This paper reports a new approach to ensuring the stability of the turning process, which is based on the frequency-time characteristics of the technological machining system (TMS). The approach uses a mathematical model of the turning process as a single-mass system with one degree of freedom, taking into account negative feedback on the normal coordinate and positive feedback with a delay in cutting depth. A new criterion for the stability of the cutting process as a system with a delay in positive feedback is proposed, based on the analysis of frequency characteristics in the form of a Nyquist diagram. It is proved that such a system will be stable when the chart of its Nyquist diagram does not cover a point with coordinates [+1, 0] on the complex plane. The validity of the new criterion has been confirmed by comparing the simulation results in the time range with the location of the Nyquist diagram on the complex plane. Based on the new criterion of stability, an algorithm for automatic construction of a Stability Lobes Diagram (SLD) has been developed. The necessary a priori parameters of TMS, the ranges of frequency change, and the calculation step for constructing such a characteristic in the coordinates "cutting depth – spindle rotational speed" have been determined. The adequacy of the obtained results is confirmed by a full-scale experiment to assess the roughness of machined parts under cutting modes that fall into the area of stability and instability on the SLD chart. The full-scale experiment proved the possibility of a significant reduction in roughness according to the Rz parameter, from 43 µm to 18 µm, while increasing productivity by 1.28 times. The use of a stability lobes diagram is especially effective when programming CNC lathes where it is possible to select the spindle speed in a wide range

Keywords: stability of the cutting process, stability lobes diagram, frequency stability criterion, machining by turning

UDC 621.91.01:621.92

DOI: 10.15587/1729-4061.2022.268637

A TIME-FREQUENCY APPROACH TO ENSURING STABILITY OF MACHINING BY TURNING

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Received date 04.10.2022
Accepted date 14.12.2022
Published date 30.12.2022

***How to Cite**: Petrakov, Y., Danylchenko, M. (2022). A time-frequency approach to ensuring stability of machining by turning. Eastern-European Journal of Enterprise Technologies, 6 (2 (120)), 85–92. doi: https://doi.org/10.15587/1729-4061.2022.268637*

1. Introduction

Most parts in mechanical engineering are made by cutting via removing the allowance. Such machining involves various technological operations: turning, milling, drilling, grinding, and others. These operations are performed on CNC machines, and CAM systems are used for their planning. This approach provides automation of the preparation of control programs but the choice of cutting mode almost always remains with the technologist-programmer.

The desire to optimize the machining process leads to the need to reduce the time of operation by increasing the cutting mode. However, any cutting process is typically accompanied by self-agitating vibrations. Therefore, the main limitation is always an increase in the level of chatter, which leads to a deterioration in the roughness of the machined surface, a decrease in accuracy, increased wear of the tool, and, in some cases, to the breakdown of the tool or machine [1].

In practice, to eliminate the excessive level of chatter, they reduce the cutting mode, employ re-machining, which, of course, leads to losses. In some cases, it is necessary to introduce additional operations to remove traces of vibrations on the surface of the part [2].

To eliminate chatter during cutting, various methods are used, which are conditionally divided into active and passive. The implementation of such methods is always associated with some modernization of equipment, which restrains their widespread use in practice. At the same time, theoretical developments on the appointment of a vibration-free cutting mode based on stability lobes diagrams in the coordinates «cutting depth – spindle speed» have not become widespread. We should expect the effectiveness of this area of research due to the ease of implementation in practice, especially when programming CNC machines, where it is possible to assign a cutting mode in a wide range. However, its widespread use is constrained mainly by two issues. First, to determine a stability lobes diagram, adequate data on the dynamic properties of the technological machining system are needed; second, the existing algorithms for determining diagrams are complicated.

Therefore, the development of effective methods for choosing a chatter-free cutting mode at the stage of technological preparation of machining is an important scientific and technical task.

2. Literature review and problem statement

The importance of questions about the nature of the occurrence of self-oscillations during cutting and the development of methods for their elimination have attracted the attention of scientists since the emergence of the science of cutting metals. It was found that the complexity of the process itself and the ambiguity of physical phenomena affecting self-oscillations make it difficult to develop practical recommendations for metal machining engineers. In the first works on the study of chatter during cutting, it was noted [3] that due to the large number of parameters that affect the phenomenon of vibration, the theoretical recommendations created to prevent chatter inevitably have great complexity. In addition, they are not presented in a form suitable for direct application in practice.

One of the first attempts to create a general theory of the occurrence of self-oscillations during cutting combined the processes of blade processing, highlighting grinding in a separate class [4]. The authors of this study are of the opinion that at the current level of knowledge about self-agitating vibrations, during machining it is enough to consider the vibration parameters of the machine in connection with its design.

