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ASSESSMENT OF PROBABILITY OF LIGHTNING DIRECT STRIKE INTO ELEMENTS OF STATIONARY GROUND LAUNCH COMPLEX

Materials presented in the paper are the first stage of realization of methodology of ensuring the required level of protection of rocket space complexes from destabilizing action of lightning. The methodology is an obligatory element of ensuring a life cycle of the complexes and is logically integrated into the system of standards of IEC 61508 series. The presented first stage includes a calculated estimation of probability of lightning direct strike into elements of the complex. The estimation was carried out with using a method based on calculation of distribution of intensity of stationary electric field over the surface of objects of the complex. It is shown that it is sufficient to use only a variant of vertical, in relation to the ground surface, vector of intensity of electric field created by a thundercloud.

Key words: lightning, rocket space complexes; probability, direct strike, electric field.

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ОЦІНКА ЙМОВІРНОСТІ ПРЯМОГО УДАРУ БЛИСКАВКИ В ЕЛЕМЕНТИ СТАЦІОНАРНОГО НАЗЕМНОГО ПУСКОВОГО КОМПЛЕКСУ

Матеріали, представлені в доповіді є першим етапом реалізації методології забезпечення необхідного рівня захисту ракетних космічних комплексів від дестабілізуючого дії блискавки. Методологія є обов'язковим елементом забезпечення життєвого циклу комплексів і логічно вбудовується в систему стандартів серії IEC 61508. Представлений перший етап включає розрахункову оцінку ймовірності прямого удару блискавки в елементи комплексу. Оцінка проведена з використанням методу, заснованого на розрахунку розподілу напруженості стаціонарного електричного поля по поверхні об'єктів комплексу. Показано, що досить використовувати тільки варіант вертикального по відношенню до поверхні землі вектора напруженості електричного поля, створюваного грозовою хмарою.

Ключові слова: блискавка, космодром, ймовірність, прямий удар, електричне поле.

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ОЦЕНКА ВЕРОЯТНОСТИ ПРЯМОГО УДАРА МОЛНИИ В ЭЛЕМЕНТЫ СТАЦИОНАРНОГО НАЗЕМНОГО ПУСКОВОГО КОМПЛЕКСА

Материалы, представленные в докладе являются первым этапом реализации методологии обеспечения требуемого уровня защиты ракетных космических комплексов от дестабилизирующего действия молнии. Методология является обязательным элементом обеспечения жизненного цикла комплексов и логично встраивается в систему стандартов серии IEC 61508. Представленный первый этап включает расчетную оценку вероятности прямого удара молнии в элементы комплекса. Оценка проведена с использованием метода, основанного на расчете распределения напряженности стационарного электрического поля по поверхности объектов комплекса. Показано, что достаточно использовать только вариант вертикального по отношению к поверхности земли вектора напряженности электрического поля, создаваемого грозовым облаком.

Ключевые слова: молния, космодром, вероятность, прямой удар, электрическое поле.

Introduction

Lightning discharge is an extremely powerful electromagnetic phenomenon having a destabilizing effect on all systems of a ground stationary launch complex (GSLC), including a carrier rocket and a module placed into orbit. Monitoring and control systems of GSLC are the most vulnerable and dangerous from the viewpoint of possible negative consequences. Lightning discharge produces pulsed electromagnetic interferences that propagate in the form of pulses of voltage and current along circuits of power supply, wire control lines, coupling circuits, earth loops and in the form of pulsed electromagnetic field. At present, harmonization between possible levels of electromagnetic disturbances at a concrete object and immunity levels of equipment installed at this object is not realized in full measure. As a rule, immunity levels of GSLC equipment are specified with use of standards [1-6]. Naturally, the levels specified in the standards are determined as a result of averaging over different objects. In doing so, characteristic properties of each object in design of its system of lightning protection were not taken into account. Therefore analysis of possible values of parameters of electromagnetic disturbances that can accompany lightning discharge into elements of RSC with a certain probability is a topical problem.

