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AN APPROACH FOR OPTIMIZING THE RADIO-ELECTRONIC SUPPRESSION SYSTEM ACCORDING TO THE "COST–EFFECTIVENESS" CRITERION

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Abstract

This paper presents the results of a study of a radio-electronic suppression system, its characteristics and capabilities, and based on these proposes an approach for designing and optimizing such a system using the "cost–effectiveness" criterion.

Key words: cost–effectiveness criterion, radio electronic suppression system

Introduction. Ever since the early 1980s there was an obvious trend towards a transition from the development and use of individual radio-electronic systems (RES) for reconnaissance and control towards their integration into unified systems with centralized processing of information received from multiple RES, which made it possible to increase the overall effectiveness of operations [1–7]. In these circumstances, the issue of a systematic approach to the organisation of electronic countermeasures (ECM), ensuring that the signal field is jammed with a certain degree of effectiveness, came to the fore. The effectiveness of jamming of an RES is determined by the degree of destruction of the useful information arriving at

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the input of the RES detector, through forming the energy sum of the useful signal and the interference. Achieving certain energy ratios between the interference and the signal at the input of the jammed RES requires solving complex technical and tactical issues related to the creation of highly effective jamming stations and their control within the ECM system. The complexity of solving the ECM effectiveness problem is due to the fact that, under specific conditions, achieving the required level of effectiveness can be realized in many different ways. Clearly, among this set of options, the optimal one is that which corresponds to the minimum cost of its implementation. Accordingly, developers of ECM means face an important problem related to selecting an ECM system that, for a given (required) level of effectiveness, has the lowest cost – i.e., there arises a need to evaluate ECM means by the "cost–effectiveness" criterion. Below are considered the energy characteristics of the ECM system that determine the effectiveness of radio countermeasures, and the approach for using the "cost–effectiveness" criterion illustrated by the example of jamming an airborne surface-surveillance and weapon-control radar using ground jamming stations (JS).

It was noted earlier that the main condition for jamming an RES is forming at the detector (receiver) input of the jammed object a sum of useful and interfering signals in such proportions that the useful information is destroyed with a given probability. A quantitative measure of the effectiveness of destroying useful information is the jamming coefficient, equal to the ratio interference/signal at the detector input, which for the case considered (Fig. 1) is given by the expression [1]:

$$\alpha_c = \frac{4\pi P_c G_c G'_q \gamma \eta_k R^4}{P G^2 \sigma k_f R_c^2} \exp\left[0.23\delta(2R - R_c)\right], \tag{1}$$

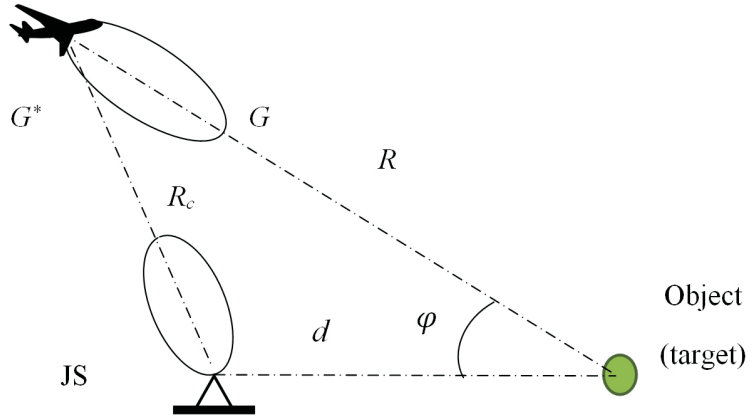

Fig. 1. Diagram of jamming an airborne radar for surface surveillance and weapon control using ground jamming stations (JS)

where: P_cG_c, PG is the energy potential of the jamming stations (JS) and the airborne surface-surveillance radar;

G is the gain factor of the sidelobe of the radiation pattern (RP) of the receiving antenna of the airborne surface-surveillance radar through which the jamming is effected;