The most urgent problem of chatter was observed during the machining of parts of low rigidity. One should note article [5], which shows that with the correct selection of cutting modes, it is possible to significantly increase the material removal rate without compromising the dimensional accuracy of the finished product. The technological machining system (TMS) for peripheral milling was represented as an elastic system, and the cutting forces and the consequences of the resulting deformation of the tool on the surface were expressed by analytical dependences.

One of the first fundamental studies on modeling chatter in cutting and grinding metals is reported in [6]. It is very important that a systematic approach to studying the dynamics of the cutting in the elastic system of the machine with the designation of feedback and the link of the delay argument is presented. However, it is noted that the application of orthogonal resistance to turning and boring operations, taking into account the nonlinearity of the cutting, complicates the solution in the frequency domain. Therefore, the assessment of the stability of the process is based on algebraic criteria. It is argued that the machining system will be stable, critically stable, or unstable depending on the roots of the characteristic equation. If the system is critically stable, then the oscillations do not increase exponentially and do not fade away but are maintained with the same amplitude at the oscillation frequency of vibration. From this approach, stability lobes diagrams (SLD) are determined, and different stability models are compared with experimentally confirmed simulation results in the time domain. In conclusion, the authors note that in the field of cutting and grinding dynamics, some research problems have not yet been solved, which complicates the practical use of results in industry.

Regenerative vibration is the most common form of self-agitating vibration [7]. The study of the causes of self-excitation is based on the study of the wavy surface left by the tool on the previous passage. When milling, the next tooth attacks the wavy surface and creates a new wavy surface. Thus, the change in the thickness of the chips and, accordingly, the force on the cutting tool is explained by the phase difference between the wave left by the previous tooth and the wave created by the current tooth [7]. At turning processing, the same effects are explained by the difference in phases between the trace on the workpiece from the oscillations of the tool on the previous rotation of the workpiece and on the current rotation.

Such a phenomenon can greatly increase vibrations, become dominant, and create prerequisites for loss of stability. The concept of dynamic thickness of chips is introduced, which depends on the phase difference between the machined and treated cutting surfaces. The influence of the dependence of this phase difference on the thickness of the chips is shown: if the phase difference is zero, the dynamic thickness of the chips is also zero, if the relative phase is equal to π, the variation in thickness is maximum. However, the cutting process is represented without taking into account the interaction with the elastic system of the machine and the delay argument function. Some studies on the elimination of chatter by passive and active methods are reported.

Analysis of the stability of machining is of paramount importance to guarantee high cutting performance while maintaining acceptable surface quality and tool stability. In the study of vibrations during cutting, there are works that employ the method of spectral elements [8]. It is shown that one of the key mechanisms for the loss of stability during machining is vibration, which is a self-agitating oscillation due to the effect of surface regeneration. This type of vibration occurs due to a change in the dynamic cutting load between successive rotations of the tool or workpiece. The usual approach to taking into account this dependence on previous states is to model the machining using differential equations with a delay. Since vibration has a detrimental effect on the cutting process, it is highly desirable to be able to anticipate combinations of parameters of the cutting process that will lead to machining without chatter. A new approach to the study of the stability of turning and milling processes using the method of spectral elements is proposed in [8]. It is claimed that this approach can successfully predict a chatter-free mode during turning and milling.

To prevent chatter during cutting, it is important to understand the mechanisms of its occurrence and create approaches to simulation and designing technological systems and assigning cutting modes. There are four groups of factors for the occurrence of chatter during cutting [9]. These include the nonlinearity of the dependence of the cutting force on the mode, the dynamic connection of the two natural vibration mods due to the small difference between the rigidity of the vibrating elements in two different directions, the parameters of the cutting mode, the geometry of the tool. When constructing a mathematical model of a machining, these four groups of factors are mainly taken into account, and the mathematical model is constructed with one, two, three, or four degrees of freedom in the representation of a single-mass dynamic model. The disadvantage of such models will be the absence of a delay argument function.

The study into building a stability lobes diagram (SLD) in the coordinates «depth (width) of cutting – cutting speed» is carried out by three methods in [9]. However, all these methods are based on the use of complex arguments related to the application of algebraic stability criteria arising from the transformed characteristic equation of the system. It is argued that the results of such studies provide the possibility of assigning cutting modes that reduce the possibility of chatter during cutting.

