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Original article

Validation of Reliability Indices during Experimental Development of a Complex Technical Series System

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Abstract
Introduction. The article studies the problem of validating the specified levels of reliability during experimental development of a complex technical series system. Such tasks arise when it is required to make a decision on testing the system as part of a larger one or on the completion of experimental development and the start of series production. The study is aimed at validating the reduction of the experimental development time. The task is to determine whether the hypothesis H_o is accepted or rejected.
Materials and Methods. To implement the research objective and task, a critical area described by the inequality was constructed based on the test results. The formulation of the requirements validation task was based on well-known approaches to testing statistical hypotheses. The conceptual apparatus of information theory, probability, and statistics was involved. The theoretical and applied literature on mathematical methods in reliability theory was studied. The particular tasks of the work were solved by known ways. Thus, the probability of obtaining the exact number of successful outcomes in a certain number of experiments was determined by the Bernoulli scheme. The exact confidence interval based on the binomial distribution was derived from the Clopper-Pearson relation. The theorem of A.D. Solovyov and R. A. Mirny made it possible to assess the system reliability based on the test results of its components.
Results. Control rules adequate to the stage of experimental development (with insufficient data on the technical system) and the stage of series production were mathematically defined. The probability of a successful outcome when testing technical systems was represented by:
– the probability of event for a system element;
– confidence value;
– required scope of tests
In these terms, the null and alternative hypotheses and the corresponding reliability control procedures were investigated. Two provisions were considered. The first one provided using the null confidence hypothesis $H_o = \{P \geq P_T\}$ and an alternative $H = \{P < P_T\}$ to confirm the requirements $(\underline{P}_T, \gamma)$ for the reliability indicator of one parameter for any $(\underline{P}_T, \gamma)$. In this case, one trouble-free test was enough. The second provision considered a sequential technical system with independent elements that were tested separately from the system according to the Bernoulli scheme for one parameter. We considered the requirements for the system in the form of a set of values $(\underline{P}_T, \gamma)$ and the requirements for any of its elements $(\underline{P}_{Ti}, \gamma)$. They coincided when the planned outcome of the tests corresponded to the cases when the ratio $\underline{P} = \lim_{1 \leq i \leq N} : \underline{P}_i = \underline{P}_m$ was fulfilled, and the null alternative hypothesis was selected from the theory of statistical hypothesis testing.

Discussion and Conclusions. The experimental development strategy should be implemented in two stages: the search and validation of the reliability of the elements through a series of fail-safe tests. In this case, the planned scope of tests of each element is determined taking into account the confidence probability, the lower limit of the confidence interval, and the requirements for reliability indices of one parameter of the technical system. If the use of the null confidence hypothesis is acceptable, one fail-safe test is sufficient to confirm the requirements for the reliability index.

Keywords: experimental development, testing of statistical hypotheses, reliability of a technical system, null hypothesis, alternative hypothesis, hypothesis of distrust, confidence hypothesis, confidence probability, scope of fail-safe tests, binomial type test model, Bernoulli scheme, Clopper-Pearson equation, theorem of A. D. Solovyov and R. A. Mirny.

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Научная статья

Подтверждение показателей надежности при экспериментальной отработке сложной технической системы с последовательным соединением элементов

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Аннотация

Введение. Статья посвящена проблеме подтверждения заданных уровней надежности при экспериментальной отработке сложной технической системы с последовательным соединением элементов. Такие задачи возникают, когда требуется принять решение об испытании системы в составе более крупной или об окончании экспериментальной отработки и запуске серийного производства. Цель исследования — обосновать сокращение сроков экспериментальной отработки. Задача — определить, принимается или отклоняется гипотеза H_o.

Материалы и методы. Для реализации цели и задачи работы по результатам испытаний строится критическая область, описываемая неравенством. Формулировка задачи подтверждения требований базируется на известных подходах к проверке статистических гипотез. Задействуется понятийный аппарат теории информации, вероятности и статистики. Изучена теоретическая и прикладная литература о математических методах в теории надежности. Частные задачи работы решены известными способами. Так, вероятность получения точного числа успешных исходов в определенном количестве экспериментов определена по схеме Бернулли. Точный доверительный интервал, основанный на биномиальном распределении, получен из соотношения Клоппера — Пирсона. Теорема А. Д. Соловьева и Р. А. Мирного позволила оценить надежность системы по результатам испытаний ее компонент.