σ is the effective radar cross-section (RCS) of the target;

γ is the polarization loss factor;

q is the interference power density;

k_f is the energy loss coefficient of the interference due to mismatch between the interference spectrum width Δf_c and the receiver passband Δf_{np};

η_k is the quality coefficient of the interference;

R is the distance between the aircraft and the object (target);

$R_c = \sqrt{R^2 + d^2 - 2Rd\cos\varphi}$ is the distance aircraft–JS, depending on the JS's distance from the protected object and the angle φ between the aircraft–object direction and the object–JS direction;

δ is the attenuation of radio waves in the atmosphere in dB per kilometer of distance.

As seen from (1), the jamming coefficient is determined both by the characteristics of the radar, the target and the JS, and by their mutual positioning.

Obviously, when developing means for electronic jamming (EJ), it must be taken into account that the effectiveness of jamming the radar can be influenced by changing the parameters P_cG_c, q, γ , η_k, k_fP and the mutual positioning of JS–target–radar. Therefore, the required energy potential of the JS is:

$$P_cG_c = \frac{\alpha_c\gamma}{qG'}, \tag{2}$$

where $\gamma = \dfrac{PG^2\sigma k_f R_c^2}{4\pi\gamma\eta_k R^4} \exp\left[0.23\delta\left(R_c - 2R\right)\right]$.

The magnitude of the energy potential of a JS, determined by (2), corresponds to the condition for jamming one radar with one JS.

In real conditions there will exist a certain set of n radars, which forms a field of signals.

Therefore, the ECM task is to create a field of interference generated by a certain set of n_0 jamming stations to cover N objects located within the area S_0.

If we a priori assume that the JS and the radars in this area are distributed uniformly at random, then the i-th radar will simultaneously be affected by some average number n_0 of jamming stations, and each j-th jamming station will affect the corresponding average number n radars.

The jamming coefficient at the detector input of the i-th radar due to the j-th jamming station will be equal to:

$$\alpha_{ci} = \left(\frac{P_cG_cG'q^{\bar{c}}}{\gamma^{\bar{c}}}\right)_j. \tag{3}$$

At the same time, the energy potential of the j-th JS is:

$$(P_c G_c)_j = \alpha_{ci} \frac{\gamma \bar{c}}{G' q^{\bar{c}}}. \tag{4}$$

Thus, for a fixed value of the jamming coefficient, the required energy potential of a JS can be determined depending on the number of radars simultaneously being jammed (forming the signal field) and the number of JSs in the ECM system that form the interference field.

Jamming coefficient. When protecting objects from detection, it does not matter whether the radar detector has identified the object because of interference (false alarm) or the object has gone undetected (miss), since in both cases the ECM has accomplished its task.

Consequently, as a measure for evaluating the effectiveness of jamming, one can take the sum of the probabilities of false alarm F and target miss D.

$$E_{je} = F + \widehat{D}.$$

In practice, the evaluation of the effectiveness of noise-masking jamming consists in specifying some detection criterion for the jammed radar (for example the optimal Neyman–Pearson, Siegart, Wald or Bayes criterion) and determining the detection characteristics as a function of the signal-to-noise ratio at the input of the jammed radar [3–6]. Since, in practice, the structure of the detection algorithm (criterion) in the jammed radar is not known a priori, the effectiveness assessment – with the aim of minimizing the required jamming coefficient and, consequently, minimizing the effort needed to provide ECM can be carried out by a known variational method.

Jamming quality. The quality of jamming is assessed by the efficiency coefficient, which indicates the use of jamming power to destroy useful information when various counter-jamming methods and protection systems are employed in radars, including exploiting correlation links in the structure of the noise signal.

Theoretical and experimental studies show that, as a criterion of jamming quality, it is advisable to use the ratio of the power of the actual noise to its mean power [5–8].

