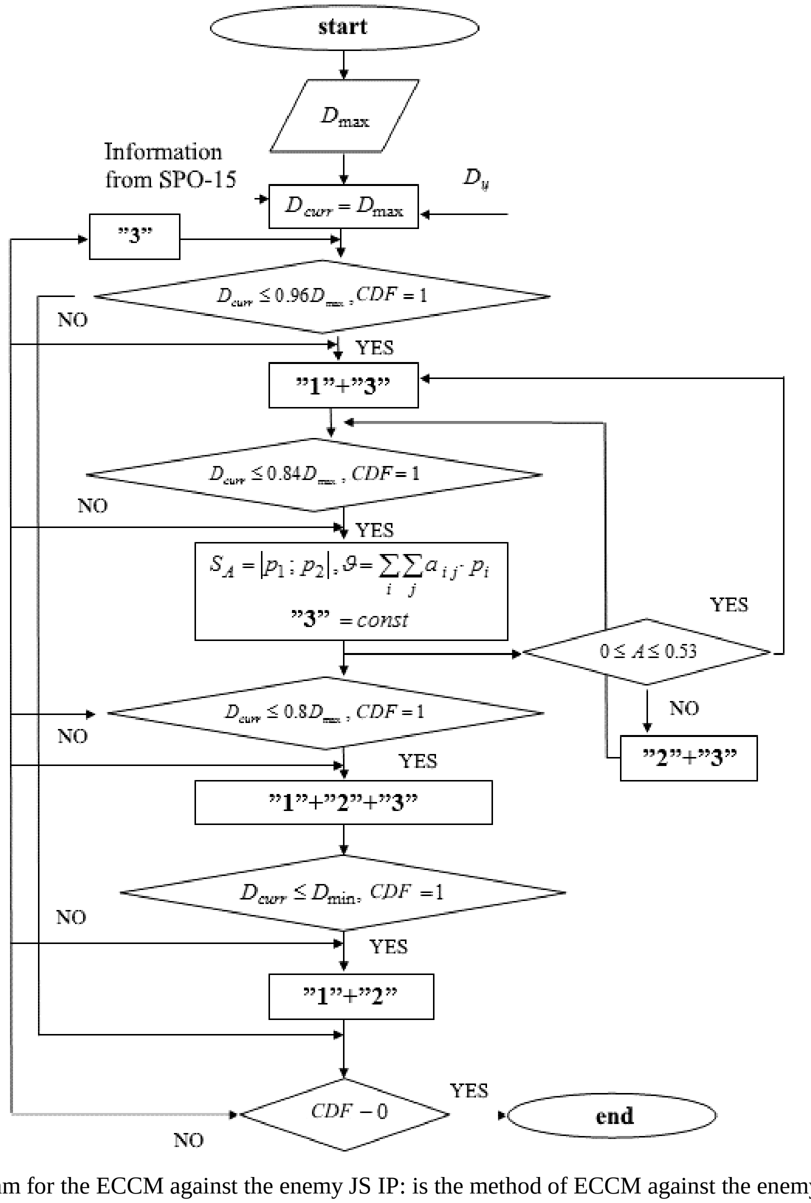

Fig. 4 - Algorithm for the ECCM against the enemy JS IP: is the method of ECCM against the enemy JS IP when it operates in PJ mode with a fixed polarization plane; is a method of ECCM against the enemy JS IP, when it forms PJ targeted by the polarization plane; is an ECCM method based on signal regularity disruption

We shall determine the overall efficiency of the ATR automatic range tracking system upon the execution of the task in the conditions of creation of PJ of different types by the enemy JS IP and simultaneous implementation of ECCM. It should be determined at each of the identified stages separately (Fig. 3). The probability of being tracked by an enemy ATR automatic range tracking system at stage 1, when the enemy JS IP with equal probabilities can operate in the mode of emitting one of the PJ and the ATR can only perform the third ECCM method in which the JS IP will either turn on or off with the jamming radiation according to the probability of the occurrence of two predetermined JS states $P^{'}(E_1) = \{0.5; 0.55; 0.6; 0.65\}$ and $P^{'}(E_2) = \{0.5; 0.45; 0.4; 0.35\}$ (based on an expert survey) will be determined as follows (full probability formula) (Eq. 6):

$$\begin{aligned} P_{tr.gen.\ 1} &= P^{'}(E_1) \cdot P_{tr.\ without\ jamming} + P^{'}_{tr.without\ ECCM} \cdot P(E_2) \\ &= \{0.5; 0.55; 0.6; 0.65\} \cdot \{0.85; 0.9; 0.95; 1\} \\ &+ \{0.13; 0.18; 0.23; 0.28\} \cdot \{0.5; 0.45; 0.4; 0.35\} \\ &= \{0.425; 0.495; 0.57; 0.65\} + \{0.065; 0.081; 0.092; 0.098\} \\ &\approx \{0.49; 0.58; 0.66; 0.75\} \end{aligned} \tag{6}$$

