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PATTERNS OF CHANGE IN TECHNOLOGICAL ACCURACY OF WOODWORKING MACHINES DURING OVERHAUL PERIOD

The patterns of changes in the technological accuracy of the machine during the overhaul period in the form of a polynomial dependence have been identified, which makes it possible to determine the time and number of adjustments to the machine to ensure its operating capacity according to the criterion of technological accuracy. On the basis of the statistical modeling method, a simulation model-program "ModDynToch" was developed for identifying changes in the technological accuracy of the machine tool with the determination of the time between failures and the required number of machine adjustments during the overhaul period. Based on the results of modeling changes in the technological accuracy of a number of machines for sawing and milling wood, it was found that in order to ensure a working capacity during the overhaul period, each machine requires three adjustments to be made at a certain interval. Based on the analysis of the results of modeling changes in the technological accuracy of machines for sawing and milling wood, it was found that the shortest period of operation for band saw machines is up to 190 hours, for circular saw machines – up to 480 hours, and for milling machines – up to 840 hours. The results of the statistical modeling of the pattern of changes in the technological accuracy of machines during the overhaul period of operation are correlated with operational data with an accuracy of up to 7%, which confirms the reliability of the modeling results.
Keywords: Simulation model, machining accuracy, machine tool, repair.

Introduction. The source of errors in the dimensions of the parts produced in the process of wood cutting is the dynamic system "machine-cutting tool-workpiece" (MCtW) [1, 2], which contains a large number of factors that have both a systematic and a random nature of influence on the accuracy of machining. The most complex and constant source of machining errors is the machine, the period of operation of which is decades. One of the main performance indicators of a woodworking machine is its technological accuracy, which during the operation of the machine is constantly decreasing compared to the initial one. The technological accuracy of machine tools is partially restored through periodic adjustment and repair [3]. That is, maintaining the necessary level of machining accuracy on machine tools requires the development of specific practical solutions to improve or restore the technological accuracy of a woodworking machine, which, in turn, requires conducting research to find out patterns of changes in machining accuracy during the overhaul period of the machine.

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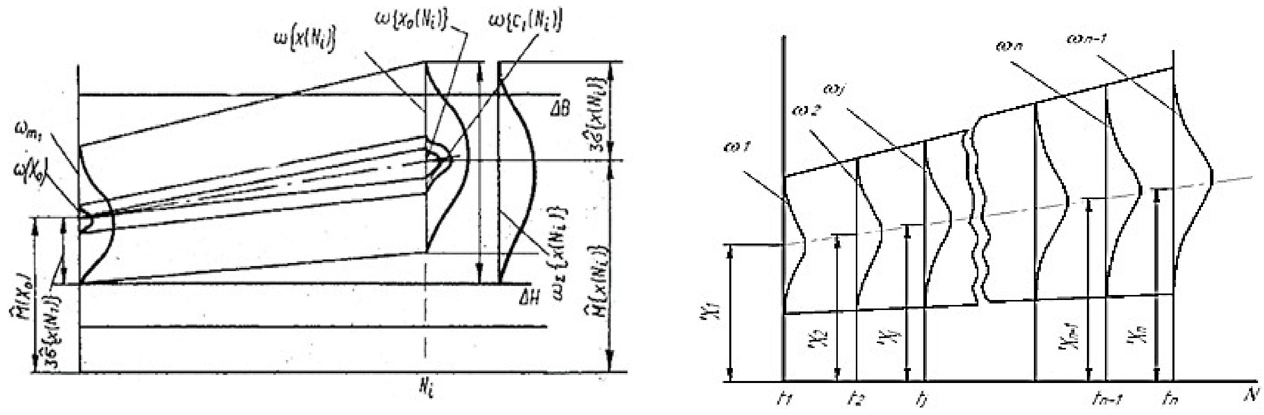
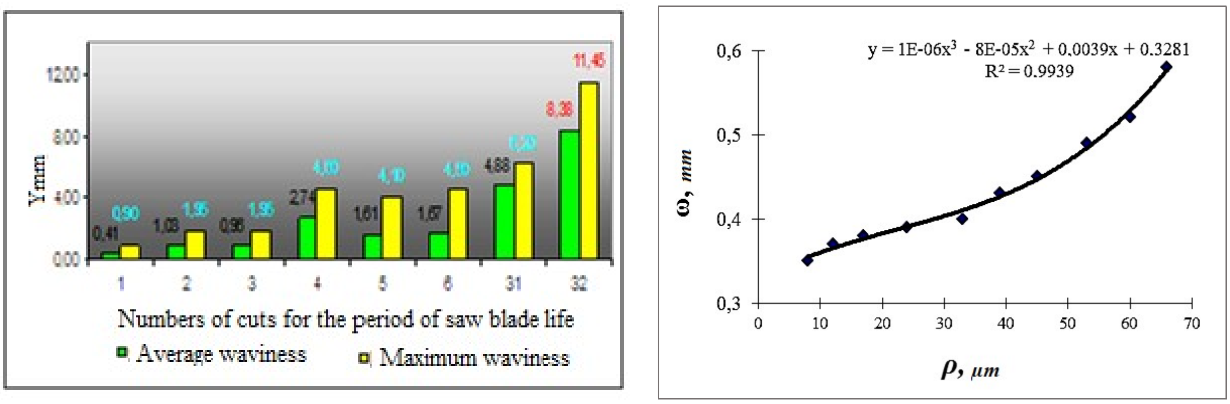
1. Analysis of well-known studies and publications. The first studies of the change in the machining accuracy caused by a number of factors were conducted by F.M. Manzhos [4], on the basis of which it was found that cutter wear has a significant effect on the machining error, also the dependence of the cutter wear on the cutting path was revealed. Models for changing the accuracy of batch blanks dimensions were proposed by the authors [5, 6], which are based on the linear dependence of the increase in the scattering field of the machining error of a batch of manufactured parts (Fig. 1 *a, b*). The size of the random error scattering field is determined on the assumption that the error scattering is subject to the normal distribution law of values, and the change in size of the parts and the scattering field over time is linear in nature [7], but in most cases such dependencies have a much more complex nature of change. Thus, according to the results of studies on the change in machining accuracy during the tool operation, regarding wear, on bandsaw and circular saw machines [8–11], it was found that the change in machining accuracy is described by a polynomial dependence (Fig. 2 *a, b*).



