UDC 621.396.987

Ermolin O. V., Kozar V. B.

System approach to assessing the effectiveness of applying combat equipment of guided missiles

The study examines combat equipment of guided weapons as a system, which may include a non-contact target sensor. We propose a logical-probabilistic model of non-contact sensor functioning in order to take into account the jamming effect on the effectiveness of combat equipment. We also carried out the analysis of the possible jamming effect on the effectiveness of combat equipment with a non-contact target sensor.

Keywords: combat equipment, non-contact target sensor, jamming, guided missile.

Combat equipment as a system

Modern weapons include guided (GW) and non-guided (NGW) types. Typical GW include guided surface-to-air, air-to-air, air-to-surface missiles, etc. Typical NGW include ballistic projectiles intended to hit air, surface, and sea threats, as well as non-guided missiles and bombs.

Common for all GW is their fitting with combat equipment (CE). The CE includes: a warhead (WH) with the property of destructiveness, a fuze safety and arming mechanism (FSAM) for safe GW storage, transportation and use, and a detonating fuze (DF) ensuring generation of the WH detonation command near the target.

The DF can comprise:

• a contact target sensor (CTS) ensuring generation of the WH detonation command at the time of the GW colliding with the target or underlying terrain;

• a non-contact target sensor (NCTS) ensuring generation of the WH detonation command when the GW is in a position aligned with the target WH damage area (a flight-type NCTS) or on the set height over the underlying terrain during GW descent (a height-finding type NCTS);

• a combination of the NCTS and CTS.

The GW development requires improvement of all its components including the CE. A variety of CE improvement options necessitates their comparison to select the best one. One of the main indicators used for the CE options comparison is its efficiency as part of a certain piece of combat equipment. To account for the effect of many factors on this indicator, it is relevant to consider the CE using a systematic approach and viewing it as a complex system having the WH, SAM, DF as its subsystems with the corresponding interconnections and connections with the supersystem being the GW [1].

Indeed, it is impossible to evaluate efficiency of the CE options as GW components without considering peculiarities of using advanced GW of different types. The following GW characteristics are usually referred to as the factors affecting efficiency of the CE as part of GW: type, velocity and angles of target approach, target range assessment accuracy, and the accuracy of its reaching by GW [2]. Formalisation of accounting for their influence on CE efficiency as part of GW can be achieved by means of introduction of external connections between the CE and GW, as well as internal connections between the CE components, which jointly ensure its proper operation. Moreover, target environment and jamming environment, which can be considered via GW external connections with the CE, should be also included in the factors affecting the CE efficiency as part of specific GW.

It is of note that when assessing the CE operational effectiveness, target environment assessment poses no difficulties, since there is quite a significant array of theoretical and test data regarding the influence of the target and background on it. Due to this, when demonstrating feasibility of CE characteristics within a specific GW, the WH destructiveness with regard to the set targets is prioritised. Then the FSAM and DF characteristics are determined.

It is known that standard operation of NCTS used in CE can be disturbed under jamming [3]. This, in its turn, can cause degradation of CE as part of GW and hence the GW itself. Thus, to avoid errors in design of advanced GW, it is required to evaluate efficiency of their use within CE under jamming conditions at early stages of their development. The article describes a general model of NCTS operation within CE of advanced GW, developed to fulfil the above task. The model ensures formalization of jamming influence on their efficiency considering the above stated facts.

Logical and probabilistic model of NCTS functioning

Three consecutive stages were distinguished during the analysis of NCTS functioning peculiarities:

1) pre-use stage;

2) stage following the last protection stage removal;

3) stage of actuation in the WH effective coverage.

Other NCTS functioning peculiarities include:

• alignment of the operating range and the length of the WH effective coverage of target;

• use of settings (time delays in generation of the WH detonation executive command, which depend on the target type, target closing rate, approach angles and other parameters) generated when preparing the GW for use or at the flight trajectory to improve the WH destructive effect.

NCTS anti-interference can be ensured by jamming either connected with the target or created at an offset point (OSP) with regard to the target. The main NCTS protection measures are obstructing reconnaissance of a used signal (radiation suppression) combined with selection in terms of the range, velocity and angle.

