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UNERRORIC OF TURBOJET ENGINES THRUST ASYMMETRY CONTROL FOR FLIGHT SAFETY

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ABSTRACT

This article shows a good idea to digitalize any unerrorics for software of turbojet engine thrust asymmetry control. The well-known results of scientific developments presented in the publications used confirm the practical usefulness and relevance of digitalization of measurement results processing methods for the software unerroric of applied algorithms for system analysis and approximate synthesis. However, the equality of addition and multiplication speeds in digital signal processors and programmable logical devices is achieved mainly by hardware. Therefore, the need to reduce hardware costs for digital signal processing increases the role of IT-research on the possibility of flight safety analytics by software. The article purpose is a research of software for unerroric of such control. The used methods of that research are the methods of system analysis and the methods of the software modeling. To achieve the stated goal, the following tasks have been set and solved: the task of directional search and comparative evaluation of digital methods for ensuring unerroric of control of mutual compliance of controlled values of thrust parameters of two-shaft turbojet two-circuit engines of the same series; the task of adapting deductive algorithms for digital processing of measurement results of controlled values of thrust parameters of two-shaft turbojet two-circuit engines for the software of an unerroric of the flight of a twin-engine aircraft with such engines; the task of selecting the element base for hardware and software experimental modeling of digital algorithms for software unerroric of thrust asymmetry of turbojet two-circuit engines. The formulation and solution of problems of selection and adaptation of methods and algorithms for digital processing of measurement results contributed to the development of software for flight safety unerroric of a twin-engine airliner with twin-shaft turbojet engines by tightening the control of the mutual correspondence of the controlled values of their thrust parameters. The results of experimental modeling of adapted algorithms have confirmed the practical feasibility of such software and the high importance of IT-research in its design. It is described the possibility of turbojet two-circuit engines tractions forces asymmetry analysis unerroric. A set of formulas for digital processing of control signals from rotors speeds sensors of civil airplane with two turbojet two-circuit engines is presented.

Keywords: *Airliner, Engine, Thrust, Quality, Unerroric.*

1. INTRODUCTION

The turbojet two-circuit engines tractions forces asymmetry analysis unerroric is the real remedy to digitalize a software for safety flight of civil airplane with two turbojet two-circuit engines [1].

The digitalization of unerroric is based on recurrent procedures for deductive transform of discrete signals [2, 3].

The unerroric of turbojet two-circuit engines tractions forces asymmetry analysis for control of flight safety for civil airplane with two turbojet two-circuit engines is the combination of hardware and software for the best reducing the error of that control by airliner power plant control system in flight [4].

The using of the recurrent methods for the digitalization of deductive transform for discrete signals is a new way to realize the possibility of such reducing [5-8]. Therefore, the unerroric of turbojet two-circuit engines tractions forces asymmetry control may be successfully implemented using the various programmable devices [9-15].

The well-known results of scientific developments presented in the publications used

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confirm the practical usefulness and relevance of digitalization of measurement results processing methods for the software unerroric of applied algorithms for system analysis and approximate synthesis [16-29]. However, the equality of addition and multiplication speeds in digital signal processors and programmable logical devices is achieved mainly by hardware [13]. Therefore, the need to reduce hardware costs for digital signal processing increases the role of IT-research on the possibility of flight safety analytics by software.

The purpose is an research of software for unerroric of turbojet two-circuit engines tractions forces asymmetry control. The used methods of that research are the methods of system analysis and the methods of the software modeling.

To achieve the stated goal, the following tasks have been set and solved:

- the task of directional search and comparative evaluation of digital methods for ensuring unerroric of control of mutual compliance of controlled values of thrust parameters of two-shaft turbojet two-circuit engines of the same series;
- the task of adapting deductive algorithms for digital processing of measurement results of controlled values of thrust parameters of two-shaft turbojet two-circuit engines for the software of an unerroric of the flight of a twin-engine aircraft with such engines;
- the task of selecting the element base for hardware and software experimental modeling of digital algorithms for software unerroric of thrust asymmetry of turbojet two-circuit engines.