By entropy power of the actual noise is meant the power of white Gaussian noise with the same bandwidth and duration whose entropy equals the entropy of the noise under consideration. Thus, the quality of the jamming in this case is determined by the quality coefficient:

$$\eta_k = \frac{\overline{P_c}}{P_c},$$

where $\overline{P_c}$ is the entropy power of the interference, equivalent to the entropy of the actual interference;

P_c is the mean power of the interference.

In fact, the jamming quality coefficient characterizes the portion of the noise signal power that cannot be removed from the additive mixture with the signal when possible counter-jamming measures are used in the receiving devices of the jammed radar and that ensures the destruction of the useful information.

For white Gaussian noise the quality coefficient equals one, while for all other interferences different from white noise, η_k is less than one.

Studies show [5, 6] that quasi-continuous noise jamming, in terms of quality, approaches white Gaussian noise.

Interference power density. The energy characteristics of the noise signal considered above – including the jamming quality, which assesses how closely the noise structure approximates that of white Gaussian noise, and the jamming effectiveness as a function of the signal-to-noise ratio at the input of the jammed radar – will be truly effective only if certain temporal characteristics of the jamming emission are met.

The nature of the useful signals received at the input of the airborne onboard radar, and the different operating modes of the aircraft's radio-electronic equipment during the task of detecting the object, require the ECM to generate continuous or quasi-continuous jamming.

A quantitative measure of the continuity of jamming is the interference power density factor q, defined by the ratio of the actual jamming time T_0 acting on the jammed radar to the total contact time T_k between the JS and the radar: $q = \dfrac{T_0}{T_k}$.

Having in mind that $T_0 = T_k - \Delta T_0$ (ΔT_0 – jamming-off time), interference power density can be defined as:

$$q = 1 - \frac{\Delta T_0}{T_k}.$$

Polarization characteristics of the jamming interference. Use of the polarization properties of the signal is one of the methods for reducing the impact of harmful signals and interference.

For this purpose, radars use devices that allow changing the polarization characteristics of the antenna. The energy losses of the interference are determined by the polarization loss factor K_p, which is the ratio of the interference power for matching polarization to the interference power for mismatched polarization at the radar input.

Typically, losses for orthogonal polarization in the main lobe of the radar antenna pattern reach 20–25 dB.

When jamming via the sidelobes, the effectiveness of the interference depends to a small extent on the polarization due to the inherent cross-polarization of the antennas. In this case, losses from orthogonal polarization do not exceed 2–5 dB or may be entirely absent, since in some cases the sidelobe levels of the radar

antenna pattern for cross-polarization are higher than the levels for the operating polarization.

The sidelobe patterns for the main polarization and for cross-polarization do not coincide. This can provide a certain advantage in jamming effectiveness if the interference is applied simultaneously in two orthogonal polarizations using jamming stations that are uncorrelated with each other. In that case the impact of nulls in the sidelobe level distribution of the jammed radar's antenna pattern is significantly reduced, and the possibility of polarization-based discrimination of the jamming is practically eliminated.

Approach for optimizing the ECM system according to the "cost–effectiveness" criterion. Protecting ground objects and areas of terrain from detection by enemy airborne radars is one of the important tasks of the air defense system. Let us assume a priori that within an area of size S there are N objects to be engaged, which may be affected by n aircraft equipped with surface-surveillance radars whose emissions form a field of signals.

The ECM organizers face the task of creating a field of interference that, with a given probability, ensures the destruction of the signal field.

The above expressions were proposed and derived for determining quantitative values of ECM effectiveness. It is clear that the number of JSs comprising the ECM system, needed to jam a given number of radars with specified effectiveness is determined by the JSs' performance characteristics, which in turn determine the complexity of the JSs and, consequently, the cost of the system as a whole.

In this case the "cost–effectiveness" criterion will serve as a universal measure of the system's optimality. It allows the designers of the ECM system to solve the current task of achieving an effectiveness not lower than the specified level with minimal resources for creating and operating that system.

