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Victor Gribov[1]
Yurii V. Hryshchenko[2]
Yurii Yu. Hryshchenko[3]

EMPIRICAL EVALUATION OF DEPENDABILITY OF AVIONICS COMPONENTS UNDER CONDITIONS OF AFTER-SALES SERVICE

National Aviation University
1, Kosmonavta Komarova Avenue, Kyiv, 03058, Ukraine
E-mail: [1]vmgribov@gmail.com; [2]hryshchenko8y@gmail.com; [3]noktinua@gmail.com

Abstract

Purpose: *the main purpose of this research is to improve the accuracy of dependability evaluation of avionics components under conditions of after-sales service. The accuracy of calculation of reliability measures offered to improve by the application of probabilistic-physical diffusion nonmonotonic failure model.* ***Methods:*** *the article proposes technique for estimating the accuracy of the quantile method based on the simulation modeling of the process of occurrence of single failures, confirming the high data validity of the empirical estimates of mean time to failure.* ***Results:*** *we obtained the quantitative assessment of evaluation errors of mean time to failure. The calculation was made for practically important in the operation of onboard equipment ranges of variation of first failure in the conjunction of the total number of sets of the same type operated. The presented results of the research show that the quantile method is effective tool for estimation the actual reliability of operated avionics components by single failures.* ***Discussion:*** *during the operational phase of aircraft the quantiles method with using of probabilistic-physical model of failure is an effective tool for obtaining adequate estimates of dependability of maintained avionics components. First of all it concerns the mean time to failure - one of the measures of reliability. This measure is widely used in international standards. The presented methodology provides increasing the efficiency of integrated logistics support in the process of monitoring the technical condition and maintenance characteristics of aircraft components.*

Keywords: DN-model of dependability; operation supportability; probabilistic-physical technology; quantile method; simulation modeling.

1. Introduction

Modern aircraft, which is definitely high technology production, has long operating life. The expenses necessary for the maintenance of predetermined characteristics of dependability, availability and safety of aircraft during operation, can greatly exceed the cost of their purchasing. That is why in the world market a precondition for the conclusion of contracts for the supply of aircraft is fulfillment of requirements of international standards for integrated logistics support (ILP), which is a complex of processes and procedures designed to reduce the costs during the aircraft operational phase and to provide the identification and analysis of the parameters **supportability of operation** of supplied products. Integrated logistics support is means of controlling of the life cyclecost (Life cycle cost – **LCC**) and the main criterion for the decision to purchase aircraft, including the cost of purchasing and maintenance [1].

2. Analysis of the latest research and publications

At the same time, the calculations of dependability by the methods of industry standards and the estimates of integrated levels of failsafe of critical systems and technological processes, techniques based on exponential (*EXP*) distribution of possible failure situations are used [1]. *EXP*-model satisfactorily described the distribution of failures of elemental base during middle of 19th century and at the same time it was introduced to all industry standards for calculations of dependability. However, for highly reliable and functionally complex element base *EXP*-model of failures has serious problems with the adequacy of predictive and empirical estimates of dependability of elements and systems: methodological error estimates of dependability measures,obtained on the basis of an exponential failure model, reach hundreds and thousands of percent, which significantly reduces the efficiency of integrated logistics support [1-3].

At the same time, the existing legal and technical basis [4, 5] offers new and modern technology of research of dependability of technical systems, which uses a probabilistic and physical approach.

3. Research tasks

The effectiveness of after-sales maintenance is characterized by **an integral index of supportability – functionality**

$$\boldsymbol{S} = \phi(\text{ MTMA, MTBMA, RML, LOR, RST, ... , MTTF, MTBF, MTTR, MTBR, ROA }),$$

arguments of which at the stage of operation of aircraft are the characteristics of maintenance and dependability measures. Integral index of supportability ***S*** eventually determines the life cycle cost: **LCC** = φ(*S*). Definitions and content of functionality arguments *S* are represented by a table 1. One of the components of integrated logistics support is information support as a part of infrastructure of maintenance and repair system which represents a set interconnected operations of collection, processing and use of information for managing the technical condition and processes of maintenance and repair system based on the modern automated information technologies. There is no doubt that the data about dependability of aircraft components – as the design and engineering, as well as empirical, which are obtained during operation, – should require high credibility, the achievement of which is possible only with small errors of parameter estimates of table. 1 [1].