a *b*

Fig. 1. Modeling of changes in the machining accuracy of a batch of blanks: *a – model of changing the accuracy of the sizes of blanks in a batch [5]; b – model of the accuracy of machining a batch of parts [6]*



a *b*

Fig. 2. Dependences of the change in the accuracy of wood machining during the period of tool service life in relation to wear: *a – change in the waviness of band saw cuts, [8]; b – change in the accuracy of machining with a circular saw, [10]*

Prof. V.V. Amalytsky [12] found that technological accuracy is the main criterion for assessing the reliability of woodworking machines and developed a mathematical model of the technological service life of a woodworking machine (Fig. 3). But along with this, it should be noted that these models have a general approximate and simplified form of mathematical equations.

The method of mathematical modeling of the state of technological accuracy of woodworking machines has become the main one for further studies of the processes of machining wood and wood-based materials. Thus, in [13], developed was a mathematical model of changing the technological accuracy of a machine tool for calibrating and grinding chipboard-made furniture parts with abrasive cylinders, which makes it possible to predict a change in the technological accuracy of a machine tool in order to prevent the appearance of defective parts. In [14], based on the analysis of the well-known methodology for studying the technological accuracy of woodworking machines, substantiated is the need for its improvement through the use of computer technologies for processing and analyzing the statistical data of the experiment. The author [15] believes that the disadvantage of the well-known methodology for studying the change in technological accuracy during the characteristic period of machine operation is a statistical-analytical method that requires conducting an experiment and mathematical processing of a large amount of statistical data. The authors of [16] developed a simulation model of changes in the technical condition of the chipboard forming-and-pressing equipment over the period of the repair cycle, and, based on the results of experiments on the model, it was found that the distribution of time-to-failure is described by the Weibull law.

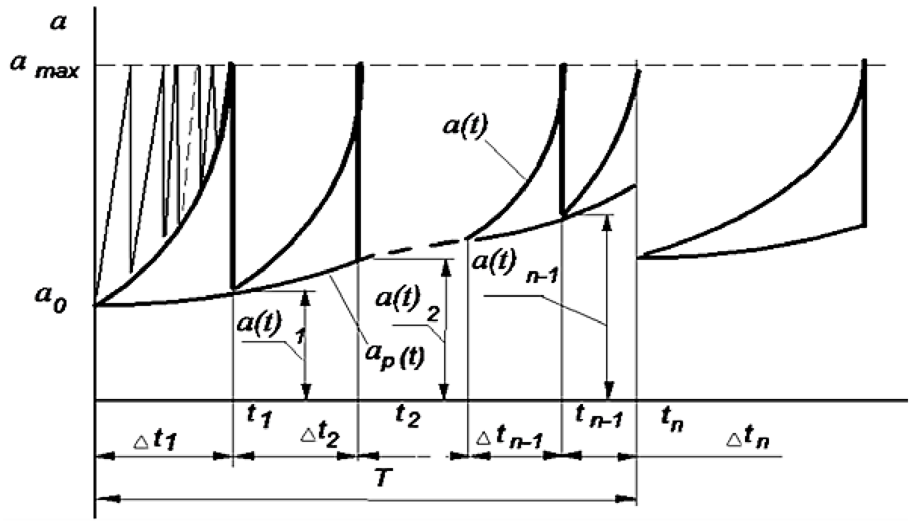


Fig. 3. Model of the technological service life of the machine according to V.V. Amalytsky [12]

So, as a result of the analysis of the known methods for studying the technological accuracy of woodworking machines, the limitations and inconsistency of the research results with the modern scientific level were revealed, which indicates the need for further development of the methodology for modeling changes in machining accuracy using modern computer technologies, which will allow finding practical solutions to ensure the operability of the machine according to the criterion of technological accuracy.