Результаты исследования. Математически определены правила контроля, адекватные этапу экспериментальной отработки (при недостаточности данных о технической системе) и этапу серийного производства. Вероятность успешного исхода при испытании технических систем представлена через:

– вероятность события для элемента системы;

– значение доверительной вероятности;

– требуемый объем испытаний.

С этих позиций исследованы нулевая и альтернативная гипотезы и соответствующие им процедуры контроля надежности. Рассмотрены два положения. Первое допускает использование нулевой гипотезы доверия

$H_o = \{P \geq P_T\}$ с альтернативой $H = \{P < P_T\}$ для подтверждения требований $(\underline{P}_T, \gamma)$ к показателю надежности одного параметра при любых $(\underline{P}_T, \gamma)$. При этом достаточно одного безотказного испытания. Второе положение рассматривает последовательную техническую систему с N независимыми элементами, которые испытываются отдельно от системы по схеме Бернулли для одного параметра. Рассмотрим требования к системе в виде совокупности величин $(\underline{P}_T, \gamma)$ и требования к любому ее элементу $(\underline{P}_{Ti}, \gamma)$. Они совпадают, если планируемый исход испытаний соответствует случаям выполнения соотношения $\underline{P} = \lim\limits_{1 \leq i \leq N} : \underline{P}_i = \underline{P}_m$, а нулевая альтернативная гипотеза выбирается из теории проверки статистических гипотез.

Обсуждение и заключения. Стратегию экспериментальной отработки следует реализовать в два этап: поиск и подтверждение надежности элементов серией безотказных испытаний. В этом случае планируемый объем испытаний каждого элемента определяется с учетом доверительной вероятности, нижней границы доверительного интервала и требований к показателям надежности одного параметра технической системы. Если допустимо использование нулевой гипотезы доверия, для подтверждения требований к показателю надежности достаточно одного безотказного испытания.

Ключевые слова: экспериментальная отработка, проверка статистических гипотез, надежность технической системы, нулевая гипотеза, альтернативная гипотеза, гипотеза недоверия, гипотеза доверия, доверительная вероятность, объем безотказных испытаний, модель испытаний биномиального типа, схема Бернулли, уравнение Клоппера — Пирсона, теорема А. Д. Соловьева и Р. А. Мирного.

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Introduction. Rational methods of validating the specified reliability levels are of current concern for experimental testing of a complex technical system when a decision is made on the possibility of testing it as part of a larger structure or on the completion of experimental development and the start of series production. The same tasks arise during series production, if it is required:

– to assess the readiness of the enterprise to produce series products based on the test data of the pilot batch;

– to make a conclusion about the compliance of the products with the requirements of technical documentation, taking into account the operating data.

The study objective was to obtain an acceptable solution for planning and reducing the scope of tests using methods of interval estimation of reliability indices of sequential technical systems. To achieve the stated goal, it was required to determine whether hypothesis H_o was accepted or rejected.

Materials and Methods. It is reasonable to formulate the task of validating the requirements in terms of the theory of statistical hypothesis testing [1–4]. Let P be the reliability of the technical system, P_T — some fixed (required) level for P. Prior to testing about P, three initial assumptions can be made: $P = P_T$, $P \leq P_T$, $P > P_T$.

Each of them is called a null hypothesis if it is written as:

$$H_o = \{P = P_T\},\ H_o = \{P \leq P_T\},\ H_o = \{P > P_T\}.$$

Set $H_o = \{P = P_T\}$ contains only one element, therefore, hypothesis $H_o = \{P = P_T\}$ is called simple. Hypotheses of the form $H_o = \{P \leq P_T\}$ and $H_o = \{P > P_T\}$ are called complex. Along with the null hypothesis expressing a pre-formulated point of view, an alternative hypothesis H is specified expressing the opposite statement $H_o(H_o \cap H = \Omega)$. We use the conceptual apparatus of the theory of information [1], probability and statistics, applicable to solving such problems. Consider two aggregates of sets H_o and H:

$$H_o = \{P \leq P'_T\},\ H = \{P > P'_T\}, \quad (1)$$

$$H_o = \{P \geq P_T\},\ H = \{P < P_T\}. \quad (2)$$

Hypothesis H_o in (1) will be called rigid, or the distrust hypothesis. Indeed, in case (1), initially (before the test), we proceed from a position of distrust of the quality level of the system. Reliability index P is assumed to be no higher than a certain fixed level P'_T. Hypothesis H_o in (2) will be called the confidence hypothesis, since in this case, it is initially assumed that reliability index P is not less than some fixed value P_T.