Table 1

The contents of the parameters - functionality argumentsS, which determine index of operation supportability

Maintenancecharacteristics		Dependabilitymeasures	
MTMA	Mean Time Maintenance Actions	**MTTF**	MeanTimeToFailure
ROA	Required Operational Availability	**MTBF**	MeanTimeBetweenFailures
RML	Required Maintenance Level	**MTTR**	MeanTimeToRepair
LOR	LevelofRepair	**MTBMA**	Mean Time Between Maintenance Actions
RST	RequiredStandbyTime	**MTBR**	Mean Time BetweenRepairs

4. Research methods

Probabilistic-physical method establishes direct connection with the probability physical sense. So, in the probabilistic-physical model of failures which is represented by diffusive nonmonotonic(*DN*) function distribution densities of mean operation time *t* to failure of achieving the level of physical limit by determining parameter, ie dependence of *the probability of failure with the value of a physical parameter,* which causes failure. As a result, the parameters of the probabilistic distribution of failures have a specific

$$f(t,\mu,\nu) = \frac{\sqrt{\mu}}{\nu \cdot t \cdot \sqrt{2\pi \cdot t}} \cdot \exp\left[-\frac{(\mu - t)^2}{2\nu^2 \cdot \mu \cdot t}\right] \quad (1)$$

and corresponding (1) reliability function

$$R(t,\mu,\nu) = \Phi\left(\frac{\mu - t}{\nu \cdot \sqrt{\mu \cdot t}}\right) - \exp\left(\frac{2}{\nu^2}\right) \cdot \Phi\left(-\frac{\mu + t}{\nu \cdot \sqrt{\mu \cdot t}}\right), \quad (2)$$

distribution scale parameter μ is inversely proportional to average rate of change of determining parameter and it makes sense to mean time to failure T_0, while the parameter of distribution form ν coincides with thecoefficient of variation of rate *V* of degradation processes and, therefore is the coefficient of variation of mean time to failure (ν≡*V*) [3].

The presence of a priori information on the coefficient of variation of operating time to failure ν, specific physical sense of scale parameter μ and the fact that this index of reliability μ = MTTF is included in analytical structure of arguments of functions of the standard normal distribution which form *DN*-model of dependability (2), is objectively undeniable advantage of probabilistic-physical technology of dependability research.

In the considered context (informational support of operation ⇒ Accuracy of dependability estimates ⇒ the accuracy of the information) the quantile method [4, 5] is recommended for obtaining the empirical estimates of dependability of the exploited aircraft components. This method consists of the fact that empirical quantiles are equated with quintiles of the theoretical distribution and as many equations are composed, as many parameters for the selected distribution are necessary to determine. At the two-parameter *DN*-distribution of failures it can be limited to defining only one parameter μ = *MTTF*, since the value of the second parameter ν – the coefficient of variation of operating time to failure is actually known [6, 7]. It is an advantage of PP- technology, which provides the possibility of obtaining the result at the individual failures of onboard equipment components during aircraft operation. The article proposes method of estimation of accuracy of the quantile method based on the simulation modeling of the process of occurrence of single failures, confirming the high reliability of the empirical estimates of MTTF.

Complex approach to the estimation of the accuracy of dependability measures for quantile method. The accuracy of prediction by MTTF the method of quantile can be estimated on the basis of complexation of statistical experiment (SE)and analytical calculations (AC) by dependencies(1) and (2), represented by the diagram in fig. 1.

