On the development of mathematical models for the reliability evaluation of aircraft operation in combat conditions

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Abstract: *The authors of this study propose a methodological approach to modelling the reliability evaluation of aircraft operation in combat conditions. When developing recommendations on operational and strategic requirements for promising aircraft, a very important aspect is the elicitation of the requirements for their reliability, namely no-failure operation. Reliability as a parameter of any equipment should be set in the technical specifications for development together with other operational requirements in the form of reasonable quantitative indicators – reliability standards. The establishment of specific reliability standards stimulates its growth and creates the basis for rational design, taking into account the requirements of reliable operation. The analysis showed that different models can be used to simulate aircraft reliability. In this case, for example, the final values of mean time to failure (MTTF) would be different. The test results show that the methods and mathematical models used to substantiate the values of time and probability of trouble-free operation of aircraft do not fully correspond to the actual processes of changing their state during the use in the military. This is confirmed by a significant discrepancy in the values of reliability indicators implemented in practice. This was due to the fact that the acquainted mathematical models of aircraft reliability do not take into account the combat conditions in which they are supposed to operate. In addition, the reliability indicators used do not take into account possible changes (decrease) in these indicators during the* *period of aircraft operation. In general, the shortcomings inherent in the methods and mathematical models currently used to describe the aircraft reliability reduce the accuracy of the results obtained, and also do not quite adequately reflect the features of the corresponding process. When using different models, the cost of time to failure differs significantly. The more factors are taken into account, the greater the operating time to failure will be. This means that when designing aircraft, it is necessary to set the value of this indicator greater than indicated in the form. Taking into account additional factors complicates the model, but at the same time makes it more accurate.*

Key Words: *mathematical models, aircraft operation, combat action, equipment, reliability*

1. INTRODUCTION

In modern conditions of technology development, reliability is no longer a desirable quality, but a mandatory requirement. Reliability as a parameter of the aircraft, and any equipment in general, should be set in the technical conditions for development together with other operational requirements in the form of reasonable quantitative indicators – reliability standards [1]. The establishment of specific reliability standards stimulates its growth and creates the basis for rational design, taking into account the requirements of reliable operation [2], [3], [4].

The task of substantiating quantitative requirements for the reliability of an aircraft is usually reduced to answering the question of what optimal reliability of this equipment is needed to perform the practical task with the required quality and at minimal cost, that is, which mathematical model to use in specific case.

The aircraft's performance is defined by its operating efficiency, which depends on a number of indicators, including reliability parameters.

Quantitatively, efficiency is usually expressed by the probability that the aircraft performs specified functions under certain conditions. The higher the required efficiency, the higher the reliability requirements should be under other equal conditions [5]. In addition, when modelling reliability, the type and purpose of aircraft should be taken into account, namely the conditions of combat operations for military equipment.

Approaches to modelling aircraft reliability are proposed by various authors. Reliability is associated in various ways with the quality of aircraft performance of specified functions under certain operating conditions, that is, with a specified efficiency.

The authors in [6] propose a method for evaluating the transport efficiency of a long-haul passenger aircraft based on mathematical modelling of all typical flight stages for precise determination of fuel consumption.

In [7], the principles of constructing mathematical models are described, the theoretical foundations of analytical and simulation modelling of the operation of technical systems and the problems of studying their reliability are considered. The author of [8] considers the choice of uniform indicators and criteria for efficiency of the air defence system of important state property in peace-time in relation to preventing terrorist attacks and using aircraft and helicopters in war-time.

Mathematical modelling of the problems of estimating and predicting weapon reliability indicators was carried out in [9]. But in the above-mentioned works, the authors hardly touch upon the issue of modelling the aircraft reliability with a specified efficiency in combat conditions. This determines the relevance of this study.

The purpose of the study is to form new methodological approaches to the development of mathematical models for evaluating the reliability of aircraft operation in combat conditions.