Currently, there are studies of chatter during cutting using the method of the frequency-time region to solve the differential equation with a delay, on the basis of which SLD can be obtained [9]. It is noted that the exact cutting force coefficient in the linearized dependence can increase the reliability of the forecast. The use of numerical methods in relation to a model with a function of a delay argument, together with the determination of stability by frequency criteria, give real results.

The main methods of eliminating chatter in cutting are also considered, which in practice can be divided into two directions: Passive Chatter Control (PCC) and Active

Chatter Control (ACC) [9]. The basis of such methods is the mathematical models of the cutting process, which in one way or another represent the processes of occurrence of oscillations.

The best results of stability forecasting are given by the representation of a dynamic cutting process in the frequency and time regions at the same time [10]. Continuous drilling analysis in the time domain is represented as an equation where cutting force and rigidity are predicted only in the normal direction. It is shown that the dynamics of the machining must be simulated taking into account the interaction between the machining and the elastic system of both the machine and workpiece. Although it is known that the vibration that occurs in different types of machines is essentially due to the same basic physical phenomena, there is now no general theory that has covered all individual cases. As a result, the vibration that occurs in each of the different types of machines has to be considered as a separate problem, which complicates theoretical developments and practical recommendations. Understanding the mechanisms of vibrations leads to the creation of control systems on CNC machines to suppress them by active methods [11].

In summary, it can be noted that the most complete studies on the determination of chatter-free cutting mode with the construction of SLD were reported in [12] and little has changed since then. The solution involves algebraic stability criteria based on an analysis of the roots of the characteristic equation of the system when representing delay argument functions using Euler's formula. A special algorithm of operations is proposed to build a stability domain, which consists of several steps [12].

However, the results of numerous studies in this area are little used by process engineers and machine tool designers. Obviously, this is due to the lack of a reliable criterion of stability, which would make it possible, with a minimum set of experimentally obtained parameters of the cutting process and the dynamic system of the machine, to build an SLD for a specific process.

3. The aim and objectives of the study

The aim of this work is to devise a procedure for determining the chatter-free cutting mode, which is based on machining simulation in the frequency and time domain, which will make it possible to assign a cutting mode that enables maximum machining performance with minimal chatter.

To accomplish the aim, the following tasks have been set:

– to build a mathematical model of the turning process in the direction normal to the machined surface, which will allow using a frequency-time approach to numerical simulation;

– to define a criterion of stability, taking into account the analysis of frequency characteristics in the form of a Nyquist diagram;

– to develop an algorithm and design an application program for the automatic construction of a turning process SLD and check the effectiveness of the proposed methodology.

4. The study materials and methods

The object of this study is the turning process, taking into account its implementation in an elastic closed TMS and machining for trace. When analyzing the stability of the machining, a method based on frequency criteria was adopted, with confirmation of the results by modeling in the time domain.

To develop a new methodology for assessing and predicting the stability of the cutting process, a systems approach was adopted, which represents the system as a connection of individual blocks. This makes it possible to build a mathematical model in the form of differential equations in variable states adapted to simulation by numerical methods. The new criterion for the stability of systems with a delay in positive feedback has made it possible to develop an algorithm for the SLD automatic determination.

The adequacy of the proposed solutions and the convergence of the developed algorithm are confirmed by software as a result of both simulations the transient process and the frequency characteristics, as well as the results of full-scale tests.

5. Results of the study of the cutting process for stability

5. 1. Mathematical model of the cutting process when turning

Any cutting process is accompanied by vibrations, the level of which (amplitude) determines the quality of machining, the tool life, and limits productivity. The amplitude and nature of its change over time depends both on the properties of elastic TMS and on the cutting mode and the material being machined. Many ways have been developed to eliminate this negative phenomenon, which are divided into passive and active. All such methods involve some modernization of TMS or CNC control system. At the same time, as the studies presented above show, for each system there are certain combinations of cutting mode parameters that provide chatter-free machining.

Such results are usually represented in the form of stability lobes diagram in the coordinates «cutting depth – cutting speed». This approach is the easiest way to ensure high performance with minimal system vibration. However, it requires the construction of an adequate mathematical model of TMS, taking into account the delay argument function, which represents the follow-up machining. Here is a new method for automatically calculating SLD depending on the specific parameters of TMS, which is based on the analysis of frequency and time characteristics.

To test the method, the turning process in TMS was considered, which is represented by a single-mass system with one degree of freedom. This is quite enough for an adequate description of dynamic phenomena since it is in the direction of the normal coordinate Y that the surface of the part is formed. The cutting process is carried out in a closed technological system and, taking into account the follow-up machining, is represented by the functional scheme shown in Fig. 1.