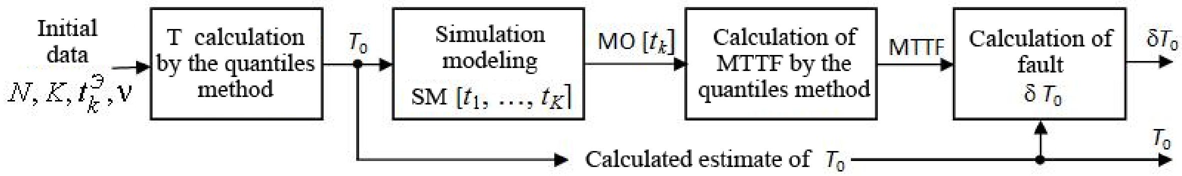

Fig. 1. Diagram of complexation the SE and AC to estimate the error δT_0

5. Statement of research tasks, results and discussion

Four procedures are implemented in the proposed technique:

Procedure 1. Actually the solution of problem of forecasting by the given input data in accordance with the algorithm given in Listing 1 and the results obtained – assessment T_0. We will implement the procedure with the example of calculation MTTF satellite navigation equipment.

Task. Let a part of the onboard equipment of airline's aircraft is operated by N = 50 similar sets of equipment for receiving and processing of satellite data, providing in-flight navigation tasks solution. Within 3,000 flight hours after the start of their operation the loss of flight functions (functionality) was recorded by built-in means of control and confirmed by ground inspections for three sets, while their times to failure were $t_1^Э = 2010$, $t_2^Э = 2580$ *and* $t_3^Э = 3000$ flight hours (K = 3). For subsequent forecasting of dependability for the entire period of operation (before reaching the limit state) it is necessary to find an estimate of mean time to failure of maintained sets of satellite navigation equipment by using the quantile method (fig. 2).

$N := 50 \quad \nu := 0.80 \quad K := 3 \quad t_1 := 2010 \quad t_2 := 2580 \quad t_3 := 3000$ **fl.hours** $k := 2$

1. **Calculations of quantiles of DN-distribution**

Given **Approximate value** $X := 0.1$ **Operational failure probability** $Q := k \div N$

$$\mathrm{cnorm}\left(\frac{X-1}{\nu\cdot\sqrt{X}}\right) + \exp\left(\frac{2}{\nu^2}\right)\cdot \mathrm{cnorm}\left(-\frac{X+1}{\nu\cdot\sqrt{X}}\right) - \frac{k}{N} = 0 \qquad Q = 0.04$$

Mean times to first failure $x_1 \ldots x_K$ **are obtained as result of Find(X) solution of equation at consecutive changes in idital data of index k from 1 to K**

$\mathrm{Find}(X) = 0.23376$ **Values** $X\left(\frac{k}{N}, \nu\right)$: $x_1 := 0.19612 \quad x_2 := 0.23376 \quad x_3 := 0.26314$

2. **Estimate MTTF of operating blocks** $$To := \frac{1}{K}\cdot\sum_{k=1}^{K}\frac{t_k}{x_k} = 1.0896\times 10^4 \text{ flight hours}$$

Fig. 2. Listing of MTTF calculation by quantile method with single failures

Procedure 2. Simulation modeling of failures on basis of *DN*-model of dependability [2] with the aim of statistical reproduction of modeling expected values mean time to failure $t_1, \ldots, t_K$ of first $K = 3$ in conjunction with $N = 50$ similar sets (лист. 2). The simulation program highlights the occurrence of the first K failures in conjunction with N maintained similar sets with parameters T_0 and ν. Generator of *DN*-sequence of random numbers, simulating the value of operating time to first failure, which is represented by operators in the cycle for $j \in 1...N$ on listing 2 and is described in detail in work [8].

In each statistical experiment in accordance with the accepted distribution of failures (*DN*-model of dependability) vector *dn* is formed of N random operating times to failure, which is converted to an increasing variation series (operator $Y \leftarrow$sort (dn)). First K series elements form a vector T (cycle $k \in 1...K$ and operator $T_{k,i} \leftarrow Y_k$) and simulate the statistics of single failures. Cycleforw$\in$1...W provides obtaining of W statistical sampling with length of N each.