2. MATERIALS AND METHODS

When setting reliability parameters for a combat aircraft, preference should be given to those parameters that fully characterise the reliability of this type of equipment. These parameters should be subject to engineering calculations at the design stage and easily measured during testing and during the operation of equipment. As for the aircraft, such an indicator of reliability is the time to failure T_0, which is recommended to be selected as a reliability parameter and which is set in the terms of reference for aircraft development.

However, this indicator alone does not fully characterise the aircraft reliability. In some cases, for example, when the operation factor is significant, an important indicator is the aircraft's adaptability to quickly find and eliminate failures.

The parameter that characterises the reliability side is the average recovery time T_R. Both parameters together clearly determine the most important criteria for aircraft reliability: the probability of trouble-free operation (1):

$$P(t) = e^{-\frac{t}{T_0}} \tag{1}$$

and readiness factor (2):

$$K_R = \frac{\mathrm{T}_0}{\mathrm{T}_0 + \mathrm{T}_R} \tag{2}$$

where: T_0 – time to failure if the system is renewable, or operating time between failures if the system is non-renewable; T_R – average recovery time; t – continuous operation time.

Therefore, the main indicators of aircraft reliability, in particular reliability according to [10] is the probability of survival *P(t)* and the time to failure *T*.

But without specifying the continuous operation time *t* the plane during which these indicators are valid, they become uncertain. Next, the question arises, which of them is primary.

In other studies [11], the primary indicator of trouble-free operation is considered to be the operating time to failure of weapons and military equipment, and then the probability of trouble-free operation for a certain time is calculated [12].

In any case, using the uptime distribution function $P(\tilde{T} > t) = f(T, t)$ an equation occurs. The equation has two unknowns if it is written explicitly, or three unknowns if this equation is written implicitly $(P, T, t) = 0$. It is considered appropriate, in relation to aircraft, to set first the probability of trouble-free operation. Let the required probability of trouble-free operation be $P_{RTFO} = 0.9 \div 0.95$.

The next indicator of trouble-free operation is continuous operation time. Based on the experience of the troops, it is assumed that the aircraft can work continuously for no more than 2 hours. Knowing two unknowns of the three indicators, it is possible to find the operating time to failure.

Since any equipment ages, it is advisable to model the aircraft reliability not by exponential distribution of a random variable of time $\tilde{T}$ operating time between failures $P(t) = e^{-\theta \cdot t}$, as is often accepted, but with a more general, more flexible distribution, such as two-parameter (θ, α) Weibull distribution (3):

$$P(t) = e^{-\theta \cdot t^{\alpha}} \tag{3}$$

where: θ – scale parameter; α – form parameter that takes into account ageing of equipment.

3. RESULTS AND DISCUSSIONS

Next, the study considers general requirements for aircraft reliability under conditions of a specified efficiency or probability of trouble-free operation. Efficiency is a broad concept and is characterised by a number of properties: reliability, performance, survivability, noise immunity, ease of operation.

If the system is an airplane, then its specified function is to destroy the target. The success of this function depends on a large number of factors that have the nature of random events and are expressed by the corresponding probabilities. Among the factors that affect the successful target destruction, it is appropriate to single out only the main ones, which are determined by pre-flight and flight reliability. In this case, a complex random event – the destruction of the target – can occur due to the joint implementation of the following three independent partial events: serviceability of the aircraft equipment at the time of take-off, trouble-free operation of the equipment during flight (during continuous operation) to the target area, and a direct hit of the target.

The probability of destroying the target will be determined in this case by the summary of the probabilities of the corresponding events [13] (4):

$$E_P = P_0 \cdot P(t) \cdot E_0 \tag{4}$$

where: P_0 – probability of serviceable condition of the equipment at the time of start of use (pre-flight reliability); $P(t)$ – probability of trouble-free operation of the aircraft during continuous flight, t; E_0 – probability of direct hit on the target.

