Modeling Parametric Failures of Woodworking Machines According to the Technological Precision Criterion

Mariya Pylypchuk[1], Lidiia Dziuba[2], Ihor Rebezniuk[1], Oksana Chmyr[2](✉), and Mykhailo Burdiak[1]

[1] Ukrainian National Forestry University, 103, Chuprynky Street, Lviv, Ukraine
[2] Lviv State University of Life Safety, 35, Kleparivska Street, Lviv, Ukraine

Abstract. A radial model of parametric failure of a woodworking machine according to the precision criterion based on the truncated normal distribution of a machine's disadjustment speed caused by the wear processes in the mating of parts and components of the structure has been developed. It has been found that the density of parametric failures of woodworking machines according to the precision criterion corresponds to alpha distribution. Based on the operational observations, the alpha distribution parameters of operating time to parametric failure for band saw, circular saw, and milling machines have been established. It has been determined that the durations of inter-adjustment periods for band saw, circular saw, and milling machines coincide with the operational data of the duration of these inter-adjustment periods for these machines with an accuracy of seven percent, which proves the adequacy of the mathematical model. The proposed model of parametric failures of woodworking machines based on the processing precision criterion allows determining the durations of inter-adjustment periods of machine operation, during which the precision of processing is ensured in compliance with the current standards.

Keywords: Alpha distribution · Operating time · Machine · Parametric failure · Precision of processing · Inter-adjustment period

1 Introduction

The quality of finished products and the efficiency of using wood depend on the precision of sawing timber in modern woodworking production. In the dynamic system "machine – tool – workpiece" (MTW), the most complex and constant source of processing errors is a machine, the service life of which equals decades.

During the operation of woodworking machines, different types of energy apply: mechanical, thermal, physical, which lead to changing the parameters of individual elements, units, and a machine as a whole. Such processes are reversible or irreversible. Reversible processes, such as elastic and thermal deformations of parts and units, temporarily change the parameters of machine parts and units within certain limits. Irreversible degradation processes, such as aging, corrosion, wear, lead to the significant deterioration of a machine's technical condition over time and significantly affect

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2022
V. Tonkonogyi et al. (Eds.): InterPartner 2021, LNME, pp. 119–126, 2022.
https://doi.org/10.1007/978-3-030-91327-4_12

the precision of wood cutting. Therefore, the maintenance of a woodworking machine should ensure the reliability and prevention of deviations of its parameters, which lead to the loss of technological precision.

This paper aims to model the parametric failures of woodworking machines based on the criterion of technological precision using α - distribution of operating time, enabling us to determine the duration of inter-adjustment periods of machine operation.

2 Literature Review

The processes of changing parameters in woodworking machines differ in speed [1]. Periodic short-lived processes continue within the machine's operation and wood cutting tool units [2, 3]. These include vibrations of a woodworking machine and tool units; changes of friction forces in kinematic pairs; fluctuations in the workload due to the heterogeneity of the processed wood; parametric oscillations of the wood cutting tool [3], and other processes that affect the mutual placement of the tool and the workpiece at any time, reducing the precision of wood sawing [4].

Slow (degradation) processes occur within the entire period of a machine's operation and are manifested between its regular repairs [5, 6]. Such processes include stress redistribution in parts, material fatigue, corrosion, wear of machine parts, and units in friction pairs [7]. As a result of wear and tear, parametric failures of a woodworking machine periodically occur according to the precision criterion. Partial restoration of the technological precision of a machine is carried out by its regular adjustment and repair [8, 9]. In the works [1], parametric failures are described using a linear model with a scattering of the initial parameter by the normal distribution law. Random processes with a normal distribution law are considered in the works [10, 11]. Published experimental failure distributions of parts and components of structures working to the point of exhaustion are usually asymmetric and modal [2, 8]. The work [12] notes that it is reasonable to use the asymmetric Weibull distribution law to study the reliability indicators and describe the failure models. In work [13], to study the reliability of mechanical equipment, the features of the processing process are used instead of the traditional description of degradation processes. However, these studies do not consider the possibility of estimating the duration of operation between equipment failures, which would allow determining the inter-adjustment periods for equipment. In [14], it is indicated that parametric failures resulting from wear do not correspond to the normal law of failure distribution. Therefore, to describe the operating time until the parametric failure of the woodworking machine, it is reasonable to use an asymmetric α - distribution [14], which allows estimating the duration of operation between failures according to the processing precision criterion.

3 Research Methodology

During machine adjustment, the size adjustment at the time t_1 is set to a particular nominal value X_0. In the course of further operation of the machine, the value X_0 is randomly changed. Therefore, size X is a polar random function of operating time $X(t)$.