The meaning of values P'_T and P_T is different. In (1), P'_T — such a rejected value that at $P \leq P'_T$, the system is considered unacceptable. In (2), P_T — such a value that at $P \geq P_T$, the system is considered acceptable for use. Obviously, $P_T > P'_T$.

Research Results. Thus, it is required to determine whether hypothesis H_o is accepted or rejected. In the theory of statistical hypotheses, a critical area is constructed for this purpose based on the test results. It is described by some inequality. Moreover, the null hypothesis (due to the initial confidence in it) is adhered to as long as it is reasonable from the point of view of the accepted level of significance α. Therefore, as is already clear that the reliability control procedure in case (1) will be significantly different compared to case (2).

Indeed, we will further make sure that to reject hypothesis H_o in (1) and accept hypothesis $H = \{P > P'_T\}$ of meeting the requirement for reliability indices, a critical area (or condition) should be used

$$\underline{P} > \underline{P}'_T , \tag{3}$$

where $\underline{P}$ — the lower bound of the confidence interval for P at the value of the confidence probability $\gamma = 1 - \alpha$; $\underline{P}'_T$ — the lower bound of the rejected interval for P at the value of confidence probability $\gamma = 1 - \alpha$.

In case (2), the condition should be used to accept hypothesis H_o about the compliance of the value of parameter P to the requirement

$$\overline{P} \geq P_T , \tag{4}$$

where $\overline{P}$ — the upper bound of the confidence interval for P at the value of the confidence probability $\gamma = 1 - \alpha$.

In (3) and (4), the requirement for the reliability index of one parameter P is understood as a set of values $(\underline{P}'_T, \gamma)$ or $(\underline{P}_T, \gamma)$, given before testing.

Let one successful test be carried out under the conditions of the Bernoulli scheme. Then, using the Clopper-Pearson relations, we find the lower and upper bounds of one parameter with the value, for example, γ = 0.95:

$$\underline{P} = (1 - \gamma)^{1/1} = 1 - \gamma = 0.05; \; \overline{P} = 1.$$

Here, even for very moderate values $\underline{P}'_T \in [0.05;\ 0.95]$, condition (3) is not fulfilled, while (4) is fulfilled at any P_T. Let us show the validity of the accepted position.

<u>First position.</u> If it is permissible to use the null confidence hypothesis $H_o = \{P \geq P_T\}$ with alternative $H = \{P < P_T\}$, then one fail-safe test is sufficient to confirm the requirements $(\underline{P}_T, \gamma)$ for the reliability index of one parameter for any $(\underline{P}_T, \gamma)$.

If the initial hypothesis H_o is the hypothesis of distrust from (1), then a significantly larger number of tests are needed. Thus, for $m = 0$, we get $n \geq log(1 - \gamma)/log\underline{P}_T >> 1$. This is quite fair, because, when testing hypotheses, they initially proceed from the validity of the null hypothesis H_o.

At the stage of experimental development, there are no sufficiently complete data, therefore, it is reasonable to use control rule (3). At the stage of series production, one can proceed from the confidence hypothesis and use a significantly easier control rule (4). This is acceptable if, according to the experimental testing, condition (3) was fulfilled.

Consider a system consisting of N independent elements connected in series, which can be tested separately. Then, the probability of a successful outcome when testing technical systems:

$$P = \prod_{i}^{N} P_i . \tag{5}$$

Here, P_i — probability of the same event for the i-th element. The requirements for value P are specified in the form of a set of values $(\underline{P}_T, \gamma)$. It is required to plan a procedure for monitoring the reliability of one parameter for each element of the system, i.e., to specify $\forall i \in [1, n]$ a pair $(\underline{P}_{Ti}, \gamma)$.

Due to the multiplication of P_i in formula (5), ratio $\prod_i^N P_{Ti} = P$ must be fulfilled. Besides, $\gamma_i = \gamma$.

As a result, the required scope of tests n_i of each element increases dramatically, and even with fail-safe results of all tests, it becomes unacceptable. At $\underline{P}_T = 0.9$ and $\gamma = 0.95$, $N = 100$ and $m = 0$, $\forall i = \overline{1, N}$:

$$P_{Ti} \sim \underline{P}_T^{1/100} = 0.999,\ n_{oi} = log(1 - \gamma) / logP_{Ti} \sim 3000.$$