Therefore, the probability of trouble-free operation of the aircraft during continuous operation t under normal operating conditions, it is calculated, as noted in (1), according to the exponential law of the distribution of the time of trouble-free operation. Taking into account the ageing and wear, the Weibull law of uptime distribution is used (3).

The product of probabilities $P_0 \cdot P(t) = P_{NO}$ there is a probability of normal operation, which is one of the most complete characteristics of system reliability. By physical nature of P_{NO} there is a chance that the system will be working properly at the time of application and will not fail during continuous operation. Given the above, the following is obtained (5):

$$E_P = P_{NO} \cdot E_0 \tag{5}$$

probability E_P, which is numerically equal to the probability of performing specified operations, can be considered the operating aircraft efficiency as a complex system. Probability E_0, which quantifies the property of the system, provided that it is absolutely reliable, can be called ideal efficiency. In general, it is determined by a number of factors and is the probability of a complex event. In the case of absolute reliability ($P_{NO} = 1$) the operating efficiency coincides with the ideal one ($E_P = E_0$).

It follows from equation (6) that normal operation can be determined in terms of the ratio of the operating efficiency of the system to its ideal efficiency (6):

$$P_{NO} = \frac{E_P}{E_0}. \tag{6}$$

This ratio shows the decrease in efficiency due to the unreliability of the system. A specified probability of completing a specified task can be called a specified efficiency. In order for the system to successfully perform the specified tasks, its operating efficiency must not be less than the specified one, that is, meeting the condition (7):

$$E_S \leq E_P = P_{NO} \cdot E_0 \tag{7}$$

Admittedly, for recoverable systems, the probability of a serviceable state at any given time is approximately equal to the readiness coefficient [14], [15], [16], i.e. (8):

$$P_0(t) \approx P_0 = K_R = \frac{\mathrm{T}_0}{\mathrm{T}_0 + \mathrm{T}_R} \tag{8}$$

Substituting the values K_R and $P(t)$ in equation (8) and considering that equality must be fulfilled $E_S = E_P$, obtain (9):

$$E_S = \frac{\mathrm{T}_0}{\mathrm{T}_0 + \mathrm{T}_R} \cdot \mathrm{e}^{-\frac{t}{T_0}} \cdot \mathrm{E}_0 \tag{9}$$

For a graphical solution of this equation, it is convenient to represent it in the following form (10):

$$\mathrm{e}^{-\frac{t}{T_0}} = \frac{E_S}{\mathrm{E}_0} \cdot \left(1 + \frac{\mathrm{T}_R}{\mathrm{T}_0}\right) \tag{10}$$

Next, plotting function graphs $f_{1e}(T_0) = \mathrm{e}^{-\frac{t}{T_0}}$ and $f_{2e}(T_0) = \frac{E_S}{\mathrm{E}_0} \cdot \left(1 + \frac{\mathrm{T}_R}{\mathrm{T}_0}\right)$, the intersection point that corresponds to the value T_0 is found, for whom equality (11) turns into an identical equation. This is the required value of the required parameter [17], [18]. [19].

Taking into account the ageing and wear of equipment components and (5), then (11):

$$E_S = \frac{\mathrm{T}_0}{\mathrm{T}_0 + \mathrm{T}_R} \cdot \mathrm{e}^{-\frac{t^{\alpha}}{T_0}} \cdot \mathrm{E}_0 \tag{11}$$

where: α – parameter that takes into account the ageing and wear of equipment components.

Therefore, the specified system efficiency is expressed in terms of reliability parameters T_0 and T_R. Thus, in order to determine the desired parameter value T_R in general it is necessary to obtain:

– the specified probability of completing the task E_S (specified efficiency);

– ideal system efficiency;

– continuous operation time.

Value T_R should be based on the experience of aircraft repair, taking into account the measures to improve recoverability that are being developed, or according to the condition of the permissible break time in work. The continuous operation time for the aircraft will be, for example, $t \leq 2$ hours [20], [21].