The proposed procedure is a calculated and experimental one. The sequence of operations in realization of calculated estimation of parameters of currents and voltages that can with a certain probability appear at the ports of GSLC equipment is analogous to the recommended in the manual [7] (subsection 5.3.1.5). For a specified appearance of models of RSC, the results of the computer simulation are presented further in section 3.

In the work [8], it is stated that creation of lightning protection of RSC that ensures a design of protection with minimal weight and price is achieved when designing is carried out in a step-by-step manner by a specified algorithm. The following step-by-step approach was used in developing the design of space vehicle Orion:

– determination of zones of lightning strike in the system;

– determination of parameters of lightning;

– assessment of parameters of effects accompanying lightning;

– development of lightning protection measures;

– verification of sufficiency of protection measures.

As applied to GSLC, a procedure, which is analogous to the procedure presented in the work [9], which includes the following main steps is proposed:

1) determination, by a computational method, of the most probable zones of lightning strike taking into account distribution of probability of lightning current parameters;

2) calculation of parameters of intensities of electric and magnetic fields accompanying lightning in places where RSC elements are situated taking into account screening properties of bodies, buildings and structures;

3) experimental investigation of integrity of ground loops at the object and determination of the value of spreading resistance of lightning current. Development of recommendations on its improvement (if necessary).

4) calculated evaluation and experimental verification of paths of spreading of lightning current when lightning strikes into selected elements of the objects;

5) determination of all components and systems that are critically important, and also any components and systems that can spread direct or indirect lightning effects on critically important components or systems;

6) determination of coefficients of transformation of lightning energy into pulses of voltage and current that propagate by galvanic circuits and enter ports of critically important components of RSC;

7) experimental determination of immunity of critically important systems of RSC to pulses of current, voltage and electromagnetic fields with parameters specified in standards;

8) comparison of requirements of the standards, according to those the tests of item 7 were carried out, with parameters of the influencing currents, voltages and fields determined at the previous steps;

9) determination of necessity to install additional protection devices at the equipment ports and formation of requirements to such devices;

10) verification of sufficiency of the adopted measures for decreasing risks of occurrence of emergency situations at the object due to lightning strike.

In this paper, methods and results of calculation of probability of direct lightning strike into GSLC elements are presented.

Description of suggested method. GSLC are complex engineering objects situated at large territory, full of metallic constructions, situated at flat country far from other tall structures. Therefore lightning regularly strikes the territory of such objects. Lightning protection system of the object is formed, as a rule, by combination of rod and wire rope air terminals. In spite of high level of reliability of such systems, they do not ensure interception of all possible lightnings. Inrushes of lightning into elements that are important for safety of object functioning can cause serious negative consequences.

Modern procedures of assessment of efficiency of lightning protection systems based on formation of protection zones are presented in standards [10, 11]. Construction of zones is carried out with using method of «protection angle» or «rolling sphere». The following discrete values for four levels of reliability of lightning protection are established: 0.99, 0.97, 0.91 and 0.84. Radius of calculated sphere depends on the required level of reliability of interception of lightning with low values of leader potentials («low» lightning currents). Efficiency of zone methods in practice is explained by the fact that they ensure excessive requirements to protection level because a zone must cover the whole building. When protection 0.99 is provided at the external side of a zone, inside the zone, naturally, protection reliability is practically equal 1.

«Low» lightning are the most difficult to intercept, but no less dangerous for equipment. It is such lightning that can strike into the middle or the base of a tall structure. A lightning protection system designed on the basis of rolling sphere radius of 20 m (having the highest regulated reliability) is able theoretically to ensure interception of 99 lightning of 100 striking into protected territory. In practice it can be otherwise because the following important circumstances are not taken into account:

Lightning can pass through the lightning protection system, which is especially characteristic of lightning with potential up to 10 MV (current less 3 kA). Such lightning are few (2%) according to international statistics but that can be caused by insufficient sensitivity of used systems of monitoring. It can be supposed that probability of their occurrence depends on conditions of the concrete region and can reach 5%. Such lightning have high destructive force because can directly strike the most susceptible elements of an object, for example, CR at the launch pad.

Zone methods do not provide the possibility of detailed assessment of probability of lightning strike into objects with large area because they do not take into account real constructions of complexes and their surroundings.

