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Substantiation of Reliability Requirements for Mobility Means of Surface-to-Air Missile Systems

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Abstract:

Common principles of substantiation of reliability requirements for vehicles (mobility means) of surface-to-air missile (SAM) systems are discussed. The principles mentioned include the impact of a hierarchically-branched structure of SAM system and reliability of their vehicles on system effectiveness under the real conditions. As the complex measure of SAM system effectiveness the coefficient of effectiveness sustainment of SAM system combat (technical) mobility means is used, which is the ratio of system output effect characteristic taking into account reliability measures of mobility means to its value in case, when mobility means do not have failures. The coefficient used here is considered to be the function of mean distance between failures (MDBF) of mobility means and their number.

Keywords:

effectiveness of the hierarchic system, mobility means, reliability requirements, surface-to-air missile system

1. Introduction

Modern experience of local wars and conflicts testifies to necessity of high mobility of military equipment in order to improve their survivability. Moreover, the mobility provides hidden combat deploying. First of all, the aforementioned applies to the SAM systems, which are the main firepower of air defense forces. At the same time, the development of new SAM systems and modernization of the existing ones are associ-

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ated with the necessity to substantiate requirements for their vehicles (mobility means) intended to provide mobility [1, 2]. Requirements for some vehicle characteristics (such as average speed, average cruising range, carrying capacity, ford depth, etc.) can be specified using some tactical considerations including SAM system external environment, and requirements to its survivability. However, the problem of substantiating the dependability requirements [3, 4] for mobility means of SAM systems, to which design and technological solutions, implemented by the motor vehicle chassis designer must comply with, needs more detailed research.

In most cases, reliability is the key factor that defines the dependability performance of any object of military equipment [3, 4]. The developed method for substantiating the reliability requirements for mobility means of SAM systems, which accounts for the functioning peculiarities of the mentioned systems, is described in the article.

2. Problem Formulation

Problems connected with reliability of the complex systems have been discussed in many works, particularly in [5-11]. At present, research of the SAM systems reliability focuses, as a rule, at problems of reliability of its land combat means, and, particularly, at the radio-electronic equipment [6, 8-12]. At the same time, it is assumed, that the vehicles, designed for transportation of combat and technical means of SAM system, are considered either as having no failures or their reliability being accounted for indirectly using simplified form of probability that combat and technical means will be successfully transported on certain distance.

Problems of reliability of vehicles of various types, which perform different functions, are studied by many specialists and described, for example, in [13-16]. However, the influence of vehicles reliability on SAM system effectiveness in the known works has not been practically examined and demands further research.

Our article is devoted to the developing the method for substantiation of reliability requirements for mobility means (vehicles) of SAM systems, which takes into account their hierarchic structure as well as the influence of the SAM system mobility means reliability on the system effectiveness.

3. Method Description and Basic Mathematical Equations

Due to the complexity of SAM systems, it is advisable to evaluate the mobility means influence on the whole system performance using the coefficient of effectiveness sustainment (K_{eff}), which can be calculated as the ratio of the target output characteristic (E_{im}) that accounts for the imperfection of the vehicles to its value (E_{id}) in the ideal case, when mobility means do not have any failures, or:

$$K_{eff} = \frac{E_{im}}{E_{id}} . \tag{1}$$

Vehicles provide delivery of combat means and SAMs to the firing positions. Therefore, it is necessary to distinguish between the performance of the combat and the technical mobility means within the SAM system. To estimate the effectiveness of mobility means, we will use the next characteristics as the target output E_{im}:

- expected number of firings, which the SAM system will perform that accounts for the number of combat means delivered to the firing positions by mobility means;

- expected number of SAMs that will be delivered to the firing positions (the launchers) by technical mobility means.

In such a case, we assume the following values E_{id} as being known in advance:

- number of firings, that the SAM system will perform in case when the combat mobility means will be operating without failures;
- number of SAMs needed to be delivered from the arms depot (technical unit) to the launchers using technical mobility means of SAM system in case when the vehicles will be operating without any failures.

It is advisable to use the following parameters as the performance characteristics of the SAM system mobility means:

- coefficient of effectiveness sustainment for vehicles of the SAM system combat means $K_{eff\ cm}$, which is the ratio of expected number of firings that the SAM system will perform by the combat means delivered to firing positions to the number of firings that the SAM system can perform by its entire set of combat means;
- coefficient of effectiveness sustainment for vehicles of the SAM system technical means $K_{eff\ tm}$, which is the ratio of expected number of SAMs delivered to launchers by the vehicles of technical means to the number of SAMs stored at the technical unit.