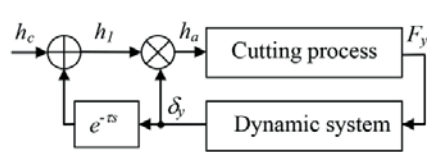

Fig. 1. Scheme of the cutting process: h_c – the commanded cutting depth, h_1 – cutting depth on the previous pass, h_a – the actual cutting depth, δ_y – elastic displacement of TMS, τ – delay time (time of one rotation of the workpiece)

The cutting process with a sufficient degree of accuracy can be described by a linearized dependence and, taking into account the time constant of chipping, can be represented by a first-order differential equation:

$$T_c \frac{dF_y}{dt} + F_y = k_c h_a, \quad (1)$$

where T_c is the time constant of chipping, F_y is the normal component of the cutting force, k_c is the coefficient of linearized dependence of the cutting force on depth.

Taking into account the dynamic model of TMS as an oscillatory system, the mathematical model takes the form shown in Fig. 2.

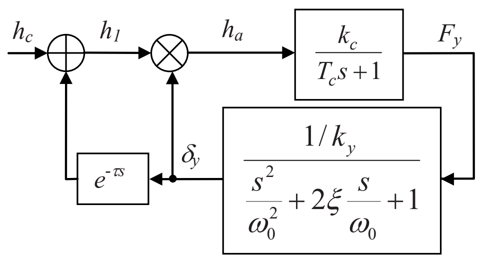

Fig. 2. Block diagram of the cutting process: k_y – TMS stiffness, ω_0 – natural oscillation frequency, ξ – oscillation attenuation

To model in time, it is necessary to find the transfer function of a closed system excluding a delay. Using the rules for the transformation of structural schemes, we obtain:

$$W_f(s) = \frac{\dfrac{k_c/k_y}{(T_c s+1)\left(\dfrac{s^2}{\omega_0^2}+2\xi\dfrac{s}{\omega_0}+1\right)}}{\dfrac{k_c/k_y}{(T_c s+1)\left(\dfrac{s^2}{\omega_0^2}+2\xi\dfrac{s}{\omega_0}+1\right)}+\dfrac{k_c}{k_y}} = \frac{k_f}{A_{f0}s^3+A_{f1}s^2+A_{f2}s+1}, \quad (2)$$

where

$$k_f = \frac{k_c}{k_y+k_c}, \quad A_{f0} = \frac{T_c}{\omega_0^2}k_f,$$

$$A_{f1} = \left(\frac{1}{\omega_0^2}+2\xi\frac{T_c}{\omega_0}\right)k_f, \quad A_{f2} = \left(\frac{2\xi}{\omega_0}+T_c\right)k_f.$$

The delay function is implemented when simulation by a numerical method in accordance with the recurrent dependence:

$$(h_a)_i = (h_c+\delta_y)_i + (\delta_y)_{i-1}, \quad (3)$$

where δ_y is the elastic displacement of TMS in the normal direction, i is the pass number.

It should be noted that this method of representing the delay argument function most fully reflects the essence of the follow-up machining process. At the same time, automatically, during numerical integration, all the necessary processes for changing the phases of the thickness of chips on the current and previous passages, which were investigated in work [7], are taken into account.

In accordance with dependence (3), when simulating any passage, the elastic displacement at each step of the simulation is written to the array, which is built depending on the angle of rotation of the spindle. On the next pass, this array is sequentially added to the cutting depth of each simulation step. This approach best corresponds to the real machining process, in contrast to modeling with the decomposition of the delay argument function into a power series.

To model the process over time, a numerical method of integration with the standard fourth-order Runge-Kutta procedure is used. The mathematical model of a third-order system is represented as three first-order differential equations, that is, for state variables:

$$\begin{cases} Su[1] = -\dfrac{A_{f1}}{A_{f0}}U[1]+U[2], \\ Su[2] = -\dfrac{A_{f2}}{A_{f0}}U[1]+U[3], \\ Su[3] = -\dfrac{1}{A_{f0}}U[1]+\dfrac{k_f}{A_{f0}}h_1, \end{cases} \quad (4)$$

where $Su[i]$ is the array of first derivatives, $U[i]$ is an array of system state variables.

Integration is performed in increments of 0.000001 s, which is quite sufficient for an adequate representation of the time characteristics of real turning TMS having a high natural oscillation frequency.