After completing all statistical tests (cycle completion for $i \in 1...W$) the mathematical expectation of operating time to failure MO_k of each of K sets of equipment (operator $MO_k \leftarrow$mean (T)), which failed at first of N operated, is determined, which appears as result of the programas a vector of sampled values of mathematical expectation (fig, 3).

```
MO := | for i ∈ 1..W
      |   | for j ∈ 1..N
      |   |   | y ← rnd(1)
      |   |   | for m ∈ 1..M
      |   |   |   | Fm ← cnorm((Xm − 1)/(ν·√Xm)) + exp(2/ν^2)·cnorm(−(Xm + 1)/(ν·√Xm))
      |   |   |   | break if Fm > y
      |   |   | dnj ← (Xm−1 + (y − Fm−1)/(Fm − Fm−1 + 10^−100)·ΔX)·μ
      |   | Y ← sort(dn)
      |   | for k ∈ 1..K
      |   |   Tk,i ← Yk
      | for k ∈ 1..K
      |   | for i ∈ 1..W
      |   |   Ti ← Tk,i
      |   | MOk ← mean(T)
      | return MO
```

Predicted reliability parameters

$\mu := 1.0896 \cdot 10^4$ **fl. hours**, $\nu := 0.80$

Number of operating components of onboard equipmentof same type $N = 50$

Expected value (EV) of mean time to failure of first K failed sets of processing satellite data hardware

$$MO = \begin{pmatrix} 2.019 \times 10^3 \\ 2.474 \times 10^3 \\ 2.811 \times 10^3 \end{pmatrix}$$

Fig. 3. Listing of simulation model and statistical estimation of MTTF

Procedure 3. Calculation of MTTF by quantile method by results of modeling, ie by modeling operating time $t_1^M = 2019$, $t_2^M = 2474$ u $t_3^M = 2811$ flight hours in accordance with the analytical dependences on fig. 2. Results are presented in fig. 4.

Probability of k-th failure is determined by DN-model of dependability, where X is the value of mean time, which corresponds operational failure probability k / N, for k := 1..K

k := 2 Given Reference X := 0.3 $\mathrm{cnorm}\left(\frac{X-1}{\nu\cdot\sqrt{X}}\right)+\exp\left(\frac{2}{\nu^2}\right)\cdot\mathrm{cnorm}\left(-\frac{X+1}{\nu\cdot\sqrt{X}}\right)-\frac{k}{N}=0$

Find(X) = 0.233761

Mean times to first failure $x_1 := 0.196125$ $x_2 := 0.233761$ $x_3 := 0.263144$

Static mean operating times to failure of operating components (K = 3)

$t_1 := MO_1 = 2.019\times10^3$ $t_2 := MO_2 = 2.474\times10^3$ $t_3 := MO_3 = 2.811\times10^3$ л. часов

Static estimate of mean time to failure by the quantiles method for individual failures (K = 3)

$\mathrm{MTTF} := \frac{1}{K}\cdot\sum_{k=1}^{K}\frac{t_k}{x_k} = 1.052\times10^4$ flight hours with failure $\delta\mu := \frac{\mu-\mathrm{MTTF}}{\mu} = 3.451\%$

Fig. 4. Listing of. calculation of MTTF by quantile method by results of modeling

Procedure 4. Calculation of methodical error of the quantile method

$$\delta T_0 = \frac{T_0 - \mathrm{MTTF}}{T_0}\cdot 100\ \% = 3{,}5\ \%. \qquad (3)$$

On the basis of stated approach there are researched relationship between the errors of the quantile method and “capacities” of statistics *K* single faults and size of *N* operated same components of onboard equipment. Influence of parameters *K* and *N* on prediction error of MTTF in a certain sense is predictable – reduction of errors by increasing the statistical data is confirmed. We obtained the quantitative assessment of evaluation errors of MTTF by the quantile method for practically significant ranges of variation of parameters *K* and *N* for operation of onboard equipment, presented in Figure. 5 and 6.