In such conditions, both expected values $K_{eff\ cm}$, $K_{eff\ tm}$ depend on the number of operable combat and technical mobility means, or, in other words, on the number of combat and technical mobility means, which had been operating without failures during certain time intervals necessary to perform combat tasks.

Functional structure of SAM system can be represented as hierarchic system [5, 8-10]. In such structure, auxiliary objects exist between basic controlling objects and the controlled ones. The objects interact on the basis of "signal transfer and transformation" by means of operable "intermediate" objects and "communication channels". Channel failure leads to impossibility of using this particular channel, and the object failure leads to impossibility of using also all slave (connected to this particular object) channels. We assume that element failures are mutually independent.

According to aforementioned, the structure of the SAM system combat mobility means is assumed to be hierarchic one. At the same time, such system can be formed recurrently, and its structure is shown in Fig. 1.

System S_f of rank f is formed by joining the system S_{f-1} of rank $f-1$ with the set of equal subsystems S_f, $f \geq 2$ according to the defined rules as shown in Fig. 1(a). System of the 1st rank is the initial system (in other words, $f = 1$, $S_1 = s_1$). The number of initial elements is $N_1 = n_1$.

In hierarchic systems with a simple dependence, the subsystem s_i, for any $i = 1, \dots, f$ consists of a single initial object O_i and n_i output objects as shown in Fig. 1(b). It is obvious that if $f \geq 2$, then for hierarchic systems S_f the following equality holds: $N_f = N_{f-1}, n_f = \prod_{i=1}^{f} n_i$.

Evaluation of the SAM system performance using hierarchic systems is done under the following assumptions:

- element of i^{th} level is thought as correctly functioning if this element along with all those elements connecting it to the zero level element of the hierarchic system S_f are operable. It is possible to assume that communication lines (branches) that unite elements are absolutely reliable. In other words, the reliability of

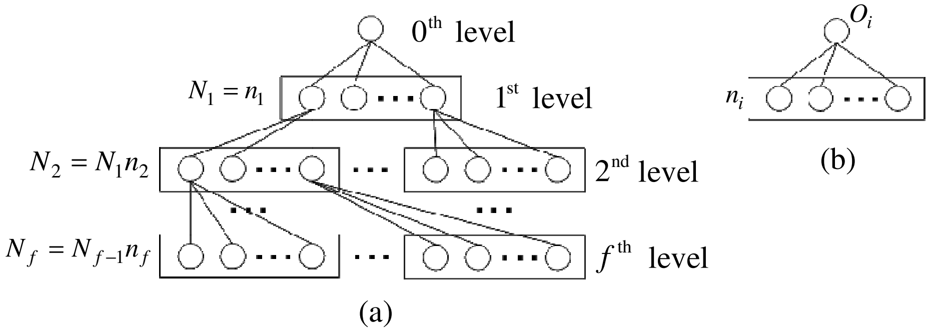

Fig. 1 Structure of considered (a) hierarchic system S_f and (b) subsystem s_i

branches can be accounted for by introducing corresponding corrections into the reliability of elements;

- performance of hierarchic system depends on the number of correctly functioning elements at each i^{th} level ($i \le f$).

As an example, let us analyze the structural diagram of mobility means of perspective medium-range SAM system (Fig. 1). It involves three levels. Mobility means of missile-guidance radar corresponds to the zero level at structural diagram. Mobility means of launchers, including the missile launch preparation equipment, form the 1st level. Mobility means of launchers without missile launch preparation equipment (launcher transporters) form the 2nd level on the diagram.

Hierarchic structural diagram of mobility means of perspective SAM system shown in Fig. 1 allows us to obtain mathematical equation for calculating the coefficient of effectiveness sustainment for the vehicles of SAM system combat means.

The statutory value of the march length for mobility means and corresponding values of reliability measures of mobility means are used as the input data for calculating the coefficients of effectiveness sustainment for the vehicles carrying the combat and technical means of SAM system. Expected values for these coefficients are the functions of the number of operable elements (mobility means of SAM system).

While calculating the coefficient of effectiveness sustainment for mobility means of perspective SAM system, we note the fact that design of the entire system allows for connection of the 2nd level launcher to any of the 1st level launchers. Also, the number of the 2nd level launchers, which can be connected to the 1st level one, is not limited. Such quality means that the necessary condition for firing is the presence of zero level element (missile-guidance radar) and at least one element of the 1st level (launcher coupled with missile launch preparation equipment) at the firing position.