2. Research methodology. 2.1. Mathematical model of changes in machining accuracy during overhaul period of machine tool operation. The formation of a mathematical model of changes in the accuracy of machining during the overhaul period of the machine is based on the following basic principles: the processes that cause errors during the machining of workpieces and the errors themselves are random in nature; the change in the technological accuracy of the machine is described by the Weibull-

Gnidenko distribution law and its scattering field ω_1; $\omega_1 = \pm 2\sigma$ is taken as the scattering field boundaries with the probability of entering the size values of the manufactured parts – 0.976. The formation of a mathematical model for changing the accuracy of processing during the overhaul period of the machine is based on the following basic principles: the processes that cause errors in the processing of workpieces, and the errors themselves are random; the change in the technological accuracy of the machine tool is described by the Weibul-Gnedenko distribution law and its stray field ω1; outside the stray field, ω1 = ± 2σ is taken with the probability of hitting the dimensions of the manufactured parts – 0.976.

The technological accuracy of the machine in the process of long-term operation decreases within the machining tolerance from x_0 to x_{max} (Fig. 4). The curve $x(t)$ will be obtained by connecting all points in the interval Δt_1. At moments $t_1, t_2, \ldots, t_n$, the value $x(t)$ reaches the upper limit $x_{\max}$ and then the machine starts to produce parts that do not meet the requirements for the accuracy of the nominal size, i.e. there occurs a parametric failure of the machine in terms of technological accuracy. In order to restore the operability of the machine, it is necessary to perform an adjustment, which makes it possible to improve the technological accuracy $x(t)_1, x(t)_2 \ldots x(t)_i$.

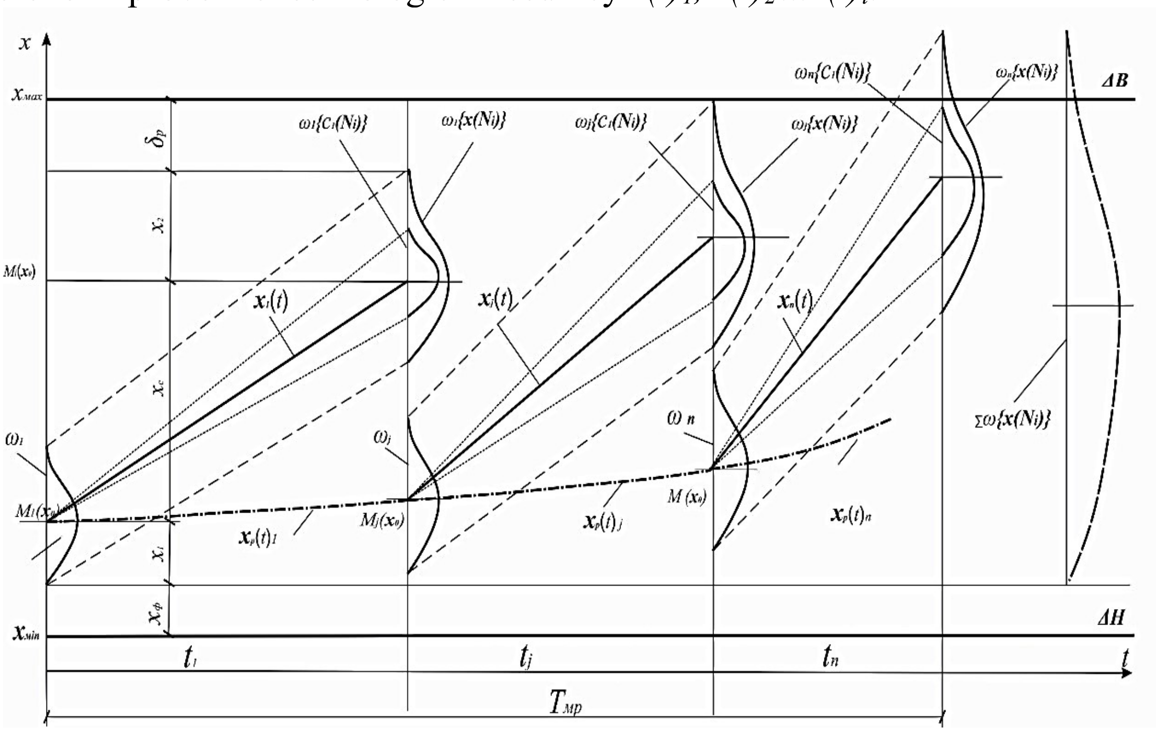


Fig. 4. Scheme of changes in the technological accuracy of the machine tool during the overhaul period of its operation

Adjustment of the machine includes a set of measures, the implementation of which allows improving the technical condition of the machine without mechanical processing of its elements and without replacing worn parts. When adjusting, only gap reduction, lubrication, tension adjustment, etc. are performed. It is impossible to reach the initial level of accuracy x_0 through the adjustment, that is, some value $x_p(t)$ is only reached, which characterizes the accuracy of the adjusted machine tool.