All implementations of random function $X(t)$ pass through one non-random stationary point – pole (X_0, t_1).

For finding the failure distribution of a woodworking machine by the precision criterion according to the characteristics of the disadjustment process, it is convenient to approximate the random value of X size of the manufactured part by a random radial function [14] as follows:

$$X(t) = X_0 + B \cdot t, \tag{1}$$

where B is the speed of the machine disadjustment process, which is a random variable, and the operating time t is calculated from the moment of arising need for adjustment. To find the numerical characteristics – mathematical expectation m_b and mean-square deviation σ_b, which roughly describe the machine disadjustment process, one should know the X_0 variable and operating time t_0 before pre-adjustment. The speed variable B of changing size X is limited by the lower b_1 and upper b_2 margins. Therefore, according to [14], it is reasonable to consider the truncated normal distribution of the size X change speed, provided that the speed of machine disadjustment is limited, i.e.: $b_1 \le b \le b_2$:

$$\bar{f}(b) = cf(b) = \frac{c}{\sigma_b\sqrt{2\pi}}\exp\left[-\frac{(b-m_b)^2}{2\sigma_b^2}\right], \tag{2}$$

where $c = \frac{1}{\Phi(u_2)-\Phi(u_1)}$; $u_1 = \frac{b_1-m_b}{\sigma_b}$;$u_2 = \frac{b_2-m_b}{\sigma_b}$; $\Phi(u)$ – Laplace's function. As a result of disadjustment, the X parameter can reach a critical value X_{max}, at which a parametric failure of the woodworking machine occurs according to the precision criterion. Therefore, we further consider B as the absolute value of a woodworking machine's disadjustment speed.

The time $T = \frac{|X_{max}-X_0|}{B}$ to parametric failure according to the precision criterion is a function of a random variable B distributed according to the truncated normal law (2). According to the rule of finding the distribution law of random arguments' functions [14] provided that $\frac{|X-X_0|}{b_2} \le t \le \frac{|X-X_0|}{b_1}$ distribution density for T variable has the form of three-parametric α - distribution [14]:

$$f(t) = \frac{\beta \cdot c}{t^2\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{\beta}{t}-\alpha\right)^2\right], \tag{3}$$

where β, α, c – distribution parameters, $\beta = \frac{|X-X_0|}{\sigma_b}$, $\alpha = \frac{|m_b|}{\sigma_b}$. Parameter β has the dimensionality of failure time (time) and is the relative margin of a machine's durability according to the precision criterion. The parameters α and c are dimensionless values. We consider the value of α parameter to be the average speed of the machine disadjustment, i.e., the relative average speed of a change of the random variable X. As a rule, when the parameter $\alpha = 2$ and may take larger values, the parameter $c = 1$ [14]. Typical density curves of α - distribution for different parameters of the relative durability of a woodworking machine and the relative average speed of its disadjustment are shown in Fig. 1.

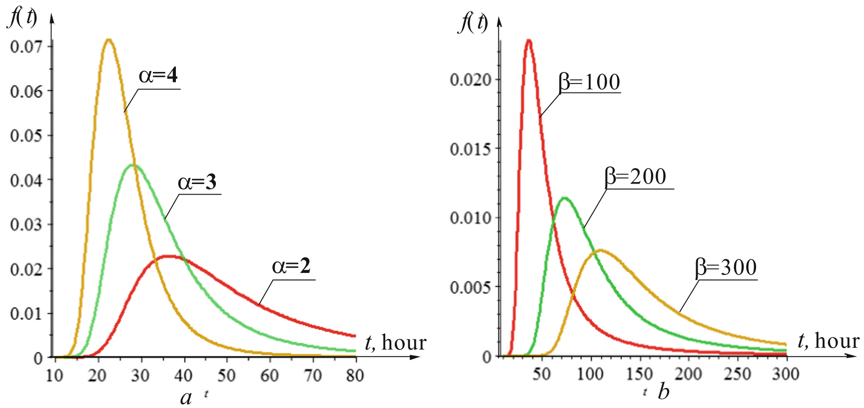

Fig. 1. Charts of α - distribution density functions at different values of parameters: ***a*** **–** for the conditional durability of a machine $\beta = 800$ hours; ***b*** – for distribution parameter $\boldsymbol{\alpha} = \mathbf{2}$**.**