CE becomes ready to perform its functional task after removal of the last NCTS protection stage upon a special command. This command is generated when the GW distance from the target is from several dozens to several hundreds of meters, in some cases – several kilometres.

There are two legs within the GW flight trajectory that correspond to the second and third stages of NCTS functioning. The second leg starts at a range $Д_{оч}$ to the target at the time of special command generation, and ends at the maximum range $Д_{о}$ of the WH effective coverage of target, which in some instances can be called the WH destructive radius. The third leg starts at a range $Д_{о}$ and ends at the range of NCTS actuation. The jamming effect on the second trajectory leg can cause NCTS' premature actuation, its probability being indicated as $P_{ПСП}$. The jamming effect on the third trajectory leg can cause failure of NCTS actuation with the distances r equal to or less than $Д_{о}$, its probability being indicated as $P_{НСП}$.

Obviously, for NCTS' premature actuation, the jamming effect should cause generation of jamming structural components in the detector, which create an imitative effect [3]. Failure of NCTS actuation at the required distances takes place under jamming creating a masking effect in the detector [3].

As first approximation, the dependence of probability $P_{ПСП}$ on the ratio between power $q^2_{ИП}$, imitative jamming, and the power of equivalent interior noise at the NCTS detector output (Fig. 1), using threshold $\gamma_{СП}$ of NCTS actuation upon a useful signal at the range $Д_{о}$ can be approximated by the ratio

$$P_{ПСП} = \begin{cases} 1 & \text{at} \quad q^2_{ИП} \geq \gamma_{СП}, \\ 0 & \text{at} \quad q^2_{ИП} < \gamma_{СП}. \end{cases} \tag{1}$$

The probability $P_{НСП}$ for an active-type NCTS can be calculated using the following ratio

$$P_{НСП} = \begin{cases} 0, & \text{at } К_{ПР}К_{ИС} > 1, \\ 1-(К_{ПР}К_{ИС})^{1/4}, & \text{at } К_{ПР}К_{ИС} \leq 1. \end{cases} \tag{2}$$

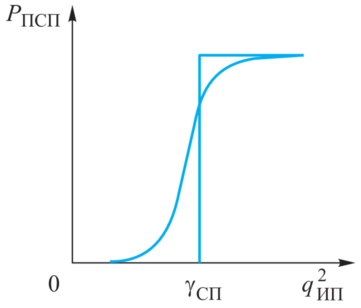

Fig. 1. Relation of probability $P_{ПСП}$ vs. ratio $q^2_{ИП}$

Here, $К_{ПР}$ – excess of the signal power at the NCTS detector output at the range $Д_о$ over the detection threshold (usually determined for the probability of the $P_{обс}$ ($P_{обс} \geq 0.95$) signal detection at the range $Д_{НДЦ}$ between the NCTS and target), $К_{ПР} = Д_{НДЦ} / Д_о$, where $Д_{НДЦ}$ – the NCTS action range, $Д_{НДЦ} > Д_о$);

$К_{ИС}$ – factor of signal energy use under masking interference [4].

Let us present the NCTS operation logics formalized. To do this, the distinguished stages of its operation should be sequentially considered and the propositional variables should be introduced: H1 – t_3 time delay of WH detonation executive command generation, calculated after the target type, closing rate, approach angles and other parameters are set; H2 – target is found; H3 – WH detonation command is generated.

At stage 1, preparation for usage, the NCTS functioning is described with conjunction and disjunction operations:

$$H1 \equiv \vee_{i=1}^{4} a_i; \quad (3)$$

$$a_i \equiv \wedge_{j=1}^{Ji} a_{ij}, \quad (4)$$

where a_i – an element selected from the elements a_{ij}, attributed to the sets A_{ij}, corresponding to the set targets ($i = 1$), closing rates ($i = 2$), approach angles ($i = 3$) and other parameters ($i = 4$), consisting of J_i elements with number j.

At stage 2, after removal of the last protection stage, the NCTS operation is described with the implication operation:

$$H2 \equiv (\bar{b}1 \rightarrow b2), \quad (5)$$

where $b1$ and $b2$ – propositional variables: target signal power a_i in the NCTS detector is less than the set threshold $\gamma_{СП}$ and target range a_i is evaluated correspondingly.