Zone methods realize the principle of minimal distance between the leader of lightning and the grounded element. The principle of minimum of voltage of discharge gap which takes into account oncoming streamers from object elements is closer to the truth.

To assess probability of lightning strike into an object, methods of calculation of induced charges [12] and electrostatic field [8] that are similar in their essence are used. Because the method of induced charges is in fact equivalent to the method of distribution of electric field intensity over the surface of the object, the method of calculation of electric field is used in the framework of this work. An illustration of the results is presented in the next section.

In the work [9], a computer program that allows to obtain the picture of distribution of density of probability of inrush of lightning over the territory of the object is presented. At the given stage, a variant based on a standardized principle of minimum of the value of the discharge gap («rolling sphere» method) is realized. The essence of this computer model is that the process of orientation of lightning leader is assumed to be initiated when its streamer zone touches the ground, a grounded object or a lightning rod. In this model, it is assumed that lightning strikes into the zone that will be the first zone which will be reached by one of the competing spark channels developing in the streamer zone from the leader channel of lightning in all possible directions to the grounded areas connection with those ensures formation of galvanically closed circuit.

The probability of occurrence of lightning return current strength exceeding a specified value is presented graphically in the standard [10]. For the purposes of this work, an analytical approximation of this dependence from the work [13], in the form of formula (1), is used.

$$P(I) = [(1 + (I/a)^b]^{-1}, \quad (1)$$

where: $P(I)$ – probability that a current strength of descending negative lightning exceeds the value I; I, kA – the value of current of descending negative lightning; $a = 31$; $b = 2.6$.

It is natural that the value of current is related to the value of the cloud potential. In its turn, a radius of the rolling sphere is determined by the value of voltage at the gap of leader head – place of strike. To take account of this statistical characteristic in the framework of the proposed method for descending negative lightning, formula (2) presented in standard [10] was used. It should be noted that the dependencies (1) and (2) can be changed when new knowledge will be obtained.

$$R = 10 \cdot I^{\,0.65}, \quad (2)$$

where: R, m – a breakdown distance (radius) in the «rolling sphere» method; I, kA – lightning current strength.

From equation (2), it is easy to determine the maximal value of lightning current strength which can overcome a lightning protection system formed from combination of rod air terminals (masts) and lightning protection ropes. Such systems are usually used at space launching sites. The dependence of the maximal value of current strength (I, kA) on the minimal distance (R_{min}, m) between the elements is presented in Figure 1.

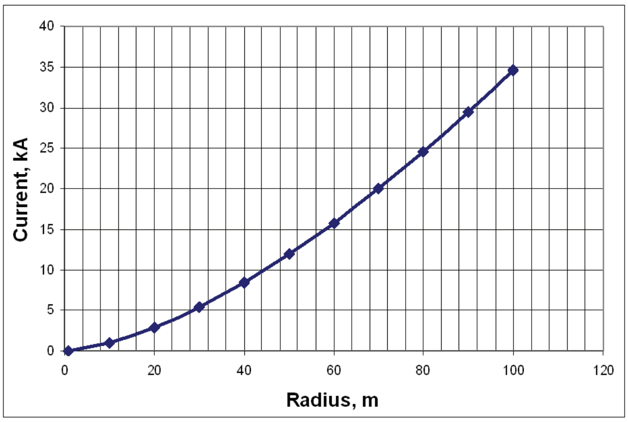

Figure 1 – Dependence of the maximal value of current strength on the minimal distance R_{min} between the elements

The probability of occurrence of lightning at the given territory with current strength which is less than that determined by Figure 1 is taken from the curves of distribution that are plotted from the results of processing of long-term observations. The averaged values can be taken from standard [10].

The proposed statistical approach has the following advantages:

1. It is possible to obtain data on probability of strike into one or another object with any degree of detail.
2. Creation of lightning protection system is possible with taking into account optimization of reliability-cost at the expense of detailed knowledge of the most probable zones of inrush of lightning into critical elements of the object.
3. In providing a specified level of reliability of lightning protection system, it is possible to take into account statistical peculiarities of lightning parameters in the location of the object (on condition that such data are available).
4. «Attraction» zone of lightning above the object is calculated automatically which radically improves reliability of the results in comparison to the data obtained with using formulae from standard [14]. These formulae will be discussed below.