At the second stage, one can create the first method of ECCM against the enemy JS IP when it is operating in the PJ mode on a fixed plane of polarization, so the overall performance evaluation of the automatic range tracking system at this stage will increase if the enemy JS IP will work in the PJ mode on the fixed plane of polarization, then the elements of the matrix model (3) in the form of a fuzzy matrix game $\mathrm{P}(\mathrm{a}_{11}/E_{1,2}) \approx \{0.83; 0.88; 0.93; 0.98\}$ and $P(a_{12}/E_{1,2}) \approx \{0.53; 0.6; 0.69; 0.77\}$) shall be calculated as follows (Eq. 7):

$$\begin{aligned} P_{tr.gen.2} &= P(a_{11}/E_{1,2}) \cdot P(E_1) + P(a_{21}/E_{1,2}) \cdot P(E_2) \\ &= 0.5 \cdot \{0.83; 0.88; 0.93; 0.98\} + 0.5 \cdot \{0.53; 0.6; 0.69; 0.77\} \\ &= \{0.415; 0.44; 0.465; 0.49\} + \{0.265; 0.27; 0.315; 0.36\} \\ &\approx \{0.68; 0.71; 0.78; 0.85\} \end{aligned} \tag{7}$$

At the third stage (the stage when two ECCM methods cannot be performed at once), there is an opportunity to create a second method of ECCM against the enemy JS IP when it is in reaction-generated PJ mode. As a result, the decision to use the desired ECCM method will be random, with the help of a random number sensor (RNS) based on the identified mixed optimal strategies for using the developed methods. The overall performance evaluation of this stage will be determined by the value of the fuzzy matrix game and will equate to (Eq. 8):

$$P_{tr.\ gen.\ 3} = \nu^{'}_{A} = \{0.64; 0.71; 0.78; 0.86\} \tag{8}$$

At the fourth stage, all of the proposed ECCM methods are possible, the overall performance evaluation at this stage will increase significantly as the target tracking probability increases when the enemy JS IP works in the mode of PJ of any type ($P(a_{11}/E_{1,2}) \approx \{0.83; 0.88; 0.93; 0.98\}$, $P(a_{22}/E_{1,2}) \approx \{0.75; 0.81; 0.87; 0.93\}$), and shall equate to (Eq. 9):

$$\begin{aligned} P_{tr.gen.4} &= P(a_{11}/E_{1,2}) \cdot P(E_1) + P(a_{22}/E_{1,2}) \cdot P(E_2) \\ &= 0.5 \cdot \{0.83; 0.88; 0.93; 0.98\} + 0.5 \cdot \{0.75; 0.81; 0.87; 0.93\} \\ &= \{0.415; 0.44; 0.465; 0.49\} + \{0.375; 0.405; 0.435; 0.465\} \\ &\approx \{0.79; 0.85; 0.9; 0.96\} \end{aligned} \tag{9}$$

At the fifth stage, both methods of ECCM against the enemy JS IP, that operates in the mode of PJ radiation of different types, will continue to be implemented, but without the simultaneous use of the third ECCM method based on a disruption of the JS IP regularity selectors.

As a result, the tracking probability will decrease to the probability values $P(a_{11}) = \{0.8; 0.85; 0.9; 0.95\}$ and $P(a_{22}) = \{0.65; 0.7; 0.75; 0.8\}$, which are used in the performance evaluation calculations by the first ECCM model, without the third method. The overall performance evaluation for the fifth stage will be determined as follows (Eq. 10):

$$\begin{aligned} P_{tr\cdot gen.4} = P(a_{11}) \cdot P(E_1) + P(a_{22}) \cdot P(E_2) = \\ = 0.5 \cdot \{0.8; 0.85; 0.9; 0.95\} + 0.5 \cdot \{0.65; 0.7; 0.75; 0.8\} \\ = \{0.4; 0.425; 0.45; 0.475\} + \{0.325; 0.35; 0.375; 0.4\} \\ \approx \{0.73; 0.78; 0.83; 0.88\} \end{aligned} \quad (10)$$

Analysis of the results obtained from evaluating the performance of ATRs while conducting ECCM significantly increases the possibility of a target being tracked by the CDF system of the ATR when counteracted by the enemy JS IP in the mode of creating one of the types of polarization jamming. In the first stage, when only the third ECCM method is created, the probability of tracking the ATR target may increase by 1.4-2.7 times. In the second stage, when both the first and the third ECCM methods are created, it increases 2.2-3.2 times. In the third stage, when the use of the first and the second ECCM methods is determined by mixed strategies for their use, with the simultaneous formation of the third method, the possibility of target tracking increases 2.7-3.3 times.

In the fourth stage, if all three methods can be created simultaneously, it is equal to its maximum value and increases by 3.1-3.6 times. In the fifth stage, when the use of the third method becomes impossible, it is reduced to 2.9-3.3 times.

Because the efficiency of the CDF system of the ATR of the fighter aircraft in conditions of the enemy JS IP creating PJ of different types for it will significantly increase, as evidenced by the research results. There is no doubt that further research into the process of developing new methods and means of ECCM against the enemy JS IP during its operation in the modes of radiation of different types of jamming.

4. CONCLUSIONS

The algorithm of conducting ECCM against the enemy JS IP by known methods is developed and the mathematical model of estimation of electronic counter-countermeasures efficiency against the airborne jamming system station of the enemy in conditions of creating polarization jamming of different types will allow: to become the basis for the formation of a mathematical model for the operation of airborne weapons in the jamming environment and simultaneous ECCM implementation with consideration of the existing restrictions on their application.

ECCM that are carried out in different ways, on the one hand, slightly reduce the efficiency of ATR operation at different stages of flight, but on the other hand, significantly reduce the effectiveness of the operation of the enemy airborne ECCM devices, which will increase the efficiency of ATR application and the possibility of damage to the enemy aircraft and the effectiveness of using those methods that currently have considerable value. In the future, it is necessary to determine the possibility of practical implementation of the developed methods during the modernization of airborne EW devices and ATRs of fighter aircrafts that are in the service of the Armed Forces of Ukraine.

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