Equation (12) with respect to the parameter T_0, which is transcendent. For a graphical solution, it is convenient to present it in the form (12):

$$\mathrm{e}^{-\frac{t^{\alpha}}{T_0}} = \frac{E_S}{\mathrm{E}_0} \cdot \left(1 + \frac{\mathrm{T}_R}{\mathrm{T}_0}\right) \tag{12}$$

Next, plotting function graphs $f_{1e}(T_0) = \mathrm{e}^{-\frac{t^{\alpha}}{T_0}}$ and $f_{2e}(T_0) = \frac{E_S}{\mathrm{E}_0} \cdot \left(1 + \frac{\mathrm{T}_R}{\mathrm{T}_0}\right)$, the intersection point that corresponds to this value T_0 is found, for whom equality (12) turns into an identical equation. Thus, the required value of the required parameter is found again [22], [23], [24].

But military equipment is designed to work in combat conditions. Therefore, it could fail not only due to limited technical reliability, but also due to enemy fire. Taking into account the conditions of the combat situation ($\varepsilon \neq 0$ – combat losses) and limited technical reliability of the aircraft $\left(\theta = \lambda = \frac{1}{T}\right)$ – failure rate, average time T to failure should be calculated based on such a generalised mathematical model, which is used to determine the probability $\boldsymbol{P^0(t)}$ of trouble-free operation of the aircraft over time t (h) of its continuous operation [25], [26], [27], [28] (13):

$$\boldsymbol{P^0(t) = e^{-(\theta \cdot t^{\alpha-1}+\varepsilon)\cdot t} = e^{-\left(\frac{1}{T}\cdot t^{\alpha-1}+\varepsilon\right)\cdot t} \geq P_{RTFO}}, \tag{13}$$

where: ε – hourly combat losses; $\boldsymbol{P_{RTFO}}$ – required probability of trouble-free operation, or ideal efficiency.

Equation (13) is more complex than (12). In view of all the above, the following equation is obtained (14):

$$\boldsymbol{E_S} = \frac{\mathrm{T}_{\boldsymbol{0}}}{\mathrm{T}_{\boldsymbol{0}} + \mathrm{T}_{\boldsymbol{R}}} \cdot \boldsymbol{e}^{-\left(\frac{\boldsymbol{1}}{\boldsymbol{T_0}}\cdot \boldsymbol{t}^{\alpha-1}+\varepsilon\right)\cdot \boldsymbol{t}} \cdot \mathrm{E}_{\boldsymbol{0}}, \tag{14}$$

Equation (14) with respect to the required parameter T_0, is also transcendent and for its graphical solution presented it in the form (15):

$$\boldsymbol{e}^{-\left(\frac{\boldsymbol{1}}{\boldsymbol{T_0}}\cdot \boldsymbol{t}^{\alpha-1}+\varepsilon\right)\cdot \boldsymbol{t}} = \frac{\boldsymbol{E_S}}{\mathrm{E}_{\boldsymbol{0}}} \cdot \left(\boldsymbol{1} + \frac{\mathrm{T}_{\boldsymbol{R}}}{\mathrm{T}_{\boldsymbol{0}}}\right) \tag{15}$$

When plotting function graphs $f_1(T_0) = \mathrm{e}^{-\left(\frac{1}{T_0}\cdot t^{\alpha-1}+\varepsilon\right)\cdot t}$ and $f_2(T_0) = \frac{E_S}{\mathrm{E}_0} \cdot \left(1 + \frac{\mathrm{T}_R}{\mathrm{T}_0}\right)$, the intersection point that corresponds to this value T_0 is found, for which equations (10), (12) and (15) turn into an identical equation.

This is also the required value of the required parameter. Next, equations (10), (12) and (15) are solved graphically and the value of the operating time to failure changes when using different models.