At stage 3, the NCTS actuation within the WH effective coverage of target a_i, the NCTS operation is described by the implication operation:

$$H3 \equiv (\bar{c}1 \rightarrow c2), \quad (6)$$

where $c1$ and $c2$ – propositional variables: evaluation of target a_1 range is greater than the WH effective range, and generation of the WH detonation command with the estimated delay time t_3 correspondingly.

Then the NCTS functioning can be generally described using the implication operation

$$(H1 \rightarrow H2) \rightarrow H3. \quad (7)$$

Let us introduce probabilities $\eta_{ИМ}$ and $\eta_{МА}$ of situations occurring when the GW is used to hit the targets, where it is possible to generate jamming that cause imitative and masking effects, respectively, in the NCTS detector.

Then, indication of probability of NCTS fulfilling its tasks at the allocated second and third stages P_2 and $P(r)$, respectively, we will have:

$$P_2 = 1 - \eta_{ИМ} P_{ПСП}, \quad P(r) = 1 - \eta_{МА} P_{НСП}. \quad (8)$$

Thus, the formalized logical and probabilistic model of the NCTS functioning is the ratios (1)–(8) that can be used when evaluating the probability of NCTS fulfilling its tasks under jamming.

Influence of NCTS fulfilling functional tasks on efficiency of CE use as part of GW

Efficiency of the CE use as part of GW is evaluated based on the target hitting probability when it is in the area of possible GW launches.

This probability calculation should be done at the NCTS pre-use stage and considering the jamming effect. Such influence occurs when the jamming acts on information channels of both GW and its carrier, appearing via the NCTS settings as per the target type, selection of the GW flight trajectory, and other channels transmitted to CE prior to the GW launch or during its flight. Misadjustment NCTS is possible under the influence of jamming, for example, at the radar station of an aircraft or ground operating complex prior to the GW launch, or in the homing head when the target is detected on the GW flight trajectory.

As mentioned above, CE can also include a CTS ensuring the WH detonation when hitting the target or underlying terrain. Thus, in case of a direct hit on the target by the GW (or collision with the underlying terrain), target destruction is possible even if the NCTS failed due to jamming. Further, the option of CE with the NCTS and CTS combination is discussed.

At the early stages of GW design, it appears sufficient to use average characteristics in line with the NCTS and WH operation conditions for the known target when formalizing the effect of CE distancing from target on the conditional probability U of its destruction. Then, considering the above, the probability U of target destruction (if it is within the area of possible GW launches) can be presented as follows:

$$U = (1-\eta_{ИМ} P_{ПСП})(P_{пр} W_0 + \\ + \int_{h_{пр}}^{h_з} \omega(h) F P(r(h)) W(r(h, t_з)) dh + \\ + \eta_{ИМ} P_{ПСП} \int_0^{h_з} \omega(h) \int_{Д_К}^{Д_Н} \omega(r) W(r(h), t_з) dr dh. \quad (9)$$

Here, $P_{пр}$ – probability of direct target kill by GW;

W_0 – probability of target destruction by WH at direct hitting (with the range $r \le h_{пр}$);

$h_з$ – set miss value aligned with $Д_о$;

$h_{пр}$ – equivalent miss value, exceeding of which ensures no direct target kill by GW;

$\omega(h)$ – density of the GW h miss distribution probability;

F – function characterising the influence of quality of the information about the target received by the NCTS and used for setting the aggregate of its parameters by $W(r(h, t_з))$;

$P(r(h))$ – probability of the NCTS finding the target at the range $r = \frac{h+y}{\sin\beta}$; (where β – axis tilt angle of the main lobe of antenna radiation pattern (ARP) of the NCTS radio location receiver (optic and electronic field-of-vision) to the GW axis, y – projection on the miss vector of the area centre coordinate generated on the target surface (or underlying terrain) when it is closed with the ARP main lobe of the radio location NCTS (optic and electronic field-of-vision) at the time of desired signal detection);

$W(r(h, t_з))$ – probability of the WH hitting the target at the range $r(h, t_з)$ to the target conditional centre $(r(h, t_з) < Д_о)$, with reliable information about it in NCTS;

$Д_Н$ and $Д_К$ – the values of the GW range to target at the starting and ending points of imitative jamming, that are determined by the extent of the enemy's awareness about the characteristics of the NCTS, WH and GW, as well as availability of range assessments with the jamming device;

$\omega(r)$ – density of range r distribution probability when detonating the WH impacted by imitative jamming, that reflects the accidental nature of r values related to uncertain location of both the GW and the jamming source with regard to the protected target.