The statement of tasks is as follows:

- we will assume that only two-shaft turbojet twin-circuit engines of the same series have been installed in the power plant of the twin-engine airliner, which have successfully passed in-depth testing in mass production conditions;
- we will assume that the control system of the airliner power plant with such engines involves a control program for the rotation frequency of the turbine rotor of a low-pressure compressor and a control program for the rotation frequency of the turbine rotor of a high-pressure compressor;
- it is required to investigate and develop digital methods of unerroric of thrust asymmetry of turbojet dual-circuit engines to build deductive algorithms for software of such unerroric with a minimum number of hardware-expensive multiplication operations.

2. THEORETICAL BASIS

Theoretical basis for unerroric of turbojet two-circuit engines tractions forces asymmetry control are the software for the deep testing of turbojet engines by hardware of serial turbojet engines technical condition test system and software for the system analyzing of turbojet two-circuit engines tractions forces parameters by hardware of any control system for a power plant of civil airplane with two turbojet two-circuit engines [1].

This deep testing software is based on the methods of mathematical modeling [4].

That system analyzing software is based on complex methods of optimal control.

3. RESEARCH RESULTS

The obtained results of the conducted research show the possibility of digitalization for unerroric of turbojet two-circuit engines tractions forces asymmetry control by deep testing of serial turbojet engines and system analysis of its thrust parameters for safety flight of civil airplane with two turbojet two-circuit engines. The dependence of turbojet two-circuit engine traction force R on low-pressure turbine rotor speed n_1 and high-pressure turbine rotor speed n_2 can and should be expressed by the formula (1) [4]:

$$R = J_1 n_1^2 + J_2 n_2^2. \tag{1}$$

In the study, a directional search was performed for digital methods of difference filtering, Fast Fourier transform, recurrent discrete Fourier transform and multi-stage discrete Fourier transform of controlled signals from sensors of rotation frequencies of low-pressure compressor turbine rotors and sensors of rotation frequencies of high-pressure compressor turbine rotors of two-shaft turbojet two-circuit engines of the same series [6-8]. The advantages of digital algorithms of difference filtering and multi-stage discrete Fourier transform for unerroric of control of the mutual correspondence of the controlled values of the

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thrust parameters n_1 and n_2 of two-shaft turbojet two-circuit engines of the same series are revealed [1, 2, 5]. The deductive algorithms of these methods are adapted for the software of the unerroric of the flight of a twin-engine aircraft with such engines [1, 3, 4]. The adapted algorithms were modeled on programmable logical devices to minimize hardware-expensive multiplications [13].

3.1 Parameters Distribution

In the application to the random distribution of the measurement results of the controlled values of the rotational speeds of the turbines of low-pressure compressors n_1 and high-pressure compressors n_2 of all N two-shaft gas turbine engines of the same series, the "*Three Sigma Rule*" can be used. According to him, the maximum possible deviation of 99% of the values of each operating parameter of the engines from their expected value is three times greater than their standard deviation σ, that is, it is equal to 3σ with the variance of their normal distribution σ^2.

Such a distribution is described by the formula (2) by a two-dimensional random probability function P_{n_1,n_2} of the normal distribution of the measured values of these rotors speeds with mathematical expectations n_1^*, n_2^* and variances σ_1^2 ,σ_2^2 respectively, for the calculated values of the thrust force $R_{min} \le R \le R_{max}$ and the value of the weighting coefficient $0<z\le 3.0$:

$$P_{n_1,n_2} = \frac{1}{2\pi\sigma_1^2\sigma_2^2}\int_{-z\sigma_1}^{+z\sigma_1}\int_{-z\sigma_2}^{+z\sigma_2} e^{-\frac{(n_1-n_1^*)^2}{2\sigma_1^2}-\frac{(n_2-n_2^*)^2}{2\sigma_2^2}} dn_1 dn_2 = \frac{1}{2\pi\sigma_1^2\sigma_2^2}\int_{-z\sigma_1}^{+z\sigma_1} e^{-\frac{(n_1-n_1^*)^2}{2\sigma_1^2}} dn_1 \int_{-z\sigma_2}^{+z\sigma_2} e^{-\frac{(n_2-n_2^*)^2}{2\sigma_2^2}} dn_2 \quad (2)$$