The overall loss of accuracy during the operation time t of the machine will be equal to the difference $x(t) - x_0$. At the moment of time $t_{мр}$, further operation of the machine becomes inefficient due to the small value of the difference $x_{max} - x_p(t)$. To determine the duration of interregulatory periods, it is assumed that the value $x(t) - x_p(t)$ has a linear dependence on the time interval of each interregulatory period with the same angular coefficient k for all intervals.

$$x(t) - x_p(t) = k(t_n - t_{n-1}), \tag{1}$$

where t_{n-1} is the last moment of adjustment before carrying out repairs $t_{мр}$.

For $t_{мр} = t_n$, equation (1) takes the form $x_{max} - x_p(t_n) = k * t_n$ (2)

In the second approximation, it is assumed that at each moment of time the rate of change of the value $x_p(t) - x_0$ is proportional to the accuracy and is recorded

$$(x_p(t) - x_0)' = x'_p(t) = \lambda \cdot x(t), \tag{3}$$

where λ - proportionality factor.

To determine the duration of interregulatory periods, prof. V.V. Amalytsky [12] proposes the dependence

$$\Delta t_n = \frac{1}{\lambda}\left[-\ln\left(1 - \frac{\lambda \cdot \Delta t_{n-1}}{1 + \lambda \frac{x_{\max}}{k}}\right)\right]. \tag{4}$$

where: $x_{\max}$ _ the upper tolerance limit for the size of parts in the batch produced by the machine; k – angular coefficient characterizing the rate of machine misalignment per unit of time; λ – proportionality factor which characterizes the rate of wear of the machine per unit of time.

To determine the zero interval Δt_0 in the dependence (4), the following is accepted

$$x(t) = x_{\max}, \quad x_p(t) = x_0 \quad t_n = 0, \quad t_n = t_0. \tag{5}$$

Then the value of the zero conditional interval is determined by the dependence

$$\Delta t_0 = \frac{x_{max} - x_0}{k}. \tag{6}$$

If the interval Δt_n is identified, the value of the function $x_p(t)$ at the end of the last interval t_n is determined from the dependence $x_p(t_n) = x_{max} - k \cdot \Delta t_n$. (7)

Thus, dependences (3), (4), and (7) provide the calculation scheme of the function $x_p(t)$. The value of the curvilinear dependence, which characterizes the pattern of change in the interregulatory periods, is given by the function

$$x_p(t) = x_p(t_{n-1}) \cdot e^{\lambda(t - t_{n-1})} \frac{k}{\lambda}\left[e^{\lambda(t - t_{n-1})} - \lambda(t - t_{n-1}) - 1\right] \tag{8}$$

Function (8) is a mathematical model of changes in the technological accuracy of the machine during the overhaul period. The overhaul period $t_{мр}$, during which the machine reaches an inoperable condition, according to the criterion of technological accuracy, consists of successively decreasing interregulatory periods

$$t_{мр} = \sum_{n=1}^{\infty} \Delta t_n \tag{9}$$

For practical results, the number of interregulatory intervals is limited to the number $n = 3$, which corresponds to the duration of the inter-inspection periods of the system of scheduled preventive repairs of woodworking machines of complexity group II.

2.2. Development of an algorithm for a simulation model – a computer program "ModDynToch". On the basis of the statistical modeling method, a simulation model was developed – the *ModDynToch* computer program for changes in the technological accuracy of the machine tool with the determination of the working time-to-failure and the required number of adjustments of the machine tool during the overhaul period of its operation. The *ModDynToch* program algorithm consists of a main program and a *ModDynam* subroutine. The program is implemented in the Visual Basic language for Applications in the Excel environment. The program provides for data input and output of results on separate sheets of the Excel environment.

The algorithm of the main program (Fig. 5) includes 21 blocks, each of which successively performs the following functions:

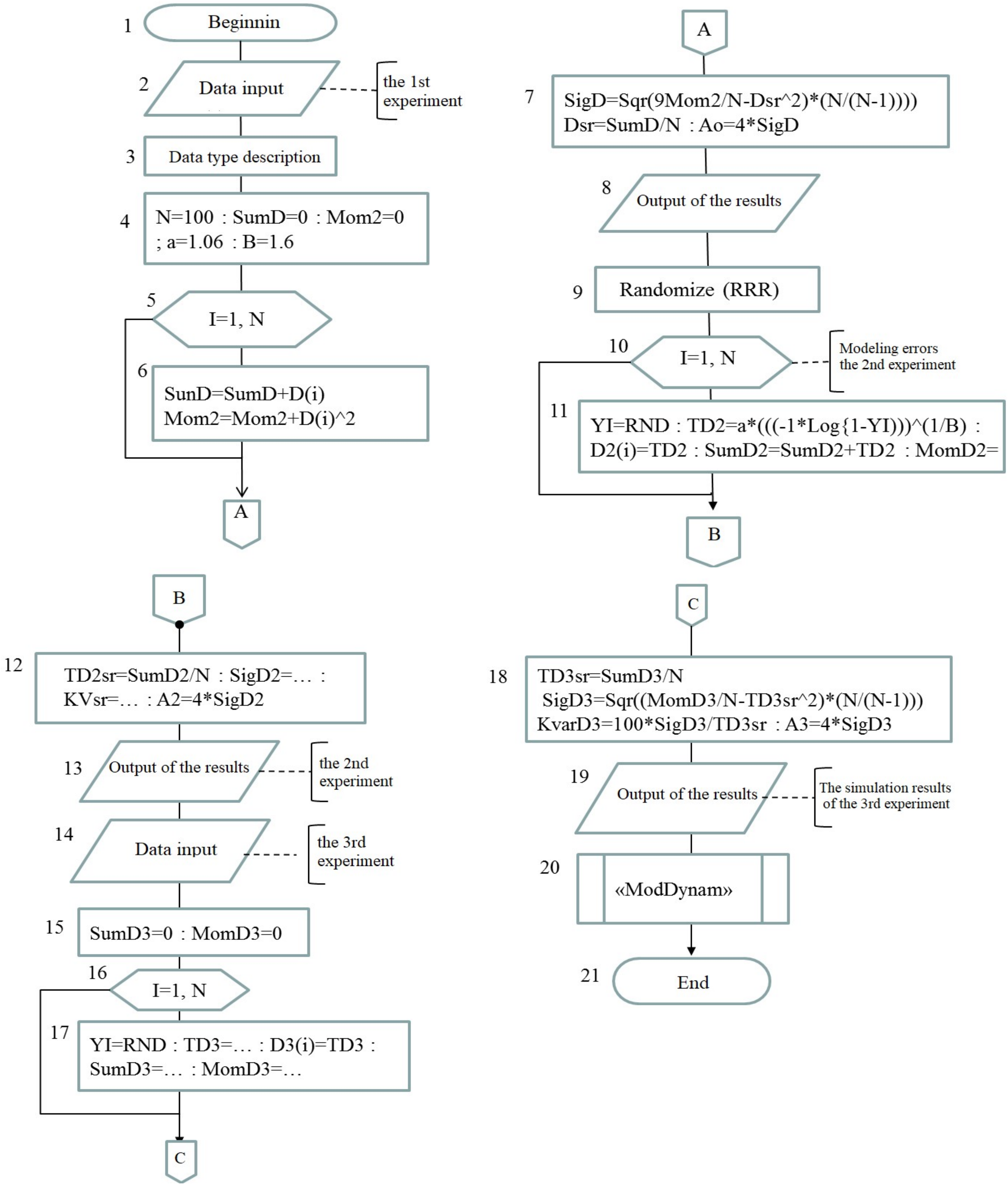


Fig. 5 – Block diagram of the algorithm for the main program ModDynToch

1 Beginning – describes the name of the program, the authors of the program; 2 Data input – organizes the entry from the "Data" sheet of the date of the 1st experiment, characterizing the initial state of the machine; 3 Data type description – characterizes the types of data and arrays: integers, valid, etc.; 4 – organizes the cleaning of cells and the input of constants; 5 – organizes cycles from 1 to N for the 1st experiment; 6 – calculates the sum of values and the second statistical point; 7 – determines standard deviations, the arithmetic mean of values and the error scattering field; 8 – organizes the output of the results of the first experiment on the Excel sheet; 9 – initiates the Randomize (RRR) function for the operation of the generator of uniformly distributed RND values; 10 – organizes cycles from 1 to N of modeling errors according to the Weibull-Gnidenko distribution; 11 – generates uniformly distributed YI numbers and calculates the array of errors according to the Weibull-Gnidenko distribution; 12 – calculates the average value of the errors, the standard deviation of the errors, the coefficient of variation and the error scattering field of the 2nd experiment; 13 – organizes the output of the results of the 2nd experiment; 14 – organizes the data input of the 3rd experiment (technological accuracy after adjusting the machine); 15 – organizes the cleaning of cells of sums and the second statistical moment of the third experiment; 16 – organizes cycles from 1 to N for the 3rd experiment; 17 – organizes the modeling of errors according to the Weibull-Gnidenko distribution; 18 – calculates the average value of errors, the standard deviation of errors, the coefficient of variation and the error scattering field after modeling the 3rd experiment; 19 – organizes the output of the simulation results of the 3rd experiment; 20 – organizes a call to the *ModDynam* subroutine to calculate indicators of technological service life; 21 End.