5. 2. Criterion of stability of the turning process as a system with a delay in positive feedback

To assess the stability of systems, criteria are used based on the analysis of the roots of the characteristic equation or frequency characteristics on the complex plane. However, the complete mathematical model of TMS, taking into account the delay, has a characteristic equation that is transcendental and therefore has many roots. Article [13] notes that the location of the extreme right characteristic roots of a closed system with a delay function in feedback determines the stability of the system. If at least one extreme right root is in the right half of the complex plane, the system is unstable. It is also proposed to calculate the roots using DDE-BIFTOOL, a numerical bifurcation tool designed for differential equations with a delay.

Another criterion for the stability of such systems is proposed. From the block diagram of the cutting process (Fig. 1) it follows that the system is closed due to the function of delay with positive feedback (Fig. 3). Therefore, the most convenient criterion for assessing stability should be considered a criterion using frequency characteristics.

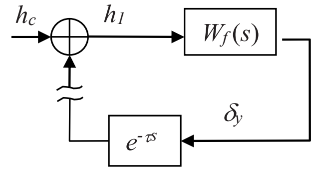

Fig. 3. Structure for stability assessment

To explain the criterion of stability based on frequency analysis, it is necessary to open the system (Fig. 3). When switching to frequency characteristics, the signal at the output of the open part of the system can be represented as:

$$\delta_y(j\omega) = kG(j\omega)h_1(j\omega), \quad (5)$$

where k is the transmission factor, $G(j\omega)$ is the frequency transfer function.

In accordance with the block diagram in Fig. 3, when closing the feedback: $h_1(j\omega)=h_c(j\omega)+\delta(j\omega)$ and in the absence of a commanded cutting depth at the input ($h_c(j\omega)=0$), we have $h_1(j\omega)=\delta(j\omega)$. Therefore, any harmonic signal at the input to the closed system $W_f(s)$ will be restored provided:

$$k|G(j\omega)| - 1 \text{ and } \varphi = n2\pi, \quad (6)$$

where φ is the phase, n=0, 1, 2...

It is clear that condition (6) defines the limit of stability of the system with a delay in positive feedback. Given that the delay function does not change the amplitude but only returns the phase of the Nyquist diagram counterclockwise, it can be assumed that if k<1, the system will be constant at any time of delay. Obviously, at k>0, the stability of the system will depend on the delay time, which in relation to turning is determined by the spindle speed $\tau=2\pi/\omega$.

It should be noted that in the study of the stability of machining systems by any method, a boundary is obtained, which is determined by a line on the stability lobes diagram. It is understood that with the processing mode, which corresponds to the zone of instability, the entire system will be unstable. Such a definition does not fully correspond to the concept of stability in the theory of automatic control, where the loss of stability theoretically means an increase in the amplitude of oscillations to infinity. The resulting boundary should be considered a theoretical limit, which in practice should turn into some zone of a certain width around such a line. It is clear that the width of such a zone will depend on the degree of adequacy of the mathematical model underlying the design of the diagram.

Also, the concepts of stability reserve are not defined, which, as a rule, are used in the analysis of the stability of closed systems with negative feedback. The application of the proposed criterion makes it possible to solve this issue since it is based on an analysis of the location of the Nyquist diagram on a complex plane. It is possible to determine the stability margin in the same way as determined for systems with negative feedback, replacing the critical point on the axis of real numbers from –1 to +1.

Thus, the new criterion of stability can be formulated as follows: a system with positive feedback through the delay argument function will be stable if the chart of its Nyquist diagram on the complex plane does not cover a point with coordinates [+1, 0].

5. 3. Automatic determination of a stability lobes diagram

The built mathematical model together with the procedures for numerical integration and construction of the Nyquist diagram allows using a new criterion of stability to determine the dependence of stability on the cutting mode. To solve such an important task, an algorithm for numerical determination of SLD was developed (Fig. 4).

The algorithm allows for a certain combination of spindle speed and cutting depth to calculate the dependence $A(\varphi)$ in the form of a numerical array with a given step. Next, all amplitudes $A_i(\varphi_i)$ of the diagram are searched in the region of the phase angle $\varphi_i=2\pi i\pm\delta$, where i=0,1,2..., and δ is chosen equal to the step of calculating the numerical array $A(\varphi)$. This search range provides a quick convergence of the algorithm when determining the maximum value $A_{\max}$. If $A_{\max}$ satisfies the condition 1, the value of the spindle speed N_{sp} and the corresponding depth h_c of cutting will define one point of the array of the SLD chart. If condition 1 is not met, then the cutting depth correction is carried out according to condition 2, the model is rebuilt, the new dependence $A(\varphi)$ of the Nyquist diagram, the search for the maximum amplitude in the region of the phase angle $\varphi_i=2\pi i\pm\delta$, where i=0,1,2... etc. until condition 1 is met.