With the value of the weighting coefficient z=3.0 and the value of the two-dimensional random probability function of the normal distribution of the measured values of such rotors speeds $P_{n_1,n_2} \approx$ 0,99, the number of M_z deeply tested turbojet engines of one series differs slightly from the total number of N turbojet engines of this series, $M_z \approx N$. An increase in the mutual correspondence of the measured values of these two rotors speeds at once M_z of deeply tested turbojet engines of one series for if $M_z < N$ is provided by their directional selection from the total number of M turbojet engines of this series, if the value of the weighting coefficient z=1.5 and the value of the two-dimensional random probability function of the normal distribution of the measured rotor speed values $P_{n_1,n_2} \approx 0{,}75$ is given.

An increase in the mutual correspondence of the M_z quality of the turbojet engine of one series with a narrowing of the intervals [$-z\sigma_1$,$+z\sigma_1$] and [$-z\sigma_2$,$+z\sigma_2$] is provided, according to formula (2), by a corresponding decrease in the values of the maximum deviation of the measured values of these rotors speeds from their expected values n_1^* and n_2^* (figure 1, figure 2).

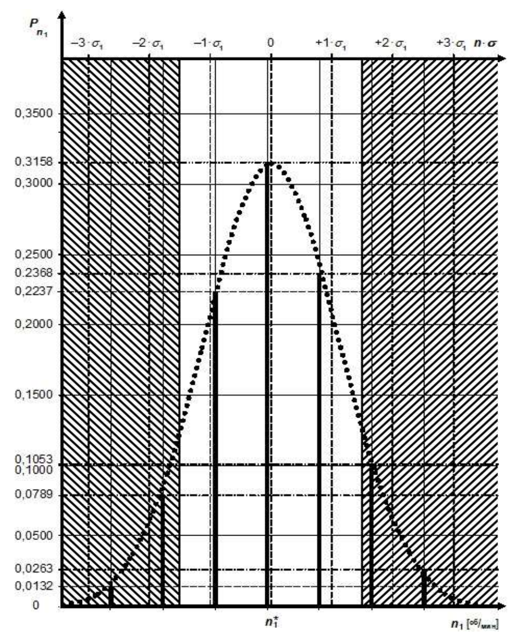

Figure 1: The graph for the values of the functions $P_{n_1} = f(n_1)$

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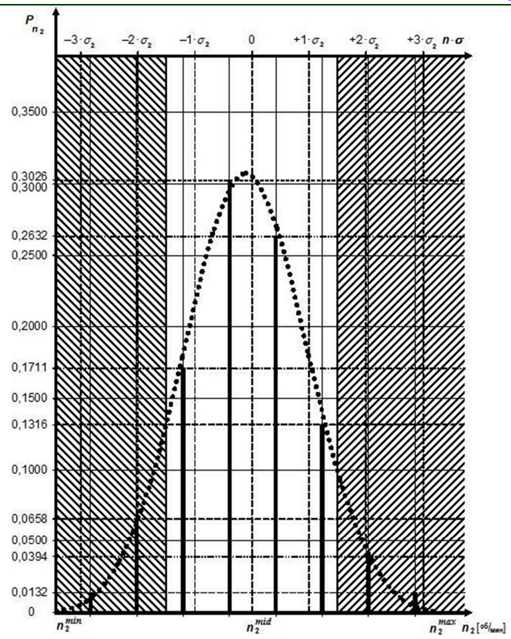

Figure 2: The graph for the values of the functions $P_{n_2} = f(n_2)$

3.2 Unerroric Condition

In-depth testing of the technical condition of turbojet engines of one series at once for two thrust parameters provides control of the tractions forces asymmetry of these engines in the conditions of mass production. The subsequent selection of turbojet engines with minimal thrust asymmetry for twin-engine airliners based on the results of such testing is necessary to improve the flight safety of such airliners.