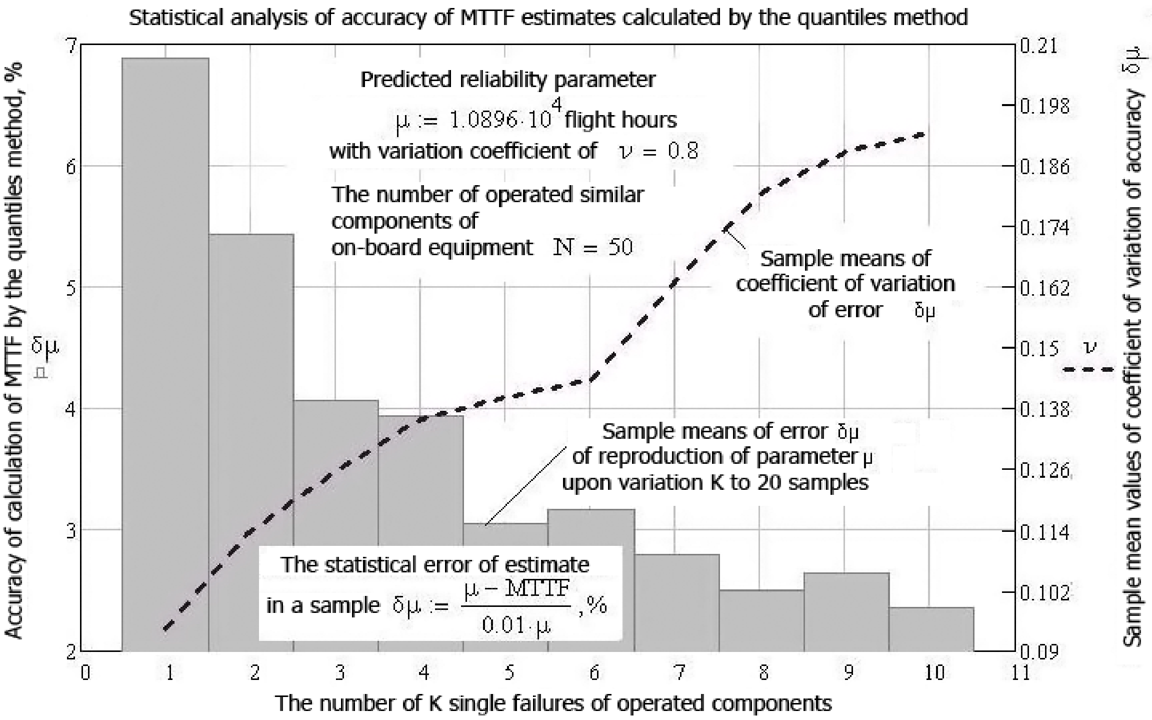

Fig. 5. The results of the statistical analysis of the accuracy of the quantiles method for variation *K*

3. Evaluation of the accuracy of the quantile method. At the estimation of error of the quantiles method it is advisable to specify its distribution between *СЭ* and *АВ*. The error of modeling of *K*single failures with the operating time t_k is determined by the characteristics of reproducibility, stability and independence of *dn*–generator of random numbers –software converter ***rnd* (1) → *dn***, which are investigated in detail in work [9].