The *ModDynam* subroutine (Fig. 6) includes ten blocks:

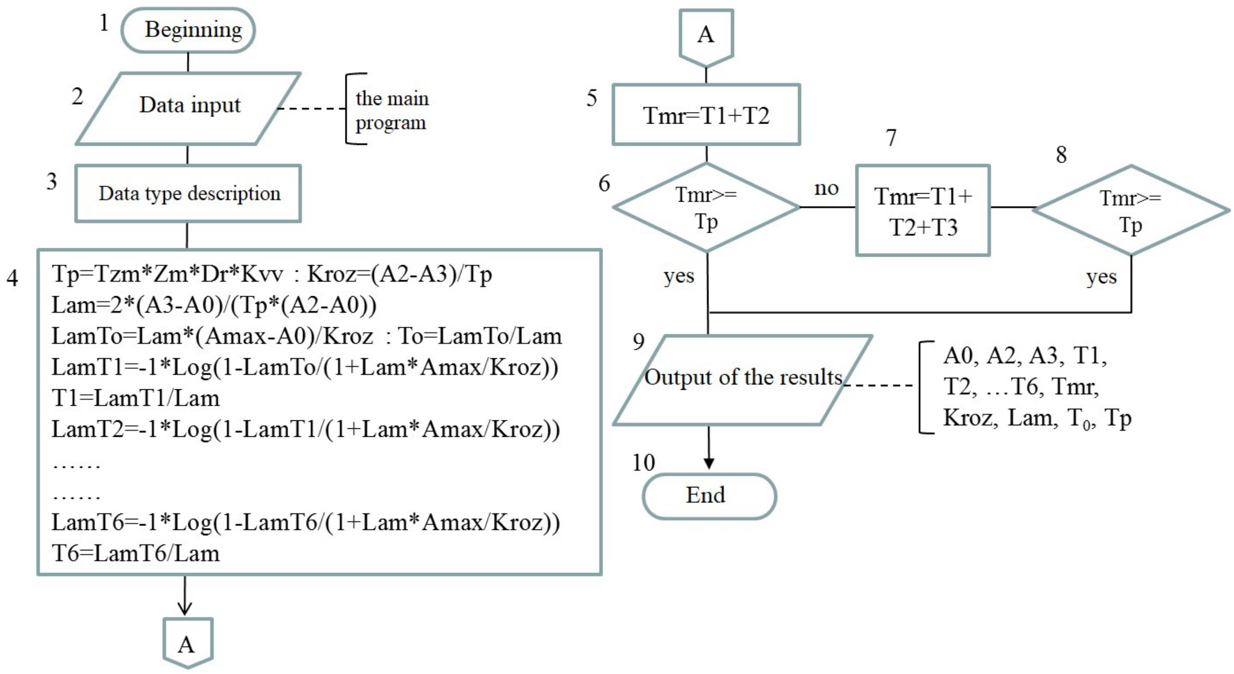


Fig. 6. Block diagram of the algorithm for the ModDynam subroutine

1 Beginning – describes the name of the program, the authors of the program, etc.; 2 Data input – organizes input from the main program; 3 Data type description – characterizes the types of data and arrays: integers, valid, etc.; 4 – calculates the parameters of technological service life: the rate of misalignment of the machine, the rate of wear of the machine, the conditional time of the misalignment of the machine before the

start of research, the duration of the interregulatory periods; 5 – assigns the first value to the duration of the interregulatory period *Tmr*; 6 – compares *Tmr* with the service life of the machine *Tr*; 7 – assigns the second value to the duration of the interregulatory period *Tmr*; *8* – compares the new value of *Tmr* with the service life of the machine *Tr*; 9–organizes the output of the results of calculating the parameters of technological service life to the Excel letter; 10–terminates the subroutine and returns to the main program.

The modeled pattern of changes in the technological accuracy of the machine tool makes it possible to determine the time and number of adjustments of the machine tool during the overhaul period in order to ensure its operable condition in terms of the technological accuracy parameter.

3. Results and discussion. 3.1 Input data for simulation modeling regarding machine operating conditions. To simulate the pattern of changes in machining accuracy during the overhaul period of the machine and to determine the time and number of machine adjustments, it is necessary to identify the operating conditions of the machine according to the requirements for machining accuracy.

1. Depending on the nominal size of the part and the quality of machining, it is necessary to set the zone of error tolerance $\delta_н$, taking into account the condition that all machines must correspond to a high accuracy class with machining according to quality grade 12, 13, 14.

2. The initial field ω_1 of a new machine should be 0.2 $\delta_н$, and for used machines (4-10 years of operation) under investigation, it is accepted within 0.4-0.6 $\delta_н$. The final scattering field $\omega_к$ is taken to be more than the tolerance zone by 5%, that is, by the allowable percentage of rejects.

3. The operating time of the machine in the first interregulatory interval of work is accepted taking into account the time of the inter-inspection period. The duration of a standard repair cycle for machine tools of category II (weighing 1–5 tons) is equal to $T_ц$ = 11200 hours of machine operation. The structure of the cycle for machines of category II includes 15 intervals (inspections, running-, medium-, and major repairs) with a length of 746 hours. The interval time may vary depending on the value of the coefficients:

$$T_ц = 11200\ K_1\, K_2\, K_3\,, \tag{10}$$

where: K_1 – coefficient of machine type (general purpose – 1.25, specialized – 1.0); K_2 – machine tool service life factor (machine tools manufactured by 1988 – 1.0; after 1988 – 1.2-1.4); K_3 – service life coefficient (machines that have undergone two major repairs – 1.0; three major repairs – 0.98; four major repairs – 0.95; five major repairs – 0.9).