Obviously, the ECM system being created will be optimal if it maximizes the cost–effectiveness ratio $\Psi = \dfrac{E}{C} \Rightarrow \max$.

The cost of a JS is determined by the sum of expenditures for its individual performance characteristics. A direct calculation of the cost of each JS is an extremely large task, given its dependence on many factors. To simplify the study, we will resort to a reference (analogue) JS and compare the costs of individual JSs with the analogue JS by main characteristics: energy potential, operating frequency band, and number of simultaneously jammed targets. In this case, the cost of the jamming can be determined by the expression:

$$C_c = C_{c.an} K_c^{\left[\ln \frac{P_c G_c}{(P_c G_c)_{an}} + \ln \frac{n}{n_{an}} + \ln K_{\Delta F} \frac{Fcp}{Fcp.an}\right]}, \tag{5}$$

where: $C_{c.an}$ is the cost of a known reference JS (analogue);

n, n_{an} is the number of targets jammed by the studied JSs and the analogue JS;

$\frac{P_cG_c}{(P_cG_c)_{an}}$ is the relative change of the energy potential of the studied JS compared to the potential of the reference JS;

K_c is the cost change coefficient for development and mass production of the JS;

$K_{\Delta F} = \Delta F/\Delta F_{an}$ is the relative change of the operating frequency band of the studied JS compared to the reference JS;

F_{cp}, $F_{cp.an}$ is the nominal operating frequency of the studied JS and of the reference JS.

If we assume that all studied JSs and the analogue JS have equal operating frequency ranges, then the cost of a JS compared to the reference JS will be determined by:

$$C_c = C_{c.an} K_c^{\left[\ln \frac{P_cG_c}{(P_cG_c)_{an}} + \ln \frac{n}{n_{an}}\right]}. \tag{6}$$

It is obvious that the cost of all n_0 JSs will equal the sum of the costs of each JS.

$$C_{kc} = C_{c.an} \sum_{j=1}^{n_0} K_{cj}^{\left[\ln \frac{P_cG_c}{(P_cG_c)_{an}} + \ln \frac{n}{n_{an}}\right]}. \tag{7}$$

In the case of identical JSs used in the ECM system, the total power will be:

$$C_{kc} = n_0 C_{c.an} K_c^{\left[\ln \frac{P_cG_c}{(P_cG_c)_a{}^n} + \ln \frac{n}{n_{an}}\right]}. \tag{8}$$

Similarly, the cost of the radio-technical reconnaissance station (RTRS) included in the ECM system can be determined as:

$$C_p = C_{p.an} K_c^{\left[\ln \frac{n}{n_{an}} + \ln \frac{P_{ekb}}{P_{ekb.an}} + \ln K\Delta F \frac{Fcpcp}{Fcp.an}\right]}, \tag{9}$$

where P_{ekb}, $P_{ekb.an}$ are the equivalent sensitivity of the receiver of the studied RTRS and the reference RTRS.

From the obtained values for the JS and the RTRS, it is seen that the cost of a JS is determined by the cost of a given reference JS and by the exponential dependence on the ratios of the energy potentials, throughput (capacity) and operating-frequency bandwidths of the studied JS and the reference JS. As these characteristics increase, the cost of the JS also increases.

The cost of the examined RTRS is determined by the cost of the reference RTRS and by an exponential dependence on the ratios of the equivalent sensitivities, throughput (capacity), and operating-frequency bandwidths of the examined RTRS and the reference RTRS.

These cost estimates allow reasonably accurate forecasting of the development and operational costs of an ECM system depending on the technical characteristics

and the specific conditions for the technical implementation of jamming stations and control systems.

Changing these characteristics allows the cost of the ECM system to be modified and thus to seek an acceptable, i.e. optimal, option for its construction.