Coefficient of effectiveness sustainment for the vehicles carrying combat means of SAM system, $K_{eff\ cm}$, can be obtained using Eq. (1). According to the aforementioned, the E_{im} in this equation is the product of reliability function for the vehicle carrying combat mean of SAM system at the 0th level and the expected number of SAMs, delivered by the vehicles carrying combat means of SAM system at the 1st and the 2nd levels of hierarchic system to the firing position, and E_{id} is the total number of missiles that the SAM system can carry. After substituting these values into Eq. (1), the coefficient of effectiveness sustainment for the vehicles carrying combat means of SAM system can be represented as follows:

$$K_{eff\ cm} = \frac{n_{\mathrm{SAM}}}{N_{\mathrm{SAM}}} \sum_{k=1}^{n_1+n_2} k R_0 R_{12}(k) , \tag{2}$$

where n_{SAM} is the number of missiles on a single launcher; N_{SAM} is the total number of missiles that the SAM system can carry; n_1, n_2 are the numbers of elements (mobility means) of the 1st and the 2nd levels respectively; R_0 is the reliability function for the mobility means of the 0th level; $R_{12}(k)$ is the probability of the event that exactly k combat means of the 1st and the 2nd level will be successfully deployed to the firing positions assigned to the SAM system by the corresponding mobility means.

Number of combat means of the 1st and the 2nd level in the SAM system delivered by the mobility means is a random variable that has binomial distribution [7-10]. The probability $R_{12}(k)$ can be expressed as the sum of probabilities of events that correspond to all possible combinations of reliable functioning of the 1st and the 2nd level elements, which ensure that the necessary number of combat means belonging to the SAM system will be delivered by the vehicles. Taking into account the hierarchic structure of SAM system and limited number of elements at each level, the expression for $R_{12}(k)$ can be presented as follows:

$$R_{12}(k) = \sum_{i=I_1(k,\,n_2)}^{I_2(k,\,n_1)} C_{n_1}^{i} R_1{}^{i} \left(1 - R_1\right)^{n_1-i} C_{n_2}^{k-i} R_2{}^{k-i} \left(1 - R_2\right)^{n_2-(k-i)} , \tag{3}$$

where R_1, R_2 are reliability functions of the 1st and the 2nd level elements (mobility means) respectively; $I_1(k,\ n_2)$, $I_2(k,\ n_1)$ are the lower and the upper summation limits respectively, which take the following values:

$$I_1(k, n_2) = \begin{cases} 1, & \text{if } k \le n_2 \\ k - n_2, & \text{if } k > n_2 \end{cases} , \quad I_2(k, n_1) = \begin{cases} k, & \text{if } k \le n_1 \\ n_1, & \text{if } k > n_1 \end{cases} . \tag{4}$$

Therefore, the equation for estimating the coefficient of effectiveness sustainment for the vehicles carrying combat means of the SAM system can be presented as follow:

$$K_{eff\ cm} = \frac{n_{\mathrm{SAM}}}{N_{\mathrm{SAM}}} \sum_{k=1}^{n_1+n_2} k R_0 \sum_{i=I_1(k,n_2)}^{I_2(k,n_1)} C_{n_1}^{i} R_1{}^{i} \left(1 - R_1\right)^{n_1-i} C_{n_2}^{k-i} R_2{}^{k-i} \left(1 - R_2\right)^{n_2-(k-i)} . \tag{5}$$

Probabilities R_0, R_1 and R_2 depend on the values of corresponding reliability measures. If possible decrease in reliability measures of vehicles carrying combat means of SAM system during their march (movement) can be neglected, then we can assume that the reliability functions for mobility means are exponentially distributed random variables [7-10]:

$$R_0\left(D_{1cm0}\right) = \exp\left(-\frac{D}{D_{1cm0}}\right), \ R_1\left(D_{1cm1}\right) = \exp\left(-\frac{D}{D_{1cm1}}\right), \ R_2\left(D_{1cm2}\right) = \exp\left(-\frac{D}{D_{1cm2}}\right), \tag{6}$$

where, D is the deployment distance (march length, in km); D_{1cm0}, D_{1cm1}, D_{1cm2} are the MDBFs (in km) for the elements (mobility means) at the 0th, 1st, 2nd level respectively.