This method of planning is logically contradicted by inequality $n_{oi} > n_o$, following from $P_{Ti} > \underline{P}_T$ when $m_i = 0$. It is clear that with fail-safe outcomes, the required scope of tests n_{oi} of i-th element, conducted separately from the system, should be equal to the required scope of tests of system n_o. To avoid this contradiction, the theorems of A.D. Solovyov and R.A. Mirny should be used [5–7]. Thus, when $m = 0$, $\forall i = \overline{1, N}$:

$$\underline{P} = \min_{1 \le i \le N} : \underline{P}_i = f\ (n,\ 0,\ \gamma) = (1 - \gamma)^{1/n}. \tag{6}$$

Here, $\underline{P}$ — the lower bound of the confidence interval for the reliability index of a technical system by one parameter, at value γ of the confidence probability; $\underline{P}_i$ — the value of the lower bound of the confidence interval for the reliability index of the i-th element of the system with the same confidence probability; n — minimum number of tests of system elements; $f(n, 0, \gamma)$ — the root of the Clopper-Pearson equation:

$$1 - \gamma = \sum_{k=0}^{m} \binom{n}{k} P^{n-k} q^k = B(n,\ P,\ m). \tag{7}$$

According to [8–12]:

$$f(n, n\overline{q}, \gamma) \le P \le f(n,\ [n\overline{q}], \gamma). \tag{8}$$

Here, $\overline{q} = 1 - P$; $P = \prod_{i=1}^{N} (1 - m_i / n_i)$; $n = \min_{1 \le i \le N} n_i$; $[n\overline{q}]$ — integral part of the product $n\overline{q}$; $f(n, n\overline{q}, \gamma)$ — root of equation $J_P(n, P, n\overline{q} + 1) = 1 - \gamma$.

From (8), it follows:

$$\underline{P} = \min_{1 \le i \le N} : \underline{P}_i = \underline{P}m, \tag{9}$$

where $\underline{P}_m$ — minimum of $\underline{P}_i$ at the value of confidence probability γ.

$$P_m = \min_{1 \le i \le N} : \underline{P}_i \ge P_T \Leftrightarrow (\underline{P}_1 \ge P_T) \cap (\underline{P}_2 \ge P_T) \ldots \cap (\underline{P}_N \ge P_T).$$

This is true not only for case (1), when $m = 0$, $\forall i = \overline{1, N}$, but also for case (2), i.e., for the outcome $n = (n_1, n_2, \ldots, n_N)$, $m = (m_1,\ 0,\ 0,\ \ldots,\ 0)$ of the tests, where n and m — the vector of tests and the vector of failures, if $n_1 = n$.

At this, only one element that has been tested a minimum number of times fails. Indeed, in this case, $n\overline{q} = m_1$ — an integer. Calculations allowed us to establish that (9) is also approximately performed at the outcome of tests n, m, i.e., in case (3), if for pair (n_1, m_1), $\min_{1 \le i \le N} : \underline{P}_i = \underline{P}_m$ is possible.

In all the cases mentioned (9), the lower bounds are not multiplied, and the system degenerates into one weakest element. This provides validating the following position.

<u>Second position.</u> Consider a sequential system with N independent elements that are tested separately from the system according to the Bernoulli scheme for one parameter. The requirements specified for the system in the form of a set of values $(\underline{P}_T,\ \gamma)$, and the requirements for any of its elements $(\underline{P}_{Ti},\ \gamma_i)$ coincide if the planned outcome of the tests corresponds to the mentioned cases of fulfillment of ratio (9), and the null alternative hypothesis is selected based on (1) and (2).

<u>Consequence.</u> In case of (3), execution of (9) — the planned scope of fail–safe tests $(N - 1)$ of elements, it is determined from:

$$n_i \ge n_0 = log\ (1 - \gamma)\ /\ log\underline{P}_T. \tag{10}$$

The volume of failures of the conditionally first element at m_1 is from the ratio:

$$\underline{P}_1 = f(n_1, m_1, \gamma) = \underline{P}_T . \quad (11)$$

Proof (11) is based on the fact that the condition $\underline{P} = P_H \geq \underline{P}_T$ is fulfilled if $P_H = \underline{P}_1 = \underline{P}_T$ and $\underline{P}_1 \leq \forall i \in [2, N]$. The latter relation is satisfied if (10) is satisfied, because:

$$n_i \geq n_0 \Leftrightarrow \underline{P}_i = (1 - \gamma)^{1/ni} \geq \underline{P}_T .$$