This can be successfully used for unerroric of turbojet two-circuit engines tractions forces asymmetry control for safety of flight according to the formulas (3)-(4) if the thrust parameters n_1^{LE} and n_2^{LE} are the values of the left engine control parameters of traction force, n_1^{RE} and n_2^{RE} are the values of the right engine control parameters of traction force:

$$0 < n_1^{STOP} \le n_1^{LE} + C_1^{LE}\frac{dn_1^{LE}}{dt} \approx n_1^{RE} + C_1^{RE}\frac{dn_1^{RE}}{dt} \le n_1^{TOP}. \quad (3)$$

$$0 < n_2^{STOP} \le n_2^{LE} + C_2^{LE}\frac{dn_2^{LE}}{dt} \approx n_2^{RE} + C_2^{RE}\frac{dn_2^{RE}}{dt} \le n_2^{TOP}.. \quad (4)$$

Differentiation of rotors speeds n_1^{LE}, n_2^{LE}, n_1^{RE} , n_2^{RE} allows to take into account the speed of their change. The preset coefficients for both rotors C_1^{LE} and C_2^{LE} of the left engine and both rotors C_1^{RE} and C_2^{RE} of the right engine allow taking into account the dynamic characteristics of these rotors. The minimum values of rotors speeds are n_1^{STOP} and n_2^{STOP}. The maximum values of rotors speeds are n_1^{TOP} and n_2^{TOP}.

Such ratios of the values of the thrust parameters of both engines ensure the implementation of flight control programs of an airliner with such engines according to the formula (5) for flight safety:

$$0 < n_2^{STOP} \le n_2^{LE} + C_2^{LE}\frac{dn_2^{LE}}{dt} \approx n_2^{RE} + C_2^{RE}\frac{dn_2^{RE}}{dt} \le n_2^{TOP}. \quad (5)$$

3.3 Deep Testing

Such unerroric will increase the flight safety of a civil airplane with two turbojet two-circuit engines, if they have successfully passed the output quality control according to the results of their in-depth testing.

In-depth testing of turbojet engines in the conditions of their mass production is an ordered set of rules for performing procedures for directional sorting and comparative evaluation of the controlled values of the thrust parameters of such turbojet engines of the series.

This testing can and should be carried out as follows:

1. Setting the required size $N_z=L$ of a sample of deeply tested turbojet engines of the same series;
2. Analysis of the ratios of the monitored parameter values thrust methods aimed busting and comparative assessment of these values and calculating the confidence interval thrust $\Delta R=R_{max}-R_{min}$ if $R_{min} \le R \le R_{max}$ for all N_z one series turbojet engines;
3. The choice of parameters n_1 and n_2 as two thrust parameters of the turbojet engines for power plants of the twin-engine airliners;
4. Calculation by the formula (6) of the probability P_{n_1} of the normal distribution of the controlled values of the low-pressure rotors speeds n_1 for N_z deeply tested turbojet engines based on the "*Three Sigma Rule*" (figure 1):

$$0 < n_2^{STOP} \le n_2^{LE} + C_2^{LE}\frac{dn_2^{LE}}{dt} \approx n_2^{RE} + +C_2^{RE}\frac{dn_2^{RE}}{dt} \le n_2^{TOP}. \qquad (6)$$

5. Narrowing the confidence interval of the normal distribution of the controlled values of low-pressure rotors speeds n_1 for N_z deeply tested turbojet engines and setting its boundaries [$-z\sigma_1$,$+z\sigma_1$] at $0<z<3.0$ in accordance with the "*Three Sigma Rule*";
6. Analysis of the ratios of the controlled values of the low-pressure rotors speeds n_1 and the calculated values of the thrust force R by the methods of their directional search and comparative evaluation, in accordance with the calculated values of the probability of the normal distribution of the controlled values of these rotors speeds in the confidence interval of their distribution with the boundaries [$-z\sigma_1$,$+z\sigma_1$] at $0<z<3.0$;
7. The calculation of the confidence interval thrust $\Delta R=R_{max}-R_{min}$ if $R_{min}\le R\le R_{max}$ for those N_1 deeply tested this turbojet engine series, which is controlled by the values of the rpm low pressure n_1 fall in the confidence interval normal distribution with bounds [$-z\sigma_1$,$+z\sigma_1$] at $0<z<3.0$;
8. The calculation according to the formula (7) probability P_{n_2} normal distribution of controlled values of rotation of the high pressure of n_2 on the basis of the "*Three Sigma Rule*" for N_z deeply tested turbojet engines (figure 2):

