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Space launch system safety estimation models

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Abstract

The paper brings forward safety estimation models for different lifecycles on the basis of principle of maximum assured result.

Keywords: Failure mechanism; Emergency; Random process; Distribution function

1. Statement of the problem

By space launch system safety we mean set of qualities of the space launch system (SLS) never in its lifecycles to develop into states that are hazardous for human welfare, environment and any kind of property.

Safety assurance problem is one of the most important systematic problems of today. Many aspects are responsible for qualitative approach to solve this problem and in necessity to quantify the safety: specification of quantitative safety requirements in normative documents [1]; requirement of compulsory certification of space technology [2]; necessity to boost competitiveness under globalization conditions; cost optimization to ensure safety of subsystems components, etc. Safety is laid during designing, proved during certification, implemented during manufacturing and confirmed in operation [3]. This paper, in addition to numerous publications (for example, [3,4]), describes safety estimation models for different lifecycles of the SLS, as well as failure probability estimation models on the basis of principle of maximum assured result [5].

Principle lifecycles of the SLS that require safety assurance and mathematical models to estimate safety are: assembly and testing at the manufacturer's; loading and unloading operations; transportation to processing area and launch site; on-site mounting and testing; fuelling; Stage 1 engine start; launch abort and neutralization; initial and subsequent flight paths and disposal of launch vehicle (LV).

SLS safety assurance model corresponds to safety control paradigm when creating a new technology: design–separation–protection–caution–training. *Design* factor assumes development of systems on the basis of principles of natural safety, excluding dangerous mishaps. *Separation* factor is implemented through physical segregation of hazardous activities from the personnel. *Protection* factor stands for organization of special safety systems (in particular, LV emergency destruction system, *protected area*on the territory of the launch facilities). *Caution* factor means compensating measures in case of emergency. *Training* factor includes systems to build equipment handling skills and personnel development.

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Let us consider approaches to estimate failure probability of the SLS subsystems' components. Doing so we will rely on two provisions by Hermeyer [5]: objective function of the operation depends on three points—human strategy, random and undetermined factors; in case of indeterminacy the principle of maximum assured result is used taking into account well-known facts.

2. Factors—probability values

Let us estimate destruction probability of spherical bottle at design moment of time (case of well-known failure mechanism).

To take into proper account the indeterminacies (inaccuracy of strength analysis mathematical model, manufacturing technology and effect of human factor, testing, loading conditions, etc.), we introduce factors x_3 and x_5, that equal to the relation between actual values of load bearing capacity plus load and design values, respectively. Note that data to estimate factor x_3 can be collected during inspection sampling tests and other break-down tests, and for factor x_5 telemetry data for similar LV. Failure probability q equals:

$$q = \int_{z_{\min}}^{0} f(z)\,\mathrm{d}z = \iint_{Z=R-Q\angle 0} f(R)f(Q)\,\mathrm{d}R\,\mathrm{d}Q \times \iint\iiint_{(z=\frac{2x_1x_2}{r}x_3-x_4x_5)<0} \prod_{i=1}^{5} f_i(x_i)\,\mathrm{d}x_i, \quad (1)$$

where $z_{\min}$ is minimal operability function z, $R = (2x_1x_2/r)x_3$ bearing capacity, $Q = x_4x_5$ internal pressure, x_1 ultimate strength, x_2 thickness, r radius (non-random value), x_4 pressure and $f(R)$, $f(Q)$, $f(z)$, $f(x_i)$ density of distribution.

Estimation (1) was first calculated for the case when factors (1)—Pearson distribution of I type with parameters taken from [6]

$$f_i(x_i) = c\left(1 + \frac{x_i-\mu_i}{x_i''-\mu_i}\right)^l \left(1 - \frac{x_i-\mu_i}{\mu_i-x_i'}\right)^k, \quad (2)$$

where μ_i is the mathematical expectation, x_i', x_i'' are minimal and maximal values, l, k are exponents and c is the normalizing factor.

Then the same data were used to determine the initial moments of distribution Z, R, Q, x_3, x_5 of first to fourth orders that acted as constraints when finding maximums of expressions of functionals (1), which depend on unknown densities $f(Z)$, $f(R)$, $f(Q)$, $f(x_i)$ $(i = 3, 5)$.

Table 1
Values of maximum estimates of failure probability

Number of moments	Random values		
	Z	R, Q	x_1, x_2, x_3, x_4, x_5
1	0.6425	0.4695	0.2784
2	0.0702	0.0346	0.0303
3	0.0471	0.0135	0.0116
4	0.009	0.003	0.00011

Values of moments Z, R, Q, are given in [6]. Table 1 contains values of maximum estimates of failure probability (MEFP), calculated from techniques of [7,8].

Results given in Table 1 allow for two conclusions. For one thing, approaches of [7,8] are barely useful to turn to practical purposes, since failure probability comes out overestimated if compared to the case when density of distribution is well known ($q = 1 \times 10^{-9}$). For another thing, the more data are used for calculation of MEFP the more accuracy is attained, which means that more data should be added. So it is suggested to use distribution of factors that characterize performance and can be accumulated from statistical data on similar LV. Pearson curves of type I is the bounded distribution of various shapes, has a simple view and is widely used, Eq. (2). Exponents l and k, giving minimum to safety estimation, are given in [6].

In this case MEFP is considerably lower than those given in Table 1: with tolerance and mathematical expectation z estimate q is equal to 0.029; with known tolerances and mathematical expectations R and Q – $q = 0.0061$; with known tolerances and mathematical expectations of four factors (x_1, x_2, r, x_4) $q = 1 \times 10^{-5}$. To further minimize MEFP it is necessary to add data on distributions of l and k in Eq. (2):

$$q = \iint\int_{l_{\min}}^{l_{\max}} \iint\int_{(z=\frac{2x_1x_2}{r}x_3-x_4x_5)<0} \times \iint \prod_{i=1}^{5} f_i(l_i)\,\mathrm{d}x_i. \quad (3)$$

Integral equations (1) and (3) are calculated by directed enumeration of possibilities algorithm in the zone of failure [6]. Since the zone is small, the required calculation accuracy can be reached within less than 10 min of personal computing.

3. Factors—probability processes

Next we will consider MEFP estimation approach with random processes and known distribution laws in