The model should be rebuilt each time you return to the beginning of the algorithm, subject to condition 1 or condition 2, since changing the cutting depth or spindle speed affects all parameters of the model. Of course, such actions slow down the speed of the algorithm, but for modern processors, the design time does not exceed a few seconds, which is quite acceptable.

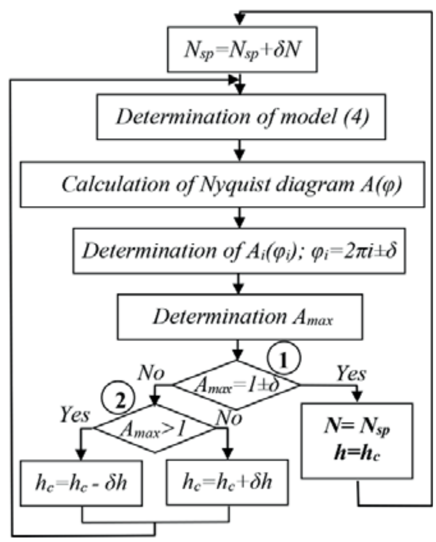

Fig. 4. Enlarged algorithm for calculating a stability lobes diagram

As a result of such procedures, in a given range of changes in the spindle speed, an array $N_{sp}(h_c)$ of SLD values is calculated and displayed (highlighted in Fig. 4). The accuracy of SLD determination depends on the tolerance value and the step of change in cutting depth.

This algorithm was implemented in a special modeling program for TMS, which is represented by a single-mass dynamic system with one degree of freedom. The following parameters were adopted, which were determined experimentally by the method presented in [14]: the natural oscillation frequency is 320 Hz, the stiffness in the direction of the Y axis is 3,500 N/mm, the diameter of the part is 30 mm. The material being machined is Steel45, the coefficient of linearized dependence was determined by formulas known from the theory of cutting. That is why when changing the conditions of calculation according to the algorithm, namely, the depth and speed of cutting, the algorithm provides for updating the procedure for calculating the coefficient. In addition, to increase the adequacy of the model, the damping properties of the cutting process itself were taken into account according to the research of Professor Kudinov. To do this, according to (1), an aperiodic element of the first order with a time constant of chipping T_c=0.001 s was introduced into the model. The simulation results in the range of 1200 rpm – 1620 rpm are shown in Fig. 5. The cutting mode corresponding to the combination of depth and speed of rotation of the spindle below the diagram guarantees a stable process, above – unstable.

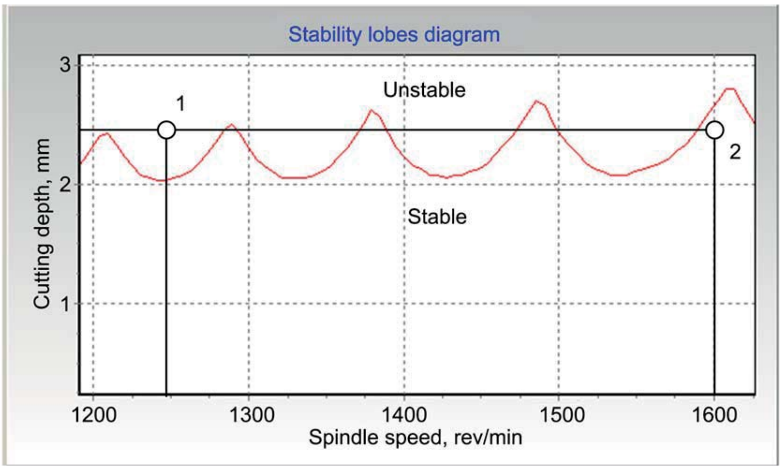

Fig. 5. Areas of stability of the cutting process

In the calculations according to the algorithm in Fig. 4, it is necessary to determine the limits of frequency change so that the natural frequency of the system is in the middle of the range. The range of change in the spindle speed is selected in accordance with the capabilities of the machine. For the analyzed TMS, where the natural frequency is 320 Hz, the frequency range of 200–400 Hz was set, the calculation step is 0.0001 rad/s.

To test the new stability criterion of the system with a delay in positive feedback, experiments were performed using a developed soft that makes it possible to perform simulations in the time domain and at the same time calculate the Nyquist diagram in the frequency domain. Full-scale experiments were conducted on a conventional 1K62 lathe, therefore, to implement the simulation results, the range of spindle speeds available on the machine was used.

Virtual and full-scale experiments were carried out in accordance with the automatically designed SLD with a cutting depth of 2.4 mm and a spindle speed of 1250 rpm and 1600 rpm. Such data correspond to points 1 and 2 in Fig. 5.