The operating time of a woodworking machine before the beginning of mass failures according to parametric precision is equal to the time when the acceleration of a distribution density change is maximum. The value of this operating time is calculated according to the recommendations [14] as the time when the third derivative of the distribution density function is zero. Then the value of the operating time before the start of mass failures is obtained as the smallest positive root of the equation

$$\frac{\beta}{\sqrt{2\pi}}\frac{d^3}{dt^3}\left(\frac{1}{t^2}\exp\left(-\frac{1}{2}\left(\frac{\beta}{t}-\alpha\right)^2\right)\right) = 0. \tag{4}$$

Having found the third-density derivative of α -distribution of a random variable X, Eq. (4) is reduced to an algebraic sextic equation:

$$\begin{aligned} -\frac{1}{t^{11}}\left(10^{-10}\beta\exp\left(\frac{0.5(\alpha t-\beta)^2}{t^2}\right)\right)\cdot\left(9.6\cdot 10^{10}t^6 + 1.4\cdot 10^{11}\alpha\beta t^5\right. \\ + t^4\left(4.8\cdot 10^{10}\beta^2 - 1.9\cdot 10^{11}\beta^2\right) + \left(4\cdot 10^9\alpha^3\beta^3 - 10^{11}\alpha\beta^3\right)t^3 \\ \left. + \left(6\cdot 10^{10}\beta^4 - 1.2\cdot 10^{10}\alpha^2\beta^4\right)t^2 + 1.2\cdot 10^{10}\alpha\beta^5 t - 4\cdot 10^9\beta^6\right) = 0. \end{aligned} \tag{5}$$

The smallest positive root of the solution (5) is the operating time's value, which equals the duration of the inter-adjustment period for the machine. For example, with the distribution parameters $\alpha = 2$, $\beta = 850$ h, we have six roots: 179.5; 266.2; 482.1; −384.5; −760.7; −2332.5, first of which determines the inter-adjustment period for a wood-working machine according to the precision criterion.

4 Results

The parameters of α -distribution for woodworking machines are calculated according to characteristics of the wear and degradation process:

$$\beta \approx \overline{\beta} = \frac{|X - X_0|}{\sigma_b}, \alpha \approx \overline{\alpha} = \frac{|m_b|}{\sigma_b} = \frac{1}{v_b} \tag{6}$$

where v_b – the variation coefficient of the random disadjustment speed process ranges within 0.25–0.50 for the degradation process of mechanical wear [1]. Variation coefficients obtained from the research results on the technological precision of machines also fall within these limits. Assuming that the disadjustment speed of a woodworking machine is associated with the processes of wear in the mating of components and parts of the construction, according to formulas (6), the α - distribution parameter of the random process of the precision loss will adopt values within $\alpha = 2 - 4$. With mean-square deviations of the random machine disadjustment speed process due to wear $\sigma_b = 0.0008 - 0.002\,\text{mm/h}$, the value of β -distribution parameter for woodworking machines will vary from 450 h for band saw machines to 9000 h for milling machines. Taking $\sigma_b = 0.002 - 0.004\,\text{mm/h}$ for the band saw machine of the SKTP505–2 brand, we have the value $\beta = 920 - 450$ h; for Barakuda-2 circular saw machine $\sigma_b = 0.0008 - 0.003\,\text{mm/h}$ - $\beta = 2200 - 600$ h; for the jointer-planer AD741 – $\sigma_b = 0.0002 - 0.0004\,\text{mm/h}$- $\beta = 8200 - 4100$ h; for four-side milling Unimat-17A - $\sigma_b = 0.0005 - 0.0008\,\text{mm/h}$ - $\beta = 4000 - 2000$ h. After considering the dependence (4) and the parametric failure formation, the model of parametric failure of a woodworking machine may be presented in the form of a chart (Fig. 2). In Fig. 2, the following notations are adopted: $T^{(1)}$, $T^{(2)}$ – durations of the first and second inter-adjustment periods, B_1, B_2 – value of disadjustment speed during the respective period,

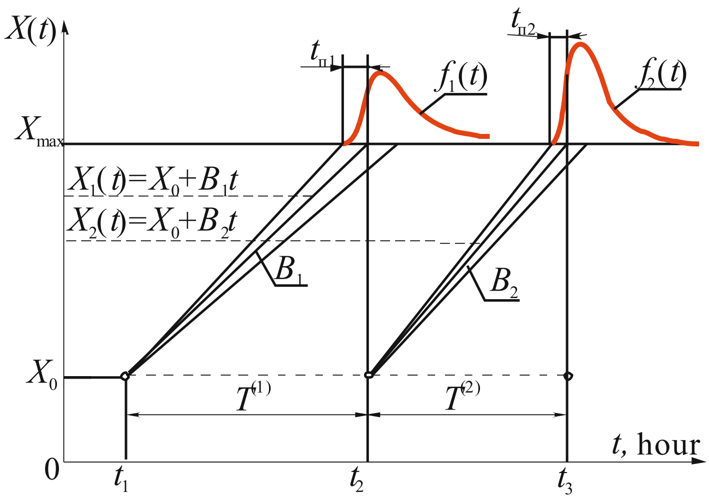

Fig. 2. The scheme of parametric failure formation according to the processing precision criterion in the inter-inspection period of a machine.