In all the cases considered, it was assumed that there was no information about P before the tests, except for the obvious fact $P \in [0, 1]$. However, it may be known that $P \geq P_H$, where $P_H = 0$. Hence, $P = \dot{P} \in [P_H, 1]$. Value P_H can be found from test data or calculations at the time of planning reliability tests. There is no method for determining P_H yet, and its development is the task of future research. But if value P_H is known, according to the full probability formula, you can find:

$$\dot{P} = P + \bar{q}\underline{P} .$$

From here:

$$P = (\dot{P} - P_H) / (1 - P_H) ,\ \underline{P} = (\dot{\underline{P}} - P_H) / (1 - P_H) . \quad (12)$$

The latter relation is fulfilled due to monotonicity of dependence $P = (\dot{\underline{P}} - P_H)$ in $\dot{P}$:

Taking into account (12), ratio (2) will take the form:

$$P_H + (1 + P_H) f(n, n\bar{q}, \gamma) \leq \dot{\underline{P}} \leq P_H + (1 - P_H) f(n, [n\bar{q}], \gamma) . \quad (13)$$

Let the condition for making a decision on the compliance of the technical system with the requirements $(\underline{P}_T, \gamma)$ still be (3), where the lower bound of the confidence interval is determined from (13), taking into account $P = \dot{\underline{P}} \in [P_H, 1]$. Then, from the ratio:

$$\dot{\underline{P}} \geq \underline{P}_T \quad (14)$$

we find the planned scope of trouble-free tests by one parameter for each of N elements:

$$n_i \geq n'_0 = log(1 - \gamma)\ log(\underline{P}_T - P_H) / (1 - P_H) . \quad (15)$$

Value n'_0 decreases in P_H. It means, n_0 (10) at $P_H = 0$ and $n'_0 = 0$ at $P_H = \underline{P}_T$.

Example. The requirements for the reliability indices $P = \prod_i^N P_i$ of the system are specified for one parameter in the form of a set of values ($\underline{P}_T = 0.90$; $\gamma = 0.95$). Number of elements of the technical system is $N = 100$. According to available data, $\underline{P}_T > P_H = 0.70$. It is required to find the planned scope of tests for each of N elements, if the fulfillment of reliability requirements is checked by condition (14). From (15), we find:

$$n_i \geq n'_0 = log\ (0.05) / log\ (0.90 - 0.70) / (1 - 0.70) = 7.$$

Note that at $P_H = 0$ $n_i \geq n'_0 = 29$.

Ratios (10) and (15) make it possible to plan the required scope of testing of the i-th element of the technical system with a certain sequence of experimental development of the system. The whole process of experimental development is divided conditionally into two periods: the search and validation of reliability requirements for a decision on the transition to the next stage of testing or on the acceptance of a technical system for series production. In the first period, improvements are possible, and it is reasonable to use models with a variable probability P of a successful outcome of the system test.

The data obtained in the first period can be used to calculate value P_H.

In the second period, we deal with an established version of the design of the technical system and technological process. This makes it possible to use the binomial type test models discussed above with constant probability P.

Let the first period of developing N elements of the technical system be completed, then, the question is raised about validating the requirements for the reliability index of the system by one parameter. It is reasonable to validate reliability if a positive decision is made only in case of a fail-safe outcome of the last series of tests for each of N elements. This strategy is convenient because it is based on the minimum possible number of tests of elements of the technical system and provides simple analytical solutions (10) and (15).

In general, it makes sense to investigate a strategy that allows for failures of elements during testing and is based on optimization of some objective function. But here, we restrict ourselves to considering only the mentioned strategy with fail-safe final series.

Discussion and Conclusions. The results of scientific research allowed us to formulate the following conclusions.

1. Even with a large number of *N* elements of the system, it is possible to plan the scope of their tests. In this case, the methods of interval estimation of reliability indices of sequential technical systems provide obtaining an acceptable solution, but only for one parameter.

2. The strategy of experimental development of technical systems is closely related to the method of validating the reliability of elements. The rational strategy of experimental development provides for confirmation of the reliability of the elements after the search period through a final series of fail-safe tests. In this case, the planned scope of tests of each of *N* elements does not depend on *N* and is determined by ratio (15), which includes the requirements ($\underline{P}_T$, γ) for the reliability indices of one parameter of the technical system as a whole and P_H. The scope of tests obtained by (15) for each element of the technical system, for any number of them, is small if moderate requirements ($\underline{P}_T = 0.80 \ldots 0.95$; $\gamma = 0.90 \ldots 0.95$) are specified for a system of *N* elements, but only for one parameter. At the same time, the scope decreases with increasing value P_H.

3. In series production, when testing upgraded technical systems, it is possible to use a control method with null and alternative hypothesis change. If the use of the null confidence hypothesis is acceptable, then one fail-safe test is sufficient to validate the requirements for the reliability index.

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