$$P_{n_2} = \int_{-z\sigma_2}^{+z\sigma_2} \frac{exp\left(\frac{-(n_2-n_2^*)^2}{2\sigma_2^2}\right)}{\sqrt{2\pi\sigma_2^2}} dn_2. \qquad (7)$$

9. Narrowing the confidence interval of the normal distribution of the controlled values of high-pressure rotation speeds n_2 for N_z deeply tested turbojet engines and setting its boundaries [$-z\sigma_2$,$+z\sigma_2$] at $0<z<3.0$ in accordance with the "*Three Sigma Rule*";
10. Analysis of the ratios of the controlled values of the high-pressure rotors speeds n_2 and the calculated values of the thrust force R by the methods of their directional search and comparative evaluation in accordance with the calculated values of the probability of the normal distribution of the controlled values of these rotors speeds in the confidence interval of their distribution with the boundaries [$-z\sigma_2$,$+z\sigma_2$] at $0<z<3.0$;
11. Calculation of the confidence interval of thrust $\Delta R=R_{max}-R_{min}$ at $R_{min}\le R\le R_{max}$ for those N_2 deeply tested turbojet engines of this series, in which the controlled values of the high-pressure rotors speeds n_2 fall into the confidence interval of their normal distribution with the boundaries [$-z\sigma_2$,$+z\sigma_2$] at $0<z<3.0$;
12. Analysis of the ratios of the controlled values of the low-pressure rotors speeds n_2 and the high pressure rotors speeds n_2 and the calculated values of the thrust force R by methods of their directional enumeration and comparative evaluation in accordance with the calculated values of the probability of the normal distribution of the controlled values of these rotors speeds in the confidence intervals of their distribution with the boundaries [$-z\sigma_1$,$+z\sigma_1$] and [$-z\sigma_2$,$+z\sigma_2$], respectively, at $0<z<3.0$ (figure 1 and figure 2);
13. Calculation of the confidence interval of thrust $\Delta R=R_{max}-R_{min}$ at $R_{min}\le R\le R_{max}$ for all M_z turbojet engines of this series, in which the controlled values of the low-pressure rotors speeds n_1 and the high-pressure rotors speeds n_2 fall into the confidence intervals of their normal distribution with the boundaries [$-z\sigma_1$,$+z\sigma_1$] and [$-z\sigma_2$,$+z\sigma_2$], respectively, at $0<z<3.0$;
14. Evaluation of the thrust asymmetry and mutual correspondence of the quality of the controlled operating parameters M_z of deeply tested turbojet engines, in which the controlled values of the low-pressure rotors speeds n_1 and the high-pressure rotors speeds n_2 fall into the confidence intervals of their normal distribution with the boundaries [$-z\sigma_1$,$+z\sigma_1$] and [$-z\sigma_2$,$+z\sigma_2$], respectively, at $0<z<3.0$ (figure 1 and figure 2);
15. The choice of turbojet engines with a minimum thrust asymmetry, in which the controlled values of the low-pressure rotors speeds n_1 and the high-pressure rotors speeds n_2 fall into the confidence intervals of their normal distribution with the boundaries [$-z\sigma_1$,$+z\sigma_1$] and [$-z\sigma_2$,$+z\sigma_2$], respectively, at $0<z<3.0$;
16. Selection of the pairs of the turbojet engines of this series from among the turbojet engines with the minimum thrust asymmetry for installation in the power plants of the twin-engine airliners.

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4. DISCUSSION

Minimizing the dispersion value σ^2 provides an increase in the mutual correspondence of the controlled values of all K thrust parameters of only N_z deeply tested turbojet engines of one series due to their selection from among L certified turbojet engines of this series.