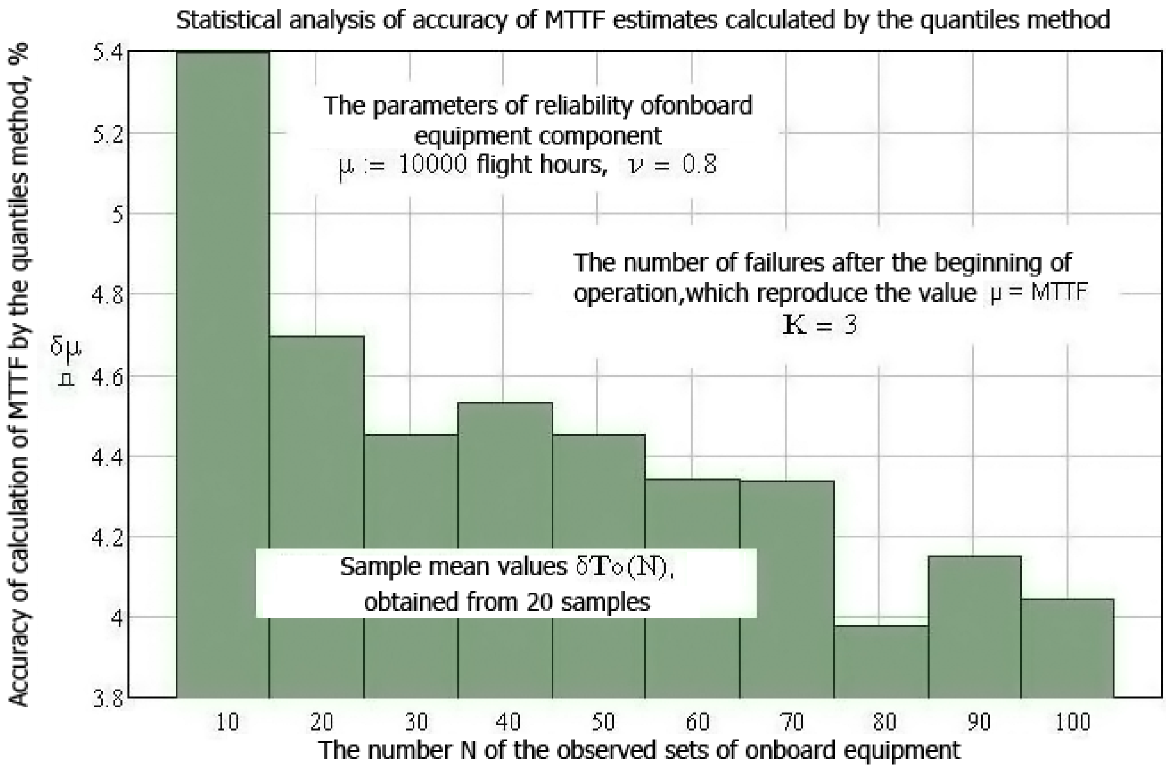

Fig. 6. The results of the statistical analysis of the accuracy of the quantiles method for variation *N*

The results of an additional experiment with *dn*-converter, consisting in the 100-a multiple it turning it on, in each of which 20 samples are implemented by 5000 appeals to the sensor *rnd* (1) in each sample, with subsequent calculation of errors of reproducing the original input parameter values μ and ν, shown in figure. 7.