If the unified vehicles are used (in this case their nomenclature and corresponding costs of spare kits to them will be reduced), then $D_{1cm0} = D_{1cm1} = D_{1cm2} = D_{1cm}$, $R_0(D_{1cm0}) = R_1(D_{1cm1}) = R_2(D_{1cm2}) = R(D_{1cm})$, and the Eq. (5) for calculating the coefficient of effectiveness sustainment for vehicles carrying combat means of SAM system can be simplified as follows:

$$K_{eff\ cm}(D_{1\,cm}) = \frac{n_{\mathrm{SAM}}}{N_{\mathrm{SAM}}} \sum_{k=1}^{n_1+n_2} k \sum_{i=I_1(k,n_2)}^{I_2(k,n_1)} C_{n_1}^{i} C_{n_2}^{k-i} R(D_{1\,cm})^{k+1} \left(1 - R(D_{1\,cm})\right)^{n_1+n_2-k} . \quad (7)$$

Increase in MDBF of mobility means leads to an increase in the coefficient of effectiveness sustainment $K_{eff\ cm}(D_{1cm})$ as shown in Fig. 2. This plot was obtained using Eq. (7) given the following input data: the lengths of march D = 50 km; the number of SAMs on a single launcher n_{SAM} = 4; the total number of missiles carried by the SAM system N_{SAM} = 48; the number of mobility means at the 1st and the 2nd level n_1 = 4 and n_2 = 8.

Using Eq. (7), it is possible to solve also the inverse problem. In particular, for the desired value $K_{eff\ cm}(D_{1cm})$ = 0.9, the boundary value $D_{1cm\ bound}$ = 950 km can be obtained.

Further on, let’s analyze the coefficient of effectiveness sustainment for the vehicles carrying technical means of the SAM system. In general, the number of SAMs that are to be delivered is not a multiple to the number of technical mobility means, thus m_1 vehicles carrying technical means of SAM system must conduct r_1 runs, and the rest of m_2 vehicles must conduct r_2 runs. The values of m_1, m_2, r_1, r_2 are determined as follows:

$$r_1 = \left[\frac{M_{\mathrm{SAM}}}{m_{\mathrm{SAM}} N_{\mathrm{TM}}} \right], \ r_2 = r_1 + 1, \ m_2 = \frac{M_{\mathrm{SAM}}}{m_{\mathrm{SAM}}} - N_{\mathrm{TM}} r_1, \ m_1 = N_{\mathrm{TM}} - m_2, \quad (8)$$

where [X] denotes the integer part of X, M_{SAM} is the number of missiles in arms depot that are to be delivered to the firing position; m_{SAM} is the number of missiles that a single technical mobility mean of SAM system can carry; N_{TM} is the number of

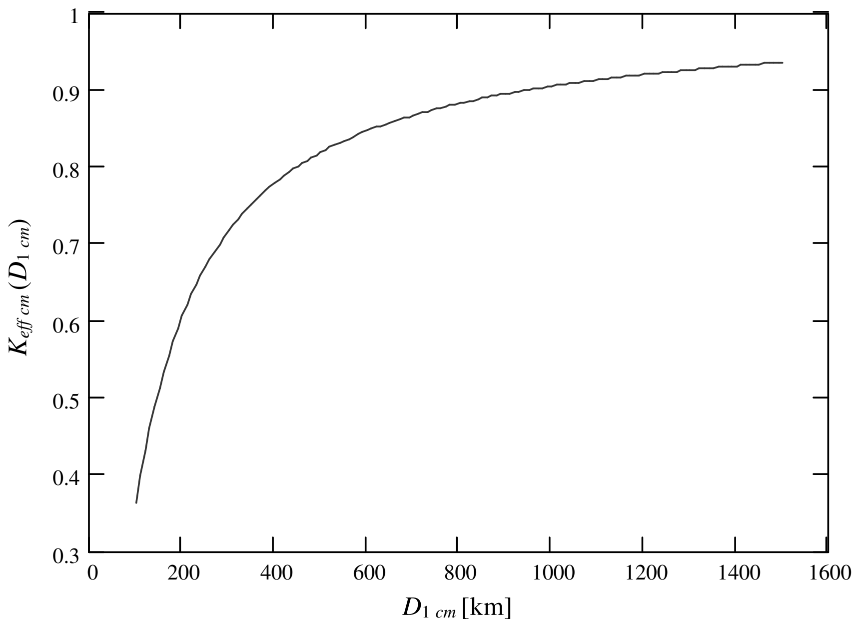

Fig. 2 Coefficient of effectiveness sustainment of vehicles carrying combat means of SAM system versus the vehicle's MDBF

technical mobility means of SAM system.

Value of the effectiveness sustainment coefficient for the vehicles carrying technical means of SAM system can be calculated using the following equation:

$$K_{eff\ tm} = \frac{m_{\text{SAM}}}{M_{\text{SAM}}}\left(m_1\sum_{i=1}^{r_1} R^i + m_2\sum_{j=1}^{r_2} R^j\right), \tag{9}$$

where R is the reliability function of a single vehicle carrying technical means of SAM system.