The ratio of the sizes L and N_z of the initial and narrowed samples of turbojet engines of the same series at $N_z \leq L$ depends on the variance value σ^2 and the dimension $K_2=2$ of the two-dimensional probability function of the random distribution of the controlled values of the low-pressure rotors speeds and the high-pressure rotors speeds $P_{n_1,n_2} = P_{n_1} \cdot P_{n_2}$, as shown in the figure, for different values of the number z of sub-ranges [$-\sigma^2/2$, + $\sigma^2/2$] of statistical analysis corresponding to the "*Three Sigma Rule*" at $0<z\leq 3.0$ and $K_1<K_2$ (figure 3).

It should be noted that by increasing the value of the coefficient $0<z<3.0$, it is possible to increase the number of $M_z \leq N_z = L$ deeply tested turbojet engines of the same series, but at the same time the level of mutual compliance of their controlled thrust parameters will inevitably decrease. However, an increase in the level of mutual correspondence of the controlled values of the thrust parameters of the same engines with a decrease in the value of the coefficient $0<z<3.0$ reduces the number of M_z deeply tested turbojet engines of this series, the quality of which corresponds to this level.

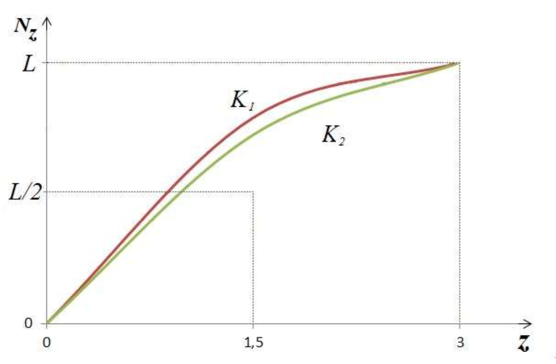

Figure 3: Graphs of the dependence of the sample size of turbojet engines of one series on the number of z sub-ranges $[-\sigma^2/2, +\sigma^2/2]$ of statistical analysis

The results of the analysis of scientific publications and patents on topics close to the subject of the study confirmed the patent purity of the proposed and developed algorithms for the unerroric software for flight safety of twin-engine airliners with twin-shaft turbojet engines. For example, there is a known method of controlling the power plant of an aircraft with gas turbine engines, according to which, after detecting a malfunction or damage to the engine caused by birds getting into it, resource allocation is performed to maintain the thrust level of a faulty engine by increasing the rotation speed of its rotor [EPO Patent No. 1281846, F02C 9/00, 2003]. However, if the working blades are damaged turbines, an increase in the limit values of the regulated parameters of the engine may lead to its final breakdown. There is also a known method for controlling the twin-engine powerplant of an aircraft with gas turbine engines, which, in order to ensure trouble-free operation, provides for an automatic increase in the thrust of gas turbine engines at certain stages of flight [UK Patent No. 2262623, F02C 9/26, 1993]. However, with continuous operation of the aircraft in high-altitude conditions, the pilot must determine the need to turn on the increased thrust mode before each takeoff, which allows for possible mistakes and risks. The general disadvantages of the known methods of controlling the power plants of aircraft with gas turbine engines include the negative consequences of switching on the increased thrust mode, which consist in accelerated development of the resource of such engines in cases where this is not required by the flight conditions. In addition, the thrust asymmetry of such engines can lead to an undesirable unfolding moment of forces acting on the aircraft.

The conducted research contributes to solving this problem. The proposed and developed flight safety unerroric software makes it possible to reduce the thrust asymmetry of turbojet twin-circuit engines of a twin-engine airliner by tightening the control of the mutual correspondence of the controlled values of their thrust parameters. The reliability of the obtained results of the conducted research is fully confirmed by their compliance with well-known results of a lot of scientific developments [16-29].

5. CONCLUSION

Unerroric of turbojet two-circuit engines tractions forces asymmetry analysis is a good remedy for flight safety of civil airplane with two turbojet two-circuit engines.