It is of note that the range $r(h, t_з)$ to the conditional target centre when detonating the WH equals

$$\sqrt{(h+y)^2 + ((h+y)\text{ctg}\beta + z - vt_з)^2}, \quad (10)$$

where z – projection of centre coordinate of the area generated on the target surface (or underlying terrain) when it is covered by the main ARP lobe of the radio location NCTS (optic and electronic field-of-vision) at the time of the desired signal detection, to the plain orthogonal to the miss vector;

v – GW and target closing rate.

Calculation of the equivalent miss value $h_{пр}$, characterising the GW direct hitting is done after the simulation modelling of GW hitting the target, or after either semi-realistic modelling or full-size tests of the GW analogue. For this, the values of probability $P_{пр}$ of direct target kill by GW and the probability density $\omega(h)$ of GW miss distribution. The direct kill probability is shown as $P_{пр}(h_{пр}) = \int\limits_0^{h_{пр}} \omega(h)dh$, with the solution $h_{пр}$. For example,

$$h_{пр} = [-2\ln(1 - P_{пр})]^{1/2} \qquad (11)$$

in case it is possible to use the Rayleigh law for approximation of the density of probability $\omega(h)$ of GW miss h distribution

$$\omega(h) = \frac{h}{\sigma^2}\exp\left(-\frac{h^2}{2\sigma^2}\right). \qquad (12)$$

Here, σ – root-mean-square error (RMSE) of the dispersion points (x, y) coordinate (crossings of the GW flight trajectory and image plane) relative to the target conditional centre, distributed under the normal law.

The last term in ratio (9) considers the imitative jamming effect in the NCTS detector, and is as follows

$$\eta_{ИМ} P_{ПСП} \int\limits_0^{h_З} \omega(h) \int\limits_{Д_К}^{Д_Н} \omega(r) W(r(h), t_З) dr dh. \qquad (13)$$

Should there be no assessment of the GW range to protected target during jamming generation, then $Д_К = 0$, and $Д_Н = Д_{max}$, where $Д_{max}$ – the maximum possible r range value at the time of imitative jamming. Obviously, $Д_{max} = \min\left[Д_{сп}, Д_{рс}\right]$, where $Д_{сп}$ and $Д_{рс}$ – range r values at the time of removal of the last protection stage and completion of the NCTS signal reconnaissance, respectively.

Currently, modern jamming devices have no information on the GW range but they may become able to acquire it in the future.

It is natural to suppose that generation of jamming causing the imitative effect in the NCTS detector comes along with the desire to avoid protected target hitting by either the WH of the attack GW or its fragments which appear in case of WH premature detonation. Due to this, GW fragments impact on the target is further disregarded. Then ratio (9) gives the following

$$\begin{gathered} U = (1 - P_{ПСП}) \times \\ \times (P_{пр} W_0 + P_З F P_{ср}(r) W_{ср}(r)), \end{gathered} \qquad (14)$$

where $P_З$ – probability of GW guidance to target with a miss, which does not exceed $h_З$, but ensures no direct kill either;

$P_{ср}(r)$ and $W_{ср}(r)$ – average values of probabilities of target hitting by WH when the NCTS actuates within the range rate $\frac{h_{пр} + y}{\sin\beta} < r \le Д_о$, respectively.

Relations $W_{ср}(r)$ and $P_{ср}(r)$ are shown in Figs. 2 and 3, respectively.