To conduct virtual experiments, a program was created where simulations of the cutting process over time and the calculation of frequency characteristics are performed numerically. Simulation in time is carried out by the standard Runge-Kutta procedure of the fourth order according to the mathematical model (4) using the recurrent ratio (3). The calculation of the coordinates of the Nyquist diagram is also performed by a numerical method in a given frequency range. When constructing a Nyquist diagram, each calculated point of the diagram on the complex plane for the frequency ω_i is rotated clockwise by an angle of $\omega_i\tau$, where τ is the delay time. The delay time for turning processing is equal to the time of one spindle rotation.

The chart of the Nyquist diagram for mode 1 covers a point with coordinates [+1, 0], which, in accordance with the proposed criterion, leads to a loss of stability of TMS (Fig. 6). Simulating of this mode of cutting in time (Fig. 7) shows that 0.3 s after the start of the process, the oscillogram of the elastic displacement of the system increases in amplitude, which confirms the conclusion that this cutting mode is unstable in this TMS.

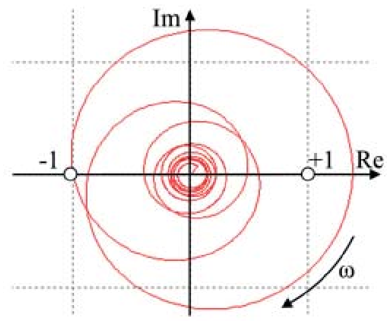

Fig. 6. Nyquist diagram for mode 1

The chart of the Nyquist diagram for mode 2 does not cover a point with coordinates [+1, 0], which, in accordance with the proposed criterion, provides a stable cutting process in a given TMS (Fig. 8). Indeed, the simulation of this mode of cutting in time (Fig. 9) confirms this conclusion. The transient process quickly fades and after 0.3 s after the start, the amplitude of elastic vibrations is significantly reduced.

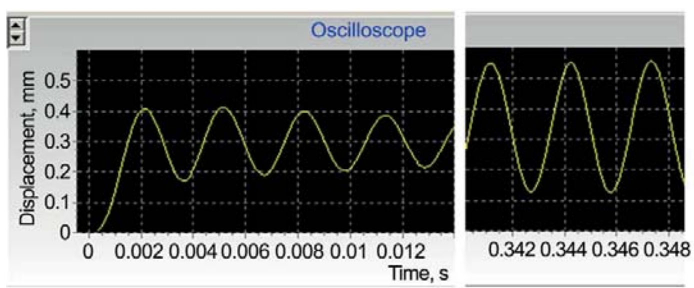

Fig. 7. Oscillogram of the process for mode 1

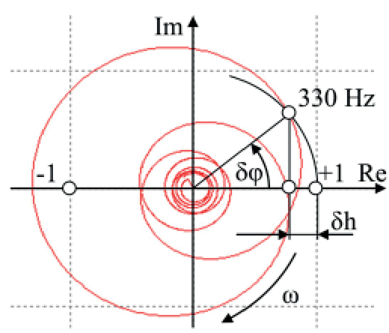

Fig. 8. Nyquist diagram for mode 2

The stability of the system in this case is fully enabled, despite the coverage by the chart of the Nyquist diagram of a critical point with coordinates [–1, 0] (Fig. 8). It is known that such a sign usually indicates a loss of stability of the system with negative feedback. Thus, a significant difference in the processes in the system is confirmed, which is covered by positive feedback with a delay argument.

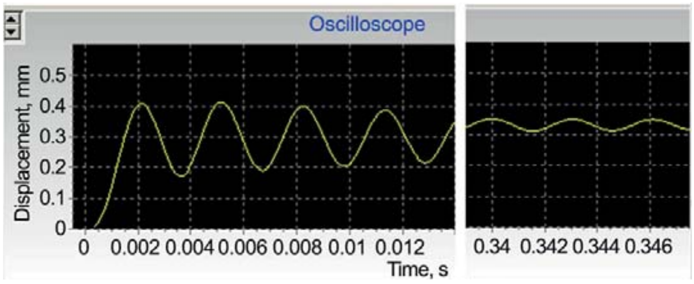

Fig. 9. Oscillogram of the process for mode 1

For further research, a full-scale experiment was performed, the results of which are shown in Fig. 10. Despite the presence of traces of vibration in both cases, measurements showed a significant difference in the roughness of the machined surface. With a cutting mode corresponding to point 1 Rz=43 µm, and with point 2 mode Rz=18 µm.

a *b*

Fig. 10. Parts surfaces machined under: *a* — mode 1; *b* — mode 2

Thus, it is practically proved that the use of the results of an automatically calculated stability lobes diagram made it possible to significantly reduce the level of vibrations in TPS while increasing productivity by 1.28 times.