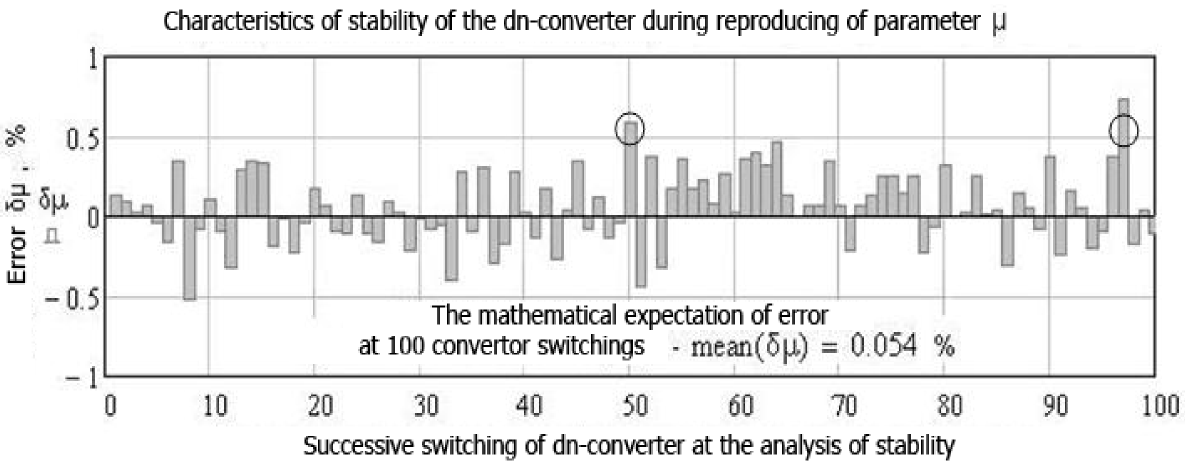

Fig. 7. Confirmation of the high reproducibility of the parameter μ by converter rnd(1) → dn

It follows from the results that b the sample d average errors $\delta\mu$ and $\delta\nu$ of reproducing set values μ and ν do not exceed 0,5 percent with the reliability of 0,98 (exceeding the level of error 0,5 % in 2 out of 100 converter inclusion share marked in Fig. 4 by symbol "O"), and mathematical expectation of error of reproducing parameterμis.

Thus, the conversion errors rnd (1) → dn are significantly less than the values shown in Fig. 3 and 4, and therefore, we can say, that the error δT_0 is a statistical error of the quantile method. It should be noted that the use of the quantile method in the dependability estimates completely meets the requirements for the accuracy of engineering calculations δ_{max} = 5 % while $K \geq 2$ and $N > 10$. The presented results of the research show that the quantile method is effective tool for estimation the actual reliability of operated avionics components by single failures.

5. Conclusion

1) Estimates for the accuracy of the method of quantiles are obtained on the basis of a complex methodology that combines analytical calculations and simulation modeling, performed in Mathcad system, which got the status of an international standard of mathematical analysis for all areas of science and technics [2, 4. 11-12].

2) During the operational phase of aircraft the quantiles method with using of probabilistic-physical model of failure is an effective tool for obtaining adequate estimates of dependability of maintained avionics components.

3) High accuracy of empirical estimates of dependability, which was achieved in the system "PP technology + quantiles method", provides increased efficiency of integrated logistics support in the process of monitoring of technical condition and the characteristics of maintenance of the aircraft components during the operational phase and it allows:

- to establish accordance (or inconsistency) of actual operational technical characteristics of the aircraft components to their calculated (design) values;
- to obtain objective data for the improvement of the components of aircraft and system of technical operation;
- to implement accurate feedback from the customer (operator) to the developer and manufacturer;
- to determine the possibility of transition from a planned preventive maintenance of onboard equipment to the maintenance on the actual condition of the aircraft components [10].

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В.М. Грібов[1], Ю.В. Грищенко[2], Ю.Ю. Грищенко[3]

Емпіричне оцінювання надійності авіоніки в умовах післяпродажного обслуговування

Національний авіаційний університет, просп. Космонавта Комарова, 1, Київ, 03058, Україна
E-mails: [1]vmgribov@gmail.com; [2]hryshchenko8y@gmail.com; [3]noktinua@gmail.com

Мета: головною метою даного дослідження є підвищення точності оцінювання надійності авіоніки в умовах післяпродажного обслуговування. Достовірність розрахунків показників безвідмовності пропонується поліпшити за рахунок застосування ймовірнісно-фізичної дифузійної немонотонної моделі відмов. **Методи дослідження:** у статті пропонується методика оцінювання точності методу квантилів на основі імітаційного моделювання процесу появи одиничних відмов, що підтверджує високу достовірність отриманих емпіричних оцінок середнього напрацювання до відмови. **Результати:** отримано кількісні оцінки похибок оцінювання середнього напрацювання до відмови методом квантилів. Розрахунок зроблений для практично значущих при експлуатації бортового обладнання діапазонів варіації перших відмов в сукупності із загальної кількості експлуатованих однотипних комплектів. Представлені результати дослідження показують, що метод квантилів є ефективним інструментом оцінювання за одиничними відмовами фактичної безвідмовності експлуатованих компонентів авіоніки. **Обговорення:** на етапі експлуатації повітряних суден метод квантилів з використанням імовірнісно-фізичної моделі відмов є ефективним інструментом отримання адекватних оцінок надійності експлуатованих компонентів авіоніки. В першу чергу це відноситься середнього напрацювання до відмови - до одного з показників безвідмовності. Цей показник широко використовується в міжнародних стандартах. Представлена методика забезпечує підвищення ефективності інтегрованої логістичної підтримки в процесі моніторингу технічного стану і характеристик технічного обслуговування компонентів повітряних суден.