The required reliability of the aircraft is determined, which solves the problem of destroying the target, for example, with a specified probability $E_S = 0.95$, if it is known that the ideal efficiency $E_0 = 0.99$, continuous operation time $t = 2$ hours, average recovery time $T_R = 2$ hours.

For the exponential distribution law value of operating time to failure for $t = 2$ hours is shown in Table 1 and Figure 1.

Table 1 – Value of functions $f_{1e}(T_0)$ and $f_{2e}(T_0)$ for the exponential distribution law

T_0, hours	50	100	150	200	250	400	600
$f_1(T_0)$	0.960789	0.980199	0.986755	0.99005	0.992032	0.995012	0.996672
$f_2(T_0)$	0.99798	0.978788	0.972391	0.969192	0.967273	0.964394	0.962795

For the Weibull distribution value of operating time to failure for $t = 2$ hours is shown in Table 2 and Figure 2.

Table 2 – Value of functions $f_{1W}(T_0)$ and $f_{2W}(T_0)$ for the Weibull distribution law

T_0, hours	50	100	150	200	250	300
$f_1(T_0)$	0.948588	0.973955	0.98256	0.986892	0.989499	0.991242
$f_2(T_0)$	0.99798	0.978788	0.972391	0.969192	0.967273	0.965993

For a model that takes into account combat conditions value of operating time to failure for $t = 2$ hours is shown in Table 3 and Figure 3.

Table 3. Value of functions $f_{1e}(T_0)$ and $f_{2e}(T_0)$ for a model that takes into account combat conditions

T_0, hours	50	100	150	200	250	300
$f_1(T_0)$	0.948588	0.973955	0.98256	0.986892	0.989499	0.991242
$f_2(T_0)$	0.99798	0.978788	0.972391	0.969192	0.967273	0.965993

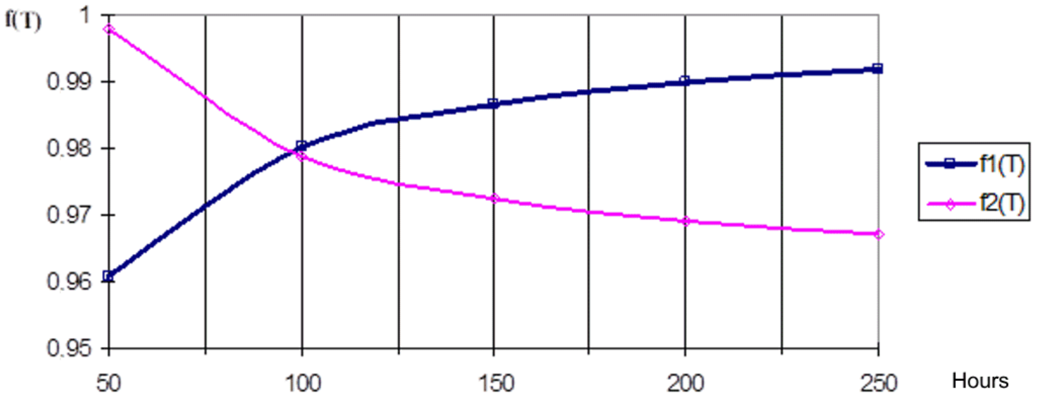

Fig. 1 – Graphical solution of the equation $e^{-\frac{t}{T_0}} = \frac{E_S}{E_0} \cdot \left(1 + \frac{T_R}{T_0}\right)$ for $t = 2$ hours (exponential distribution law)

The intersection point of the curves corresponds to the value of the desired parameter approximately $T_0 = 90$ hours.