Let us consider characteristic features of GSLC. As an example, consider GSLC presented in Figure 2. Assume that the height of masts of lightning protection is 80 m, the number of masts is 4, a distance between the masts is 72 m; masts serve as downward conductors; protection rope – between the masts. In this case the minimal distance is R_{min} = 36 m. The maximal value of current strength of lightning that can overcome the lightning protection system is, according to Figure 1, 5,42 kA.

Figure 2 – Ground launch complex (appearance) [https://www.flickr.com/groups/ares/pool]

An important feature of the stationary complex is that presence of rod air terminals (masts) 80 m in height increases essentially the probability of lightning strike comparing to the average density of probability of lightning in this region. The effect is caused by attraction of lightning from large distances which leads to an increase in «attraction area». An empirical formula (3) for calculation of the «attraction area» was taken from standard [14].

$$A_D = L \cdot W + 6 \cdot H \cdot (L+W) + 9\,\pi \cdot (H)^2, \qquad (3)$$

where: L, W and H – length, width and height of the object, respectively (m).

Results obtained with using formula (3) do not take into account connection with lightning current strength and therefore are not suitable for assessment of the number of lightning strikes into CR (when current strength is 5,42 kA). The number of strikes (N_D) of lightning into the object per a year is estimated with formula (4) [14].

$$N_D = N_G \cdot A_D \cdot C_D \cdot 10^{-6}, \qquad (4)$$

where: N_G – the density of lightning strikes during a year per km^2 in the region of object location; A_D –attraction area determined by formula (3) in m^2; C_D - coefficient given in Table 1.

Table 1 – The values of coefficient C_D

Conditions of location	**C_D**
Object is surrounded by the higher objects	0.25
Object is surrounded by objects commensurable in height or lower	0.5
Isolated object: there are no other objects near it	1.0
Isolated object at the top of hill or hillock	2.0

N_G can be estimated by the number (T_D) of thunderstorm days per year according to empirical formula (5) [14].

$$N_G = 0.1 \cdot T_D. \qquad (5)$$

At the initial stage of flight, a flare from the engine causes an increase in effective height H which increases attraction area A_D and, respectively, the probability of lightning strike into CR. It is important that in this case a lightning current strength will be no longer limited by lightning protection system. For this reason, various methods of monitoring thunderstorm environment are used and criteria of permissibility of launch as to thunderstorm danger are strictly regulated.

Results of calculation of zones of probable strike of lightning into GSLC obtained by the method of numerical simulation of electrostatic field are presented onward.

Numerical realization of the method of determination of probability of lightning strike into object elements by distribution of electrostatic field. To obtain a solution the mode Electrostatics, Boundary Elements (*esbe*) which is situated in the module AC/DC COMSOL is used который находится в модуле AC/DC COMSOL. The mode allows to carry out computations of distribution of potential in dielectrics in conditions when distribution of electric potential (V_S) at boundaries is specified. The solution is based on the method of finite elements. The Laplace equation (6) is being solved for scalar electric potential (V) as a dependent variable.

$$\nabla \cdot \left(\varepsilon_0 \varepsilon_r \nabla V\right) = 0\,. \qquad (6)$$

The external boundary at which a distribution of potential (V_S) is specified is selected in the form of a spherical shell which allows to change easily a direction of the vector of initial uniform electrostatic field (E_0). A three-dimensional model of GSLC (analogous to the presented in Fig. 2) with a plotted grid is presented in Figure 3.

The value of magnitude of intensity E_0 is assumed to be 10 kV/m which is typical of before-storm environment [15]. The following procedure of ranking of probable zones of direct lightning strike was realized:

– calculation of the surface integral of modulus of electric field intensity for assigned zones of possible direct lightning strike and probable directions of movement of thunderstorm cloud field;

– averaging of obtained values over directions of vector of electric field of thundercloud for each zone taking into account weight factors calculated at the previous stage;

– smoothing of obtained results taking into account stochastic factor.