To simplify ratio (14) a number of auxiliary factors with a clear physical meaning will be introduced:

$\mu = (W_{ср}(r)) / W_0$ – rated relation of the WH average efficiency value vs. r within the WH effective range to target (as the first approximation, it can be approximated with the constant value not exceeding 1 and depending on the WH and target characteristics);

$\alpha = P_{пр} / (P_З + P_{пр})$ – share of GW direct kills of targets in the image plane $(P_З + P_{пр} = P(h_З)$ – probability of GW guidance to target with a miss not exceeding $h_З)$;

$\gamma = P_З / (P_З + P_{пр})$ – share of GW hits (excluding direct ones) within the WH effective range to target in the image plane.

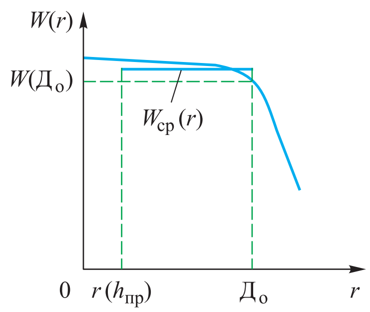

Fig. 2. Relation of probabilities $W(r)$ and $W_{ср}(r)$ vs. range r to target

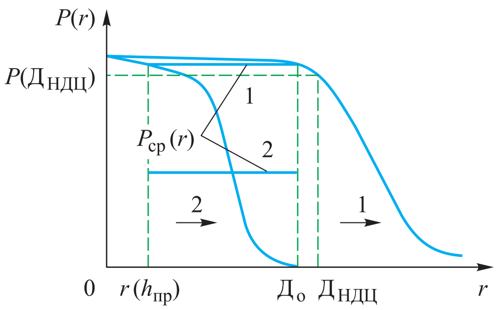

Fig. 3. Relation of probabilities $P(r)$ and $P_{ср}(r)$ vs. range r, without (1) and with (2) masking jamming

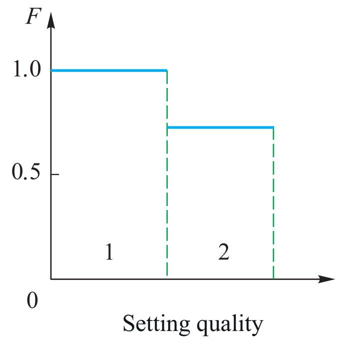

Fig. 4. Relation of F vs. quality of NCTS parameters setting:
1 – best setting values for one target;
2 – average setting values for several targets

The implemented factors can be used for the following:

$$U = \left(1 - \eta_{ИМ} P_{ПСП}\right) \times \times \left(\alpha + \gamma\mu F P_{ср}(r)\right) P(h_з) W_0. \quad (15)$$

Thus, based on the systematic approach to CE, a convenient analytical relation was obtained that allows assessing its efficiency at the early stages of GW design with and without jamming.

Analysis of efficiency decrease of CE as part of GW under jamming

Let us analyse the obtained ratio (15) in terms of practical use of WH destructiveness when it is part of GW and affected by jamming. For this Figs. 4 and 5 are used.

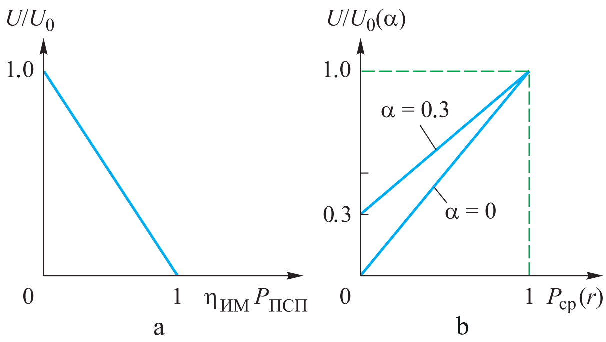

Fig. 5. Relation of CE rated efficiency $U/U_0(\alpha)$, with NCTS under jamming causing only premature actuation: a – parameter $\eta_{ИМ}P_{ПСП}$; b – only decrease of the NCTS actuation range (parameter $P_{ср}(r)$)

The CE efficiency value (specific for each combination of initial data: target type, GW type, peculiarities of GW use) without jamming, when $P_{ПСП} = 0$, $F = 1$, and the values α and $P_{ср}(r)$ are at their maximum, is indicated as U_0.