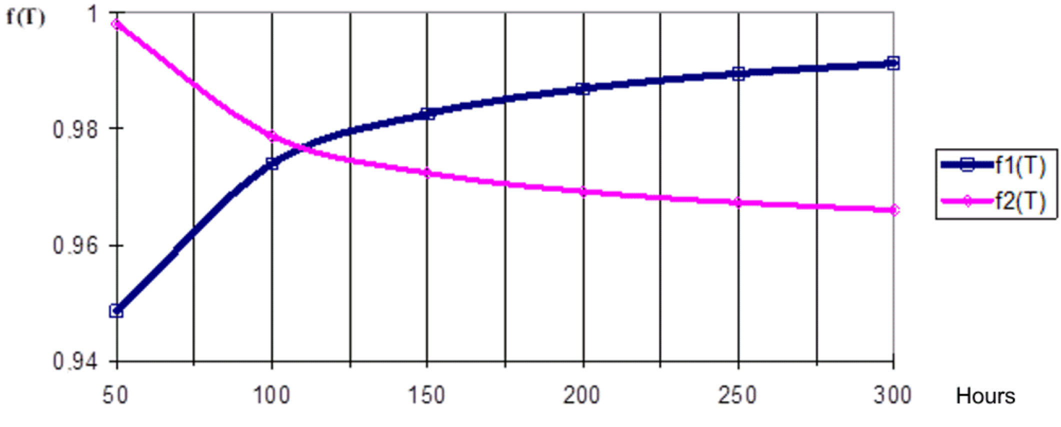

Fig. 2 – Graphical solution of the equation $e^{-\frac{t^\alpha}{T_0}} = \frac{E_3}{E_0} \cdot \left(1 + \frac{T_B}{T_0}\right)$ for $t = 2$ hours (Weibull distribution law)

The intersection point of the curves corresponds to the value of the required parameter approximately $T0 = 110$ hours.

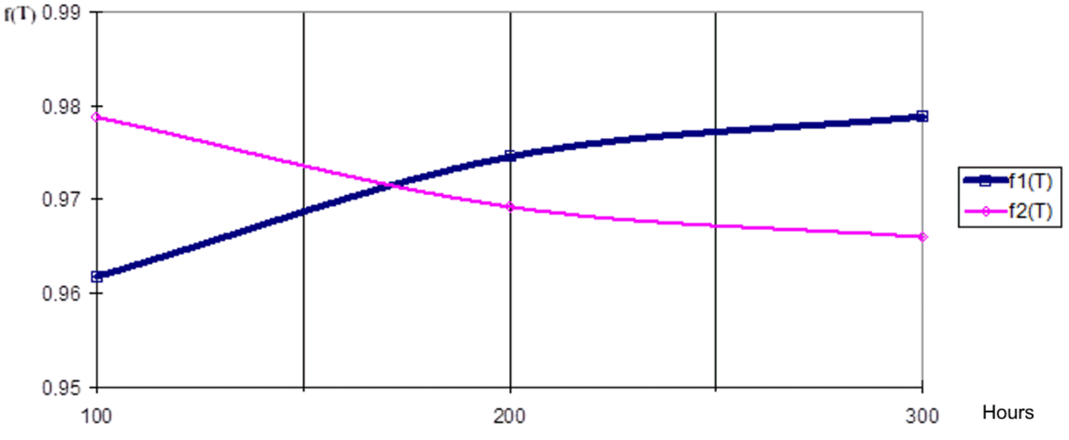

Fig. 3 – Graphical solution of the equation $e^{-\left(\frac{1}{T_0}\cdot t^{\alpha-1}+\varepsilon\right)\cdot t} = \frac{E_S}{\mathrm{E}_0}\cdot\left(1+\frac{\mathrm{T}_R}{\mathrm{T}_0}\right)$ for $t = 2$ hours (a model that takes into account the combat conditions)

The intersection point of the curves corresponds to the value of the required parameter approximately $T0 = 170$ hours.

Thus, using different models, uptime with constant continuous operation time, the value of the operating time to failure changes. The more complex the model, the greater the time to failure required to ensure the necessary reliability and efficiency of the aircraft. The operating time to failure, depending on the continuous operation time for using different models, is shown in Table 4.