Ключові слова: DN-модель надійності; імітаційне моделювання; ймовірносно-фізична технологія; метод квантилів; підтримуваність експлуатації.

В.М. Грибов[1], Ю.В. Грищенко[2], Ю.Ю. Грищенко[3].

Эмпирическое оценивание надёжности авионики в условиях послепродажного обслуживания

Национальный авиационный университет, просп. Космонавта Комарова, 1, Киев, 03058, Украина
E-mails: [1]vmgribov@gmail.com; [2]hryshchenko8y@gmail.com; [3]noktinua@gmail.com

Цель: главной целью данного исследования является повышение точности оценивания надёжности авионики в условиях послепродажного обслуживания. Достоверность расчетов показателей безотказности предлагается улучшить за счет применения вероятностно-физической диффузионной немонотонной модели отказов. **Методы исследования:** в статье предлагается методика оценивания точности метода квантилей на основе имитационного моделирования процесса появления единичных отказов, подтверждающая высокую достоверность получаемых эмпирических оценок средней наработки до отказа. **Результаты:** получены количественные оценки погрешностей оценивания средней наработки до отказа методом квантилей. Расчет произведен для практически значимых при эксплуатации бортового оборудования диапазонов вариации первых отказов в совокупности из общего количества эксплуатируемых однотипных комплектов. Представленные результаты исследования показывают, что метод квантилей является эффективным инструментом оценивания по единичным отказам фактической безотказности эксплуатируемых компонентов авионики. **Обсуждение:** на этапе эксплуатации воздушных судов метод квантилей с использованием вероятностно-физической модели отказов является эффективным инструментом получения адекватных оценок надёжности эксплуатируемых компонентов авионики. В первую очередь это относится средней наработки до отказа – к одному из показателей безотказности. Этот показатель широко используется в международных стандартах. Представленная методика обеспечивает повышение эффективности интегрированной логистической поддержки в процессе мониторинга технического состояния и характеристик технического обслуживания компонентов воздушных судов.

Ключевые слова: вероятностно-физическая технология; *DN*-модель надёжности; имитационное моделирование; метод квантилей; поддерживаемость эксплуатации.

Gribov Victor (1939). Candidate of Engineering. Associate Professor.
Department of Avionics, National Aviation University, Kyiv, Ukraine.
Education: Military Academy of F.E.Dzerzhinsky, Moscow, Russian Federation (1973).
Research area: dependability and diagnostics of technical systems
Publications: 191.
E-mail: vmgribov@gmail.com

HryshchenkoYurii (1958). Candidate of Engineering. Associate Professor.
Department of Avionics, National Aviation University, Kyiv, Ukraine.
Education: National Aviation University, Kyiv, Ukraine (1987).
Research area: flight safety and dependability of technical and ergonomics systems.
Publications: 42.
E-mail: hryshchenko8y@gmail.com

HryshchenkoYurii (1994). Master. Senior Engineer.
Department of intelligent control, International Research and Training Center for Information Technologies and Systems of NAS of Ukraine and MES of Ukraine.
Education: National Aviation University, Kyiv, Ukraine (2017).
Research area: flight safety and dependability of technical and ergonomics systems.
Publications: 2.
E-mail: noktinua@gmail.com