The formulation and solution of problems of selection and adaptation of methods and algorithms

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for digital processing of measurement results contributed to the development of software for flight safety unerroric of a twin-engine airliner with twin-shaft turbojet engines by tightening the control of the mutual correspondence of the controlled values of their thrust parameters. The results of experimental modeling of adapted algorithms have confirmed the practical feasibility of such software and the high importance of IT-research in its design.

The proposed and developed software for in-depth testing of serial turbojet engines and analysis of the system of thrust force parameters of turbojet twin-circuit engines of an airliner allows you to maintain flight safety for any twin-engine airliner with such engines.

REFRENCES

[1].V.M. Novichkov, and A.Y. Burova, “Algorithm of Two Turbojets Thrust Asymmetry Minimization for Digital Control System of Twin-Engine Jet Airliner”, in *2019 International Multi-Conference on Industrial Engineering and Modern Technologies, FarEastCon 2019*, 2019, p. 8934285

[2].A.Yu. Burova, and V.V. Kabakov, “«Unerroric» of multistage discrete Fourier transform of digital signal without arithmetic operations of multiplication”, *Amazonia Investiga*, Vol. 9, No. 25, 2020, pp. 429-437.

[3].A.Yu. Burova, “Reducing the Error of Digital Algorithms for Deductive Signal Processing Based on Their Multi-Stage Discrete Fourier Transform by the Difference Digital Filters”, in *2020 22th International Conference on Digital Signal Processing and its Applications, DSPA 2020*, 2020, p. 9213275.

[4].A.Yu. Burova, “Minimisation of asymmetry of thrust of the dual-flow turbojet engines of the airliner in accordance with the results of the system analysis of the thrust parameters”, *Asia Life Sciences*, Vol. 21, No. 2, 2019, pp. 629-643.

[5].A.Yu. Burova, “Digital signal processing without performing arithmetic multiplication operations”, *Amazonia Investiga*, Vol. 9, No. 25, 2020, pp. 200-205.

[6].A.Yu. Burova, and T.O. Usatenko, “Digital Algorithms for the Discrete Frequency Selection of Signals that Do Not Use Algorithmic Multiplication Operations”, *TEM Journal*, Vol. 9, No. 2, 2020, pp. 501-506.

[7].A.Y. Burova, “Concept of multistage discrete Fourier transform without performing multiplications”, *Journal of Physics: Conference Series*, Vol. 1889, No. 2, 2021, p. 022003.

[8].A.Y. Burova, and T.O. Usatenko, “Digital methods of discrete Fourier transform, allowing minimizing the number of algorithmic multiplication operations”, *Journal of Physics: Conference Series*, Vol. 1889, No. 3, 2021, p. 032035.

[9].V.V. Vityazev, and S.V. Vityazev, “*Digital signal processing processors TMS320C67x of Texas Instruments”*, Ryazan State Radio Engineering University, Ryazan, 2007.

[10]. V.B. Steshenko, “*PLD implementation by firm ALTERA: element base, design system and hardware description languages”*, DODEKA, Moscow, 2007.

[11]. V.S. Speransky, “*Signal microprocessors and their application in telecommunication systems and electronics”*, Hot Line – Telecom, Moscow, 2008.

[12]. V.B. Steshenko, “*PLD implementation by firm ALTERA: element base, design system and hardware description languages”*, DMK-Press, Moscow, 2016.

[13]. A.Yu. Burova, A.V. Ryapukhin, and A.R. Muntyan, “Reduced hardware costs with software and hardware implementation of digital methods multistage discrete Fourier transform on programmable logic devices”, *Amazonia Investiga*, Vol. 9, No. 27, 2020, pp. 227-233.

[14]. V.S. Speransky, and T.P. Kosichkina, “*Signal microprocessors and their application in communication systems and electronics”*, Hot Line – Telecom, Moscow, 2021.

[15]. A.Yu. Burova, and V.V. Kabakov, “Automatic control of working car engine vibrations using multi-stage discrete Fourier transformation”, *Journal of Physics: Conference Series*, Vol. 1679, No. 2, 2020, p. 022025.