6. Discussion of the frequency-time approach to enabling the stability in turning

The proposed frequency-time approach to enabling the stability in the turning process allows us to solve the problem at the level of assigning a chatter-free cutting mode. The greatest effect from the application of the results of our work is expected when assigning a cutting mode for turning operations on CNC machines.

When representing the cutting process as occurring in a closed elastic system with a delay argument in positive feedback (Fig. 2), its mathematical model was derived. Moreover, the mathematical model was obtained from state variables (4), and the delay argument function is in the form of a recurrent ratio (3). This approach allows the use of numerical modeling methods, which leads to the creation of a tool for a technologist-programmer to use the results of this work in practice.

The representation of the cutting process model in the frequency region together with the Nyquist diagram led to the definition of a new criterion of stability and made it possible to obtain a stability condition (6) for such systems. The criterion is based on the analysis of processes occurring in the system with a delay in the positive feedback chain (Fig. 3). Moreover, when analyzing, the TMS is represented in a generalized form, which allows us to hope for the extension of this criterion to systems with more complex mathematical models, for example, with three degrees of freedom [14].

A soft has been created that operates according to the developed algorithm (Fig. 4) and automatically designs a stability diagram based on the minimum amount of a priori data. The stability lobes diagram is represented in the coordinates «cutting depth – spindle speed» (Fig. 5). Therefore, it should be expected that the use of the developed algorithm, in contrast to existing [12] complex multi-step procedures for determining SLD, will make it easy to use in practice in the preparation of control programs for CNC machines.

This criterion is fully confirmed by simulating the transients of the system in time domain (Fig. 7, 9). The course of processes in time is fully consistent with the location of the corresponding Nyquist diagram on the complex plane (Fig. 6, 8). The full-scale experiment, even within the framework of universal equipment, also proved the correctness of the theoretical developments presented. The change in the spindle speed according to the stability lobes diagram (mode 1, mode 2 in Fig. 5) with the same cutting depth led to a significant decrease in roughness (compare Fig. 10, *a* and Fig. 10, *b*) with increased productivity.

In terms of practical use of the results of the study, a promising and useful combination of results with the use of control over feedback signals from vibration sensors used in OKUMA NAVI technology [15]. With an increase in the level of vibrations, the search for a new value of the cutting speed is considered appropriate to carry out in the direction of the greatest productivity, using the SLD designed according to the developed method, which will increase the efficiency of such adaptive control.

It should be noted that our results require the use of such a priori TMS data as stiffness, the frequency of natural oscillations, and the coefficient of linearized dependence of the cutting force on depth. However, such data can be obtained using procedures set forth in [14].

However, for the design of the stability lobes diagram, the problem of operational determination of the dynamic parameters of the TMS during cutting remains unresolved. These include the stiffness of the system, the frequency of natural oscillations, and the coefficients of linearized dependences of the cutting force on the mode. Parameters such as stiffness and natural oscillation frequency constantly change when the process propagates along the forming coordinate, and therefore require a permanent determination procedure.

7. Conclusions

1. A mathematical model of the turning machining as such that is implemented in a single-mass system with one degree of freedom, taking into account negative feedback on the normal coordinate and positive late feedback on the cutting depth, has been built. The mathematical model is compiled at state variables, which makes it possible to directly use standard procedures for numerical integration and calculation of frequency characteristics. The delay argument function is implemented by a numerical method through a recurrent dependence.

2. A new criterion for the stability of the cutting process as a closed system with a delay in a positive feedback chain is

proposed, based on the analysis of frequency characteristics in the form of a Nyquist diagram. The system will be stable if the chart of its Nyquist diagram does not cover a point with coordinates [+1, 0] on the complex plane. The validity of the new criterion is confirmed by simulating in the frequency-time range using the created soft.

3. Based on the new criterion of stability, an algorithm for automatic construction of SLD has been developed. The necessary a priori parameters of the TMS, cutting mode, frequency change ranges, and calculation step for constructing a diagram are determined. The adequacy of the obtained results is confirmed by a full-scale experiment to assess the roughness of the machined parts under cutting modes that fall into the area of stability and instability on the SLD chart. The use of the algorithm in the design of control programs for CNC machines will allow for a targeted search for the most effective cutting mode.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

Financing

The study was conducted without financial support.

Data availability

All data are available in the main text of the manuscript.

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