Partial loss of the ability to use the WH destructiveness and the corresponding decrease of GW efficiency appear in case of distortion of the NCTS $(F < 1)$ settings used to improve the WH destructiveness for the set target (refer to Fig. 4). Such distortions are caused by jamming acting on the information channels used to generate settings. These information channels are external for CE (they can be conditionally indicated as “the NCTS setting channels”).

Full loss of the WH and GW destructiveness is possible under jamming causing the NCTS premature actuation $(\eta_{ИМ} P_{ПСП} = 1)$ at ranges to the set target exceeding the range of its hitting with GW fragments. Thus, jamming creating the imitative effect in the NCTS detector are the most dangerous type (refer to Fig. 5, a).

Such effect on the WH, including the NCTS failure to the target $(P_{ср}(r) = 0)$ can be caused by jamming creating the masking effect in the NCTS detector (to put it differently, desensitizing it), but only in case of $\alpha = 0$, i.e. when direct target kills by GW are excluded (refer to Fig. 5, b). This becomes possible when jamming affects the GW guidance information channels.

The results of calculation of jamming influence on the efficiency of CE using NCTS and CTS are shown in Figs. 6–9 with the parameter values $W_0 = 1$, $\mu = 0.8$, $P_{ПСП} = 1$, $\alpha = 0.3$.

Conclusions

1. It is stated that early stages of development of CE using the NCTS require assessment of its possible efficiency decrease as part of an advanced GW under jamming.

2. The proposed logical and probabilistic model of the active NCTS allows assessing probability of its fulfilling its functional tasks as part of CE and under jamming at the early stages of its development.

3. The analytical ratio was obtained to assess a decrease in the efficiency of CE using NCTS as part of GW and under jamming

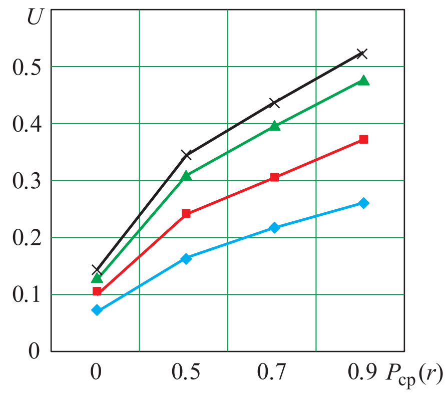

Fig. 8. CE efficiency at changing $P_{cp}(r)$ when jamming affects the NCTS and GW guidance system ($P(h_3) = 0.7$) at $\eta_{ИМ}$: – 0.5; – 0.3; – 0.1; – 0

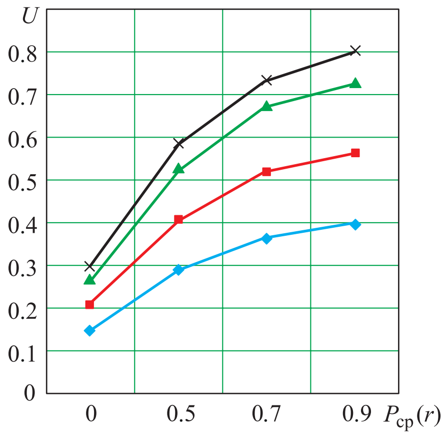

Fig. 6. CE efficiency at measuring $P_{cp}(r)$ when jamming affects only the NCTS at $\eta_{ИМ}$: – 0.5; – 0.3; – 0.1; – 0

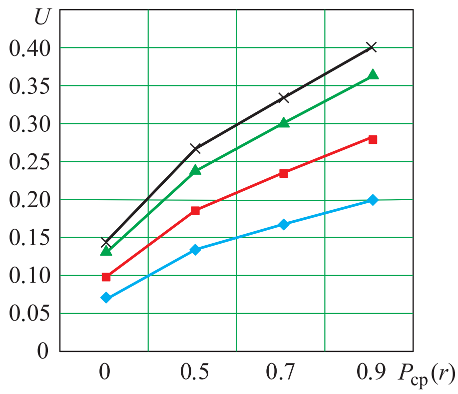

Fig. 9. CE efficiency at changing $P_{cp}(r)$ when jamming affects the NCTS, its setting channels ($F = 0.7$) and the GW guidance system ($P(h_3) = 0.7$) at $\eta_{ИМ}$: – 0.5; – 0.3; – 0.1; – 0