Table 4. Changing the operating time to failure depending on the continuous operation time when using different models

Continuous operation time, hours / Model	1	2	3	4	5
Exponential	80	90	130	160	175
Weibull	60	110	160	220	310
Mathematical model of equipment reliability, taking into account the hostilities	80	170	290	550	1190

Table 4 shows that using any model of non-failure operation, the value of time to failure also increases with increasing uptime.

4. CONCLUSIONS

Therefore, this study considers a methodological approach to modelling the aircraft reliability in combat conditions. The analysis showed that different models can be used to simulate the aircraft reliability. Mathematical models used to substantiate and confirm the values of time and probability of trouble-free operation of combat aircraft do not fully correspond to the actual processes of changing their state during the use in the military. This is confirmed by a significant discrepancy in the values of reliability indicators implemented in practice. In the conventional mathematical models of aircraft reliability, there is no consideration of the ageing and wear conditions, including the combat situations in which they are supposed to operate.

When using different models, the time to failure differs significantly. When using the exponential law of uptime distribution, the time to failure for 2 hours of continuous operation amounts to 90 hours. Taking into account other factors, such as ageing and wear of equipment components, i.e., using the Weibull model, then the value of the operating time to failure (for 2 hours of continuous operation) amounts to 110 hours. Taking into account the ageing and wear of components and the enemy's fire impact, that is, using the developed model, then the operating time to failure would amount to 170 hours. The more factors are taken into account, the greater the operating time to failure will be. Therefore, when designing aircraft, it is necessary to set the value of this indicator greater than indicated in the form. Taking into account additional factors complicates the model, but at the same time makes it more accurate.

The further research will take into account other factors that affect aircraft reliability.

REFERENCES

[1] I. A. Ushakov, *Course of the theory of system reliability,* Bustard, 2008.

[2] I. N. Kravchenko, V. A. Zorin and E. A. Puchin, *Fundamentals of machine reliability,* Nauka, 2007.

[3] A. A. Bessonov, *Prediction of reliability characteristics of automatic systems*, Energiya, 1971.

[4] Yu. K. Belyaev, *Reliability of technical systems,* Radio i Komunikatsiya, 1985.

[5] N. A. Shishonok, V. F. Repkin and L. L. Barvinsky, *Fundamentals of the theory of reliability and operation of radioelectronic technology,* Sovietskoe Radio, 1964.

[6] S. V. Levitsky and E. V. Levitskaya, Methods for assessing the transport efficiency of the main passenger aircraft, *MSTU GA, vol.* **205**, no. 6, pp. 99-106, 2014.

[7] A. P. Kovtunenko, V. V. Zubarev, B. N. Lanetsky and A. A. Zverev, *Mathematical modeling in the problems of research on the reliability of technical systems,* Book Publishing House of the National Aviation University, 2006.

[8] A. M. Zharik, The choice of uniform indicators and criteria for the effectiveness of the functioning of the systems of the PPO of important state objects, *Systems of Protection and Technology*, vol. **2**, no. 26, pp. 199-204, 2011.

[9] S. V. Lapitsky, I. V. Odnoralov, B. N. Lanetsky, A. N. Shatrov, B. P. Kredentser, M. A. Shishanov and A. A. Lyubarets, *Fundamentals of military-technical research. Theory and applications,* Publishing House Dmitra Burago, 2019.

[10] * * * DSTU 2860-94, 1994, Available at http://fulgentworld.weebly.com/blog/dstu-2860-94

[11] B. A. Kozlov and I. A. Ushakov, *Handbook of reliability calculation*, Sovietskoe Radio, 1966.

[12] A. M. Shirokov, *Reliability of radioelectronic devices*, Visshaya Shkola, 1972.

[13] E. S. Wentzel, *Probability theory,* Nauka, 1964.

[14] A. A. Ryzhkin, B. N. Slyusar and K. G. Shuchev, *Fundamentals of reliability theory,* Center of DSTU, 2002.