Probability R is the function of MDBF for the technical mobility means. If possible decrease in reliability measures of SAM system technical mobility means during the SAM transportation can be neglected, then we can assume that reliability function for mobility means is the exponentially distributed random variable [7-10]:

$$R(D_{1\,tm}) = \exp\left(-\frac{D}{D_{1\,tm}}\right), \tag{10}$$

where, D is the distance (in km) to which the SAMs are to be transported; D_{1tm} is the MDBF of technical mobility means (in km).

Accounting for Eq. (10), the Eq. (9) can be presented as follows:

$$K_{eff\ tm}(D_{1\,tm}) = \frac{m_{\text{SAM}}}{M_{\text{SAM}}}\left(m_1\sum_{i=1}^{r_1} \mathrm{e}^{-i\frac{D}{D_{1\,tm}}} + m_2\sum_{j=1}^{r_2} \mathrm{e}^{-j\frac{D}{D_{1\,tm}}}\right). \tag{11}$$

An increase in MDBF of technical mobility means of SAM system leads to an increase in the effectiveness sustainment coefficient $K_{eff\ tm}(D_{1tm})$, as illustrated in Fig. 3. The plot was obtained using Eq. (11) given the following input data: the distance between technical unit (arms depot) and firing position D = 50 km; the number of missiles that single technical mobility mean can transport m_{SAM} = 2; the number of missiles in technical unit that are to be delivered to the firing position M_{SAM} = 50; the number of technical mobility means N_{TM} = 12.

U sing Eq. (11), it is possible to estimate $D_{1tm\ bound}$, which is the limiting value of MDBF for technical mobility means. In particular, given the value of effectiveness sustainment coefficient $K_{eff\ tm}(D_{1tm})$ = 0.8, one can obtain from Eq. (11) that $D_{1tm\ bound}$ = 345 km.

4. Conclusions

A method of substantiation of reliability requirements for mobility means of SAM systems was proposed in the article. The method described here accounts for the hierarchic structure of SAM system as well as the influence of reliability of combat and technical mobility means on the SAM system effectiveness. Mathematical equations for the coefficients of effectiveness sustainment for the vehicles of SAM system carrying combat and technical means versus MDBF of the mentioned vehicles have been obtained. Using these equations, the limiting values of such reliability measures as MDBF of vehicles carrying combat and technical means of SAM system can be obtained for any given values of coefficients of effectiveness sustainment. The method developed here has an important practical application at the stage of development of perspective SAM systems and modernization of the existing ones.

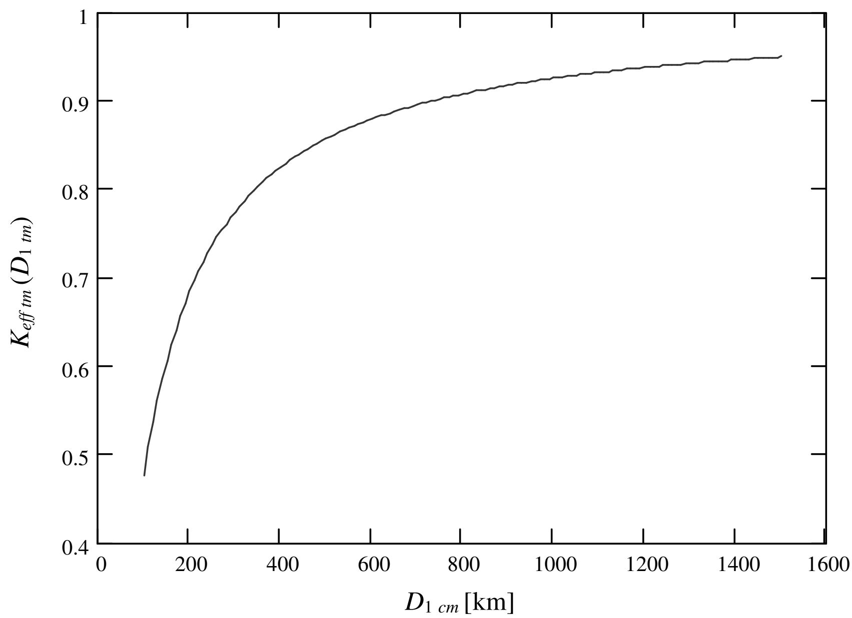

Fig. 3 Coefficient of effectiveness sustainment of vehicles carrying technical means of SAM system versus the vehicle's MDBF

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