$f_1(t), f_2(t)$ – α - distribution density functions in the respective inter-adjustment period, $t_{\Pi 1}, t_{\Pi 2}$ – the smallest positive roots of Eq. (5). X_0 is the determining parameter as the initial error value of processing the nominal size of the part, which is the mode of the Hnidenko-Weibull distribution.

Mathematical modelling of the duration of inter-adjustment periods for woodworking machines has been performed using the scheme shown in Fig. 2. Solving Eq. (5) for specific values of α - distribution parameters, the durations of inter-adjustment periods for SKTP505-2 band saw machine, Barakuda-2 circular saw machine, and milling machines: jointer-planer AD741(Felder) and four-side longitudinal milling machine Unimat-17A, have been obtained. It has been established that the duration of inter-adjustment periods for woodworking machines increases with the increase of conditional durability of a machine β. However, logically, with the increase of relative disadjustment speed, which we consider to be the α -distribution parameter, the duration of inter-adjustment periods decreases. There is a linear relationship between α -distribution parameters and the duration of the inter-adjustment period. For example, for the SKTP505-2 band saw machine, with a reduction of the relative durability of the machine, i.e., β parameter ranging from 850 h up to 450 h (by 47%), the duration of the inter-adjustment period also decreases by 47%. With a decrease in the relative disadjustment speed (α -distribution parameter) by 11.7%, the duration of the inter-adjustment period increases by 17.5%. This increase in the duration of the inter-adjustment period does not depend on β parameter value. Similar linear dependences of the duration of the inter-adjustment period on the distribution parameters apply to Barakuda-2 circular saw machines and Unimat-17A four-side milling machines. The β distribution parameters for the new jointer-planer AD741 and the used four-side milling machine Unimat-17A are significantly different. For the used machine, the relative durability is 40% lower compared to a new machine.

Estimated durations $T^{(1)}$, $T^{(2)}$ and $T^{(3)}$ of the first three inter-adjustment periods for the following machines: SKTP505-2 band saw machine, Barakuda-2 circular saw machine and milling machines: new jointer-planer AD741 and used four-side milling machine Unimat-17A, are shown in the chart in Fig. 3. Operational values of machines' operating time in the first inter-adjustment period of operation are adopted considering the duration of an interrepair cycle. The standard interrepair cycle for machines of the II category (weighing 1–5 tons) is equal to 11200 h of operation [8]. The structure of the interrepair cycle for category II machines consists of 15 periods (inspections, regular, medium, and capital repairs) lasting 746 h. Taking into account the durability coefficient of a machine, the values of the periods may vary.

For the SKTP505-2 band saw machine, the estimated duration of the first disadjustment period differs from operational duration by 5% with distribution parameters $\alpha = 2$ and β = 850 h; duration of the second period of disadjustment – by 2.7% with parameters of distribution $\alpha = 3.2$ and $\beta = 850$ h or by 7.4% with distribution parameters $\alpha = 2$ and $\beta = 650$ h, the duration of the third period of disadjustment – by 3.6% with distribution parameters $\alpha = 3.2$ and $\beta = 850$ h.

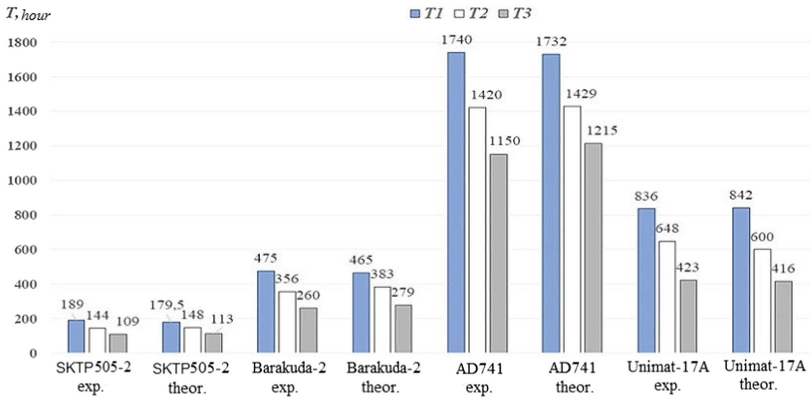

Fig. 3. Diagram for experimental and theoretical results of the duration of inter-adjustment periods of machines' operation.