3.2. Simulation results of changes in the technological accuracy of machine tools for the overhaul period. Based on the specified conditions, the modeling of the pattern of changes in the technological accuracy of the SKTP505-2 horizontal band saw machine was carried out (Fig. 7).

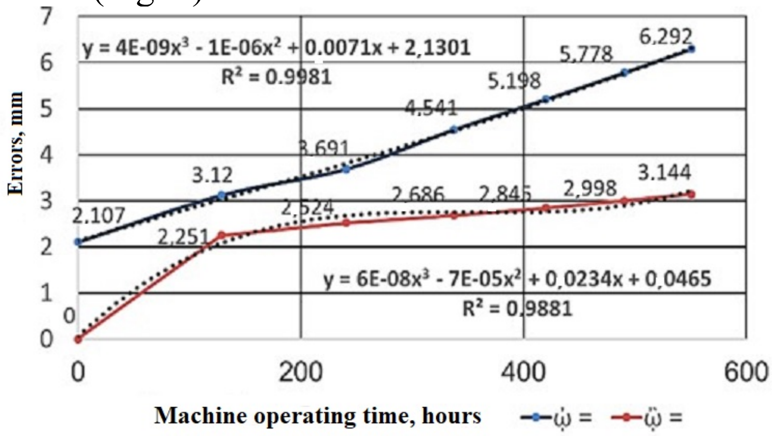


Fig.7. Simulation results of changes in the technological accuracy of the SKTP505-2 machine during the overhaul period

Based on the results of the simulation, the patterns of changes in the scattering field of machining errors and wear of the SKTP505-2 machine were established in the form of regression equations that are adequately described by polynomials of the third degree:

$$\omega = 4\,E\text{-}09\; t^3 - 1E\text{-}06\; t^2 + 0.0071\; t + 2.13\;; \quad (11)$$

$$\lambda_в = 6\,E\text{-}08\; t^3 - 7E\text{-}05\; t^2 + 0.0234\; t + 0.047. \quad (12\;)$$

To ensure the operability of the machine in accordance with the criterion of technological accuracy during the overhaul period, a constantly decreasing frequency of machine adjustment is determined (Fig. 8). It was found that in order to ensure the accuracy of sawing wood on the SKTP505-2 machine within ± 2.5 mm, it is necessary to perform three adjustments with the following frequency: T_1 = 189 hours, T_2 = 144 hours and T_3 = 109 hours.

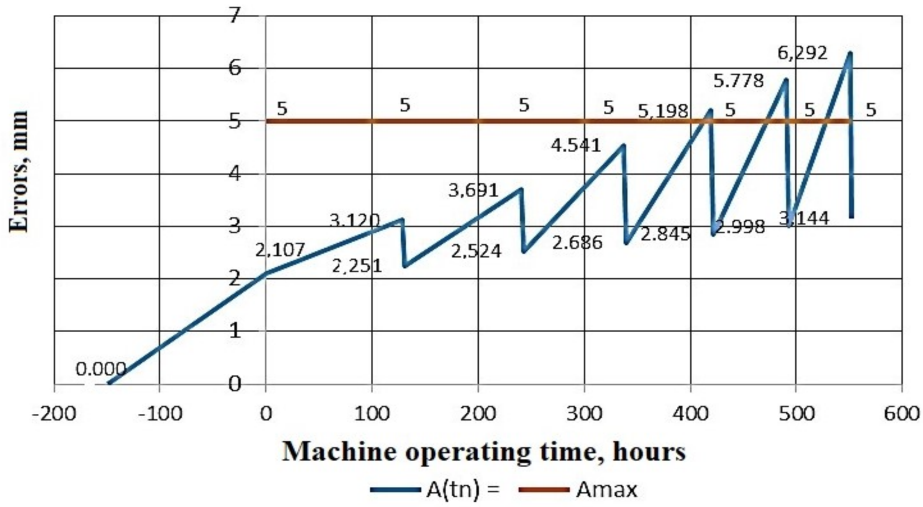


Fig. 8. Simulation results of the frequency of adjustments of the SKTP505-2 machine during the overhaul period of its operation

Modeling of changes in the technological accuracy for the following woodworking machines has been carried out: band saws of brands SKTP505-2 and LT-20; circular saws for orthosawing, brands Barakuda-2 and UN-500; circular saws of through-passage and position-oriented types of brand VK-40; milling machines of brands AD741 and CP6-9, four-side plano milling machines of brands S-20 and Unimat-17A; also the duration of interregulatory intervals with an average number of up to three was determined (Fig. 9).