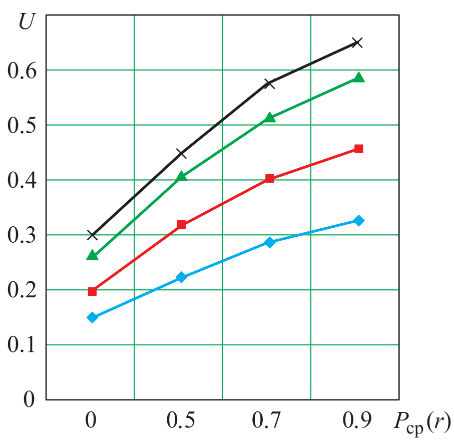

Fig. 7. CE efficiency at changing $P_{cp}(r)$ when jamming affects the NCTS and its setting channels ($F = 0.7$) at $\eta_{ИМ}$: – 0.5; – 0.3; – 0.1; – 0

at the early stages of its development. The following has been considered: imitative effect causing premature actuation of NCTS, masking effect causing reduction of the NCTS operating range, distorting effect causing errors in NCTS setting as per the data from information channels external for CE, as well as decrease of the GW guidance accuracy.

4. Efficiency of CE using NCTS and CTS and being part of GW was assessed. The assessment revealed its possible decrease up to 5-fold when jamming affects only the NCTS, and up to 10-fold when jamming affects the NCTS, its setting channels and the GW guidance system.

Bibliography

1. *Platunov V. S.* Methodology of the defence scientific research in aviation complexes. M. Delta, 2005. 344 s. (Russian)

2. *Baraev A., Gladilin A., Kozar V.* Sovremenniy podkhod k vyboru aviatsionnyh informatsionnykh kanalov voyennogo naznacheniya // Fazotron, 2013. No. 3 (22). S. 40–44 (Russian)

3. *Perunov Yu. M., Fomichev K. I., Yudin L. M.* Radio-electronic suppression of information channels and weapon control systems / ed. by *Yu. M. Perunov.* 2-nd ed., rev. and ext. M.: Radiotekhnika, 2008. 416 p. (Russian)

4. *Vladimirov V. I., Doktorov A. L., Elizarov F. V.* Elektromagnitnaya sovmestimost' radioelektronnykh sredstv i sistem / pod. red. *N. M. Tsar'kova.* M.: Radio i svyaz, 1985. 272 s. (Russian)

Submitted on 17.08.2016

Ermolin Oleg Vladimirovich – Candidate of Engineering Sciences, Associate Professor, Head of the Federal Air-Force Research Center of the Ministry of Defense of Russia, Schelkovo.
Science research interests: guided missiles.

Kozar Vitaliy Borisovich – Doctor of Engineering Sciences, Senior Research Officer at Joint Stock Company Moscow Research Institute Agat, Zhukovskiy.
Science research interests: missile guidance systems.

Системный подход к оценке эффективности применения боевого снаряжения управляемых средств поражения

Рассмотрено боевое снаряжение управляемых средств поражения как система, в состав которой может входить неконтактный датчик цели. Выполнен анализ возможного влияния организованных помех на эффективность боевого снаряжения с неконтактным датчиком цели. Предложена логико-вероятностная модель функционирования неконтактного датчика цели для учета влияния организованных помех на эффективность боевого снаряжения.

Ключевые слова: боевое снаряжение, неконтактный датчик цели, организованные помехи, управляемое средство поражения.

Ермолин Олег Владимирович – кандидат технических наук, доцент, начальник НИЦ ФГБУ «ЦНИИ ВВС Минобороны России», г. Щёлково.
Область научных интересов: управляемые ракеты.

Козарь Виталий Борисович – доктор технических наук, старший научный сотрудник, старший научный сотрудник АО «МНИИ «Агат», г. Жуковский.
Область научных интересов: системы наведения управляемых ракет.