Thus, in each period of disadjustment, α - distribution parameters take on different values. Each subsequent disadjustment of the machine occurs either at a higher relative speed of disadjustment, or with a lower value of the conditional durability of the machine. The differences between the operational and calculated values of the duration of inter-adjustment periods are the following: for "Barakuda -2" circular saw machine in the first period – 2.1%, in the second period – 7%, in the third period – 6.8%; for the new jointer-planer AD741 in the first period – 0.5%, in the second period – 0.6%, in the third period – 5.6%; and for the used Unimat – 17A in the first period – 0.3%, in the second period – 5.5%, in the third period – 1.4%. Therefore, the proposed model of parametric failures of woodworking machines allows determining the durations of inter-adjustment periods with accuracy sufficient for engineering calculations.

5 Conclusions

According to the precision criterion based on the truncated normal distribution of a machine's disadjustment speed, a radial model of parametric failure of a woodworking machine has been developed. It has been established that the density of parametric failures of woodworking machines according to the precision criterion corresponds to α - distribution. Based on α - distribution of parametric failures, the durations of inter-adjustment periods have been determined for a range of woodworking machines: SKTP505–2 band saw machine, Barakuda-2 circular saw, and AD741 and Unimat-17A milling machines, which coincide with the operational data with an accuracy of 7%.

The proposed model of parametric failures of woodworking machines based on the processing precision criterion, with accuracy sufficient for engineering calculations, allows determining the durations of inter-adjustment periods of machine operation. The precision of processing is ensured in compliance with the current standards.

In further studies, the developed methodology can be used to determine the duration of inter-adjustment periods of other woodworking machines and any mechanical equipment that has been under operation for a long time and requires developing the optimal structure of repair cycles.

References

1. Pronikov, A.S.: Parametric Reliability of Machines. Publishing House of MSTU named after N.E. Bauman, Moscow (2002)
2. Amalitsky, V.V., Bondar, V.G., Volobaev, A.M., Voiakhin, A.S.: Reliability of Machines and Equipment of the Forestry Complex. Textbook. MSFU, Moscow (2000)
3. Gao, J., Jiang, Z., Zhang, J., Li, H., Shen, D., Zhao, H.: Band saw blade crack before and after comparison and analysis of experiments (2). In: MATEC Web of Conferences, vol. 68, pp. 02003 (2016)
4. Baranov, A.V.: Reliability and diagnostics of technological systems. Textbook. RSATU, Rybinsk (2006)
5. Novoselov, V.G., Pomekhova, T.V.: Theoretical study of the reliability of woodworking technological system according to the "precision" product quality parameter. In: Woodworking: Technologies, Equipment, Management of the XXI Century. Proceedings of the International Eurasian Symposium, pp.108–114, Ekaterinburg (2006).
6. Novoselov, V.G., Glebova, I.T.: A physical method for calculating the reliability of a technological system of woodworking according to the "precision" product quality parameter. In: Reliability and quality: Proceedings of the international symposium, pp. 276–278. Tech. University, Penza (2006)
7. Tsarev, A.M.: Reliability and diagnostics of technological equipment. Textbook. TSU Publishing House, Togliatti (2013)
8. Shostak, V.V.: Installation, maintenance and repair of woodworking equipment. Textbook for higher educational institutions. UkrSFU, Akhil Publishing House, Lviv (2000)
9. Pylypchuk, M.I.: Methods for studying the dynamics of technological accuracy of woodworking machines. In: Proceedings of the IV International Scientific-Practical Conference on T. 1, pp. 70–71. SHEI "Vasyl Stefanyk Precarpathian National University", Ivano-Frankivsk (2020)
10. Jazwinski, A.H.: Stochastic Processes and Filtering Theory. Dover Publications Inc., Mineola (2007)
11. Knill, O.: Probability and Stochastic Processes with Applications. Overseas Press India Private Limited., New Delhi (2009)
12. Rinne, H.: The Weibull Distribution: A Handbook. Publisher Chapman Hall/CRC (2008)
13. Dai, W., Chi, Y., Zhiyuan, L., Wang, M., Zhao, Y.: Research on reliability assessment of mechanical equipment based on the performance-feature model. Appl. Sci. **8**, 1619 (2018). https://doi.org/10.3390/app8091619
14. Druzhynin, G.V.: Reliability of Automated Production Systems. Energoatomizdat, Moscow (1986)