Based on the analysis of the results of modeling changes in the technological accuracy of machines for sawing and milling wood, it was found that the shortest period of operation for band saw machines is up to 190 hours, for circular saw machines – up to 480 hours, and for milling machines – up to 840 hours. The results of statistical modeling of the pattern of changes in the technological accuracy of the machines are correlated with operational data with an accuracy of up to 7%, which confirms the reliability of the modeling results. Determining the maximum operating time of the machine tool makes it possible to timely perform the next adjustment of the machine to restore its operable condition in accordance with the criterion of technological accuracy. Based on the results of modeling the technological service life according to the parameter of the accuracy of processing data of the machines, it was found that in order to ensure the operable condition during the overhaul period, each machine needs three adjustments to be performed at a specified interval.

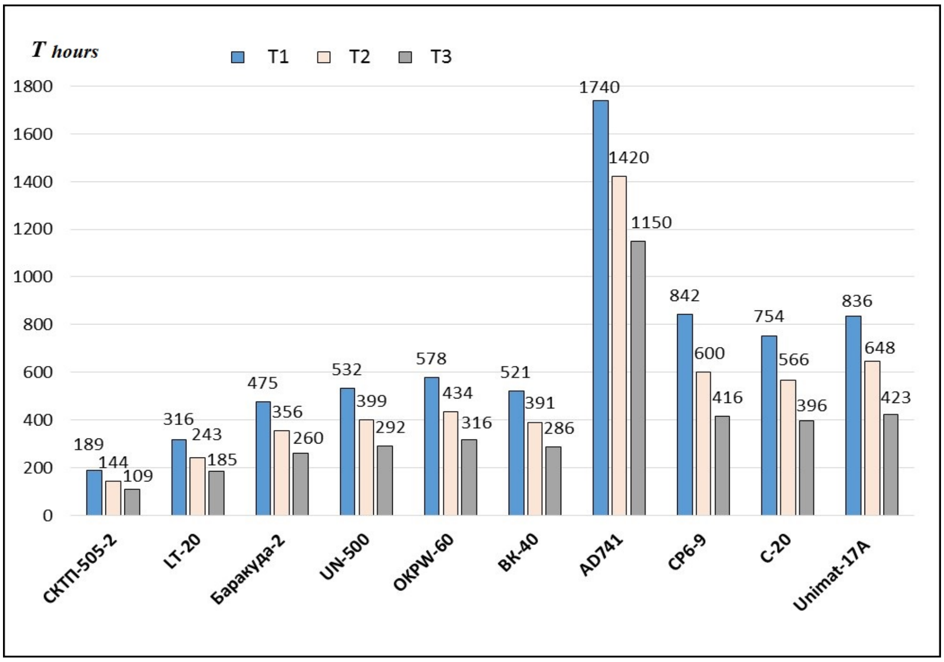


Fig. 9 – Diagram of the duration of interregulatory intervals of machine operation

Conclusions

1. A pattern of changes in technological accuracy during the overhaul period was identified, which made it possible, on the basis of the statistical modeling method, to develop the *ModDynToch* simulation model-program for changing the technological accuracy of the machine tool with the determination of the time between failures and the required number of machine adjustments during the overhaul period.

2. Based on the results of the simulation of changes in the technological accuracy of a number of machines for sawing and milling wood, it was found that in order to ensure the operability during the overhaul period, each machine requires three adjustments to be made at a certain interval.

3. The results of statistical modeling of the patterns of changes in the technological accuracy of machine tools for the period between repairs correlate with operational data with an accuracy of up to 7%, which confirms the reliability of the simulation results.

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Закономірність зміни технологічної точності деревообробних верстатів упродовж міжремонтного періоду роботи

Встановлено закономірність зміни технологічної точності верстата упродовж міжремонтного періоду роботи у вигляді поліноміальної залежності, що дає змогу визначати час і кількість виконання регулювань верстата для забезпечення його працездатного стану за критерієм технологічної точності. На основі методу статистичного моделювання розроблено імітаційну модель-програму «ModDynToch» зміни технологічної точності верстата з визначанням напрацювання на відмову та необхідної кількості регулювань верстата упродовж міжремонтного періоду роботи. За результатами виконаного моделювання зміни технологічної точності низки верстатів для розпилювання та фрезування деревини встановлено, що для забезпечування працездатного стану упродовж міжремонтного періоду роботи кожен верстат потребує виконання з визначеним інтервалом трьох регулювань. На основі аналізу результатів моделювання зміни технологічної точності верстатів для розпилювання та фрезування деревини встановлено, що найменший період роботи у стрічковопилкових верстатів – до 190 год., у круглопилкових верстатів – до 480 год., а у фрезувальних – до 840 год. Результати статистичного моделювання закономірності зміни технологічної точності верстатів упродовж міжремонтного періоду роботи корелюються із експлуатаційними даними з точністю до 7%, що підтверджує достовірність результатів моделювання.

Ключові слова: Імітаційна модель, точність оброблення, верстат, ремонт.