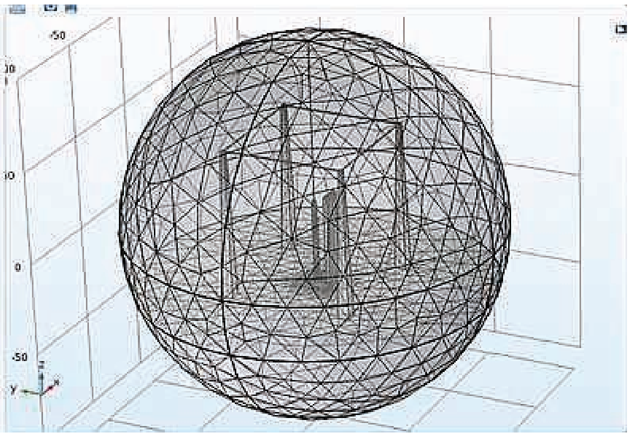

Figure 3 – Three-dimensional model of GSLC with plotted grid

The result of calculation of distribution of electric field intensity over the surface of GSLC elements under vertical direction of vector E_0 is presented in Figure 4.

Results of assessment of probability of lightning strike into object elements in the case of vertical direction of vector E_0 are presented in Table 2.

Comparison of results presented in Table 2 with results of averaging over possible directions of vector of electric field intensity of thundercloud shows insignificant difference (less than 2%). Therefore, in calculation of probability of lightning strike into elements of ground RSC, it is possible to limit oneself by calculation only of vertically directed vector of electric field intensity.

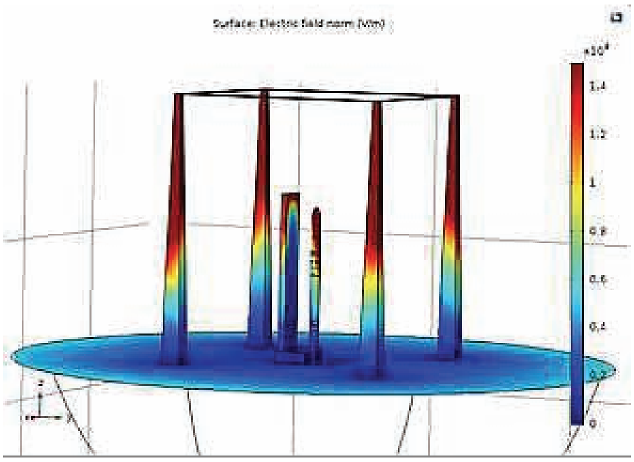

Figure 4 – Result of calculation of distribution of electric field intensity over the surface of GSLC elements under vertical direction of vector E_0

Table 2 – Results of assessment of probability of lightning strike into object elements

Zone of probable damage by direct lightning strike	Integral E over surface of zone, (V/m)	Probability of damage of zone by direct lightning strike, (%)	Probability of damage of zone taking account of stochastic factor, (%)
The higher part of mast 1	1.2839E7	21.73	21.35
The higher part of mast 2	1.2839E7	21.73	21.35
The higher part of mast 3	1.2839E7	21.73	21.35
The higher part of mast 4	1.2839E7	21.73	21.35
Connecting ropes	3.8223E6	6.48	7.23
The higher part of service tower	1.9056E6	3.20	3.60
The higher part of CR	1.9972E6	3.40	3.77

Conclusion. The first stage of the methodology of ensuring the required level of protection of RSCs from destabilizing action of lightning has been presented.

Method of calculated assessment of probability of direct lightning strike into elements of the complex based on calculation of distribution of intensity of stationary electric field over the surface of objects of the complex is efficient. It is shown that it is sufficient to use only a variant of vertical, relative to the ground surface, vector of intensity of electric field created by a thundercloud.

Method of statistical assessment of probability of lightning strike that takes into account probability of occurrence of lightning as function of lightning return stroke current strength has important advantages. This allows to elaborate zones of possible lightning strike for «low» lightning.

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