[15] Y. K. Kyaw, E. L. Kuznetsova and A. V. Makarenko, Complex mathematical modelling of mechatronic modules of promising mobile objects, *INCAS Bulletin,* vol. **12**, pp. 91-98, https://doi.org/10.13111/2066-8201.2020.12.S.8, 2020.

[16] M. Y. Kuprikov, N. M. Kuprikov and L. N. Rabinskiy, The dependence of the appearance of the aircraft on the conditions of the arctic basing, *INCAS Bulletin,* vol. **11**, pp. 115-123, https://doi.org/10.13111/2066-8201.2019.11.S.11, 2019.

[17] S. V. Vasylyuk, A. D. Suprun, L. V. Shmeleva and O. D. Kachkovsky, Configuration of charge waves in polymethine linear dye systems, *Springer Proceedings in Physics,* vol. **246**, pp. 189-201, 2021.

[18] O. V. Prokopenko, Consumer choice types in marketing of ecological innovations, *Actual Problems of Economics,* vol. **116**, 2, 109-116, 2011.

[19] N. Kuzhel, A. Bieliatynskyi, O. Prentkovskis, I. Klymenko, S. Mikaliunas, O. Kolganova, S. Kornienko and V. Shutko, Methods for numerical calculation of parameters pertaining to the microscopic following-the-leader model of traffic flow: Using the fast spline transformation, *Transport*, vol. **28**, no. 4, pp. 413-419, 2013.

[20] A. Mustafin, Coupling-induced oscillations in two intrinsically quiescent populations, *Communications in Nonlinear Science and Numerical Simulation,* vol. **29**, no. 1-3, pp. 391-399, 2015.

[21] H. Yuilin, A. Beljatynskij and A. Ishchenko, Non-Roundabout design of cancel the intersection signal light on horizontal plane, *E3S Web of Conferences,* vol. **91**, 05003, 2019.

[22] A. Beljatynskij, N. Kuzhel, O. Prentkovskis, O. Bakulich and I. Klimenko, The criteria describing the need for highway reconstruction based on the theory of traffic flows and repay time, *Transport,* vol. **24**, no. 4, pp. 308-317, 2009.

[23] A. Mustafin and A. Kantarbayeva, Supply chain modeled as a metabolic pathway, *Mathematical Modelling and Analysis,* vol. **28**, no. 3, pp. 473-491, 2018.

[24] O. M. Alekseev, K. M. Kovalov, M. M. Lazarenko, M. V. Lazarenko, Y. E. Grabovskii and S. Y. U. Tkachov, Nature of dielectric relaxation in microcrystalline cellulose, *Cellulose Chemistry and Technology,* vol. **53**, no. 1-2, pp. 15-22, 2019.

[25] S. Y. Tkachev, O. M. Alekseev, M. M. Lazarenko, M. V. Lazarenko, K. M. Kovalov, S. I. Bokhvan, Y. E. Grabovskii and N. V. Hoshylyk, Topological solitons in branched aliphatic molecules, *Molecular Crystals and Liquid Crystals,* vol. **665**, no. 1, pp. 166-180, 2018.

[26] * * * Recommendations on the procedure for applying the methodological approach to the military-economic substantiation of the choice of the reconnaissance and strike system or complex in the programs (plans), 2021, Available at https://paperssds.eu/index.php/JSPSDS/article/view/319

[27] V. O. Shuenkin and M. O. Slyusarenko, Modeling the reliability of anti-aircraft missile forces taking into account the fire of the enemy, *Collection of Science in Central Research Institute of the Armed Forces of Ukraine*, vol. **1**, no. 71, pp. 36-46, 2015.

[28] L. A. Lyusternik, O. A. Chervoninkis, A. R. Yanpolskiy, *Mathematical analysis. Calculation of elementary functions,* Fizmatgiz, 1963.