[16]. D.A. Kozorez, M.N. Krasil’shchikov, D.M. Kruzhkov, and K.I. Sypalo, “A solution of the navigation problem for autonomous insertion of payload into a geostationary orbit using a low-thrust engine”, *Journal of Computer and Systems Sciences International*, Vol. 54, No. 1, 2015, pp. 104-115.

[17]. D.A. Kozorez, M.N. Krasilshchikov, D.M. Kruzhkov, and K.I. Sypalo, “Autonomous navigation during the final ascent of a spacecraft into the geostationary orbit.

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

Autonomous integrated navigation system concept", *Journal of Computer and Systems Sciences International*, Vol. 54, No. 5, 2015, pp. 798-807.

[18]. Y.I. Choni, A.G. Romanov, I.Y. Danilov, V.V. Mochalov, V.A. Bartenev, and A.O. Shemyakov, "On the efficiency of defocusing a large satellite multi-beam hybrid parabolic antenna", *IOP Conference Series: Materials Science and Engineering*, Vol. 450, No. 2, 2018, p. 022020.

[19]. N.A. Bulychev, and A.V. Ivanov, "Effect of vibration on structure and properties of polymeric membranes", *International Journal of Nanotechnology*, Vol. 16, No. 6, 2019, pp. 334-343.

[20]. N.A. Bulychev, "Preparation of Stable Suspensions of ZnO Nanoparticles with Ultrasonically Assisted Low-Temperature Plasma", *Nanoscience and Technology: An International Journal*, Vol. 12, No. 3, 2021, pp. 91-97.

[21]. O. Guschina, T. Shevgunov, E. Efimov, and V. Kirdyashkin, "The Exact Frequency Domain Solution for the Periodic Synchronous Averaging Performed in Discrete-Time", in *Proceedings of the Computational Methods in Systems and Software*,Springer, Cham, 2019.

[22]. L.A. Kondratenko, L.I. Mironova, V.G. Dmitriev, O.V. Egorova, and A.O. Shemiakov, "Investigation of the dynamics of nonlinear mechanical systems with long power lines through digital modelling", *Periodico Tche Quimica*, Vol. 16, No. 33, 2019, pp. 668-680.

[23]. A.I. Maron, T.K. Kravchenko, and T.Y. Shevgunov, "Estimation of resources required for restoring a system of computer complexes with elements of different significance", *Business Informatics*, Vol. 13, No. 2, 2019, pp. 18-28.

[24]. L.B. Metechko, A.E. Sorokin, and S.V. Novikov, "Aerospace monitoring in solving problems of modern precision agriculture", *Amazonia Investiga*, Vol. 8, No. 19, 2019, pp. 638-646.

[25]. E.O. Bykova, G.R. Kamaletdinova, and A.E. Sorokin, "Analysis of the Flexibility of a Soft Hinge with a Floating Power Connection", *IOP Conference Series: Materials Science and Engineering*, Vol. 753, No. 4, 2020, p. 042080.

[26]. A.N. Tarasova, "Vibration-based Method for Mechanochemical Coating Metallic Surfaces", *International Journal of Pharmaceutical Research*, Vol. 12, No.2, 2020, pp. 1160-1168.

[27]. P.A. Ukhov, B.A. Dmitrochenko, and A.V. Ryapukhin, "The practice of technological deception in videoconferencing systems for distance learning and ways to counter it", *Amazonia Investiga*, Vol. 10, No. 40, 2021, pp. 153-168.

[28]. M.V. Arkhipov, L.B. Kocherevskaya, and V.V. Matrosova, "Control of Manipulation Robot Interacting with Elastic Objects Using Simmechanics", in *2021 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)*, 2021, pp. 630-635.

[29]. M.V. Arkhipov, E.A. Vzhesnevsky, M.A. Eremushkin, E.A. Samorukov, and L.B. Kocherevskaya, "Tensometry of soft biological tissues with manipulation robot", in *IOP Conference Series: Materials Science and Engineering*, Vol. 489, No. 1, 2019, p. 012051.