Changes in the ECM system's characteristics will necessarily lead to changes in its effectiveness at jamming a given field of n signals. A system that is optimal with respect to cost may turn out to be suboptimal in effectiveness, and vice versa – optimal in effectiveness but suboptimal in cost. Therefore, optimization must be carried out simultaneously for both effectiveness and cost.

It is more expedient to assess jamming effectiveness by using specialized methods for specific cases of organizing an ECM system. Effectiveness can be determined by two components – the probability (effectiveness) of jamming the onboard radars E_1 and the probability (effectiveness) of directing the JSs at the onboard radars E_2:

$$E = E_1 E_2.$$

If we assume a priori that the j-th JS provides jamming of the i-th radar with some probability p, then the effectiveness of jamming all n onboard radars by the interference field of n_0 JSs can be determined as:

$$E_1 = \prod_{i=1}^{n} \left[1 - \prod_{j=1}^{n_0} (1 - P_j)_i \right]. \tag{10}$$

In the special case when the probabilities of jamming the i-th radar by the j-th JS are equal and when the numbers of JSs and radars are the same, (10) takes the form:

$$E_1 = \left[1 - (1 - p)^{n_0} \right]^n, \tag{11}$$

where n_0 and n are the number JSs and radars.

Since the j-th JS will be directed at the i-th radar with some probability P_{jn}, the effectiveness of steering the interference field toward the radar signal field will be:

$$E_2 = \prod_{i=1}^{n} \left[1 - \prod_{j=1}^{n_0} (1 - P_{jn})_i \right]. \tag{12}$$

In the special case, as in (11), the effectiveness will transform into:

$$E_2 = \left[1 - (1 - p_n)^{n_0} \right]^n. \tag{13}$$

In accordance with the above expressions, the cost–effectiveness criterion applicable to the interference field formed by the JSs, as an assessment for building

an ECM system, will have the form:

$$\psi_c = \frac{E_1}{C_{kc}} = \frac{\prod_{i=1}^{n}\left[1-\prod_{j=1}^{n_0}(1-p_j)_i\right]}{C_{c.an}\sum_{j=1}^{n_0} K_c^{\left[\ln\frac{(P_nG_n)}{(P_nG_n)_{an}}+\ln\frac{n}{n_{an}}\right]}}. \tag{14}$$

In the special case, as in (8) and (11):

$$\psi_c = \frac{[1-(1-p)^{n_0}]^n}{n_0 C_{c.an} K_c^{\left[\ln\frac{(P_nG_n)}{(P_nG_n)_{an}}+\ln\frac{n}{n_{an}}\right]}}. \tag{15}$$

If it is noted that, for the considered variants of building an ECM system, with specific fixed characteristics of the signal field regarding the operating frequency range and the throughput system, the cost of the RTRS will be constant and may be omitted when evaluating the ECM system by the "cost–effectiveness" criterion.

After brief mathematical transformations, the final form of the "cost–effectiveness" criterion for the conditions considered becomes:

$$\psi_c = \frac{\prod_{i=1}^{n}\left[1-\prod_{j=1}^{n_0}(1-p_j)\right]}{C_{c.an}\sum_{j=1}^{n_0}\left[\frac{(P_nG_n)}{(P_nG_n)_{an}}\frac{n}{n_{an}}\right]^{\ln K_c}}. \tag{16}$$

The given relations for the criterion ψ make it possible, by using the cost–effectiveness assessment and by varying the parameters and number of JSs in the ECM system, to find the optimal option for building that system.

Conclusion. The issue of optimizing the electronic countermeasures system is a topical one, particularly in view of the current escalation of local and regional conflicts of varying intensity.

The proposed approach to such optimization takes into account, in real conditions, all elements related to electronic countermeasures.

The approach is relatively easy to use and can be implemented as an algorithm running on an ordinary computer for faster determination of the characteristics and parameters of the constructed electronic countermeasures system.

The presented approach can be applied to different variants of the system.

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