Assignment of the cutting mode when boring holes on CNC machine

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Abstract. Due to structural limitations, the processes of boring holes are performed in a low-rigidity machining system, which predetermines their susceptibility to vibrations. The article is devoted to the study of the process of boring holes on CNC machines, and the subject of the study is the effect of the cutting mode on the stability of the machining. The mathematical model of the machining system is presented in the form of a two-mass dynamic system, which forms a closed loop structure with negative feedback by elastic displacement. In addition, positive feedback is taken into account through the delay argument function, which represents machining along traces. It has been proven that this process provokes the emergence of regenerative oscillations in the machining system. The application of the system's approach made it possible to obtain a mathematical model in the form of state variables, which is acceptable for the use of numerical modeling methods in both time and frequency space. An applied engineering program for determining the stability diagram in "cutting depth - spindle speed" coordinates has been created. The program uses a new criterion of stability of systems closed through positive feedback loop with a delay argument function. For the first time, the validity of such a criterion was proved for systems described by differential equations of the fourth order. The importance of taking into account the results of the study in the form of a stability lobes diagram when assigning a cutting mode, especially in the area of high speeds, is proven. Thus, according to the results of the experiments, a change in speed of only 7% from 2150 rpm to 2320 rpm with the same cutting depth of 0.4 mm allows the process to become stable. The use of the created program is possible in the system of automatic control of the online cutting mode when the machine is equipped with vibration sensors with appropriate systems for identifying the dynamic parameters of the machining system, which will significantly increase the machining efficiency.

Keywords: hole boring, stability lobes diagram, transient and frequency responses.

1. Introduction

Boring holes in machine parts, as a rule, is a finishing operation, which must provide the required quality indicators - accuracy and surface roughness. The main feature of such operations, which hinders technological capabilities, is the insufficient rigidity of the machining system, due to design limitations, especially when boring deep holes.

Therefore, the most important problem in performing such operations is the elimination of chatter, which can lead not only to deterioration in quality, a decrease in tool life, but also to a loss of stability of the cutting process with the onset of catastrophic consequences [1].

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Chatter elimination methods are divided into passive chatter control (PCC) and active chatter control (ACC) [2]. PCC methods are based on the use of various damping devices built into the boring bar or on the application of special laws of cutting mode control. ACC methods are performed on CNC machines equipped with special automatic control systems with feedback sensors for the level of vibrations in the machining system. All these methods involve the modernization of equipment, equipping machines with special complex control systems.

The most simple to implement and no less effective are methods based on the correct choice of cutting mode. Such methods are based on the formation of a stability lobes diagram (SLD) in the "depth of cut - cutting speed" coordinates, which is designed using a dynamic model of the machining system, including using online experimental data obtained. It is clear that the best effect can be achieved with the simultaneous use of one of the methods of absorbing vibrations and setting a stable cutting mode.

Thus, the improvement of SLD design methods by creating special software using a digital twin of a technological processing system is an urgent scientific and technical task.

2. Problem status analysis

The operation of boring a hole is the finishing one and is usually performed on a CNC machine after the hole is countersinked (Fig. 1). When setting up, the angular position of the boring bar is important to ensure the required cutting angles and the length of the bar to reduce the likelihood of vibrations in the machining system (MS). Usually, due to geometric restrictions, it is not possible to provide sufficient rigidity of the MS, and therefore the main problem remains the elimination of vibrations.
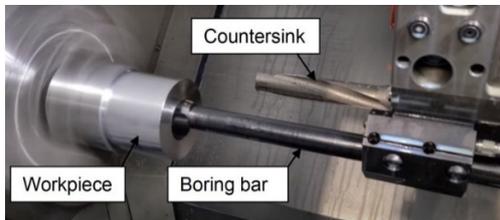
Fig. 1. Boring holes on a CNC machine

The main direction of vibration elimination during boring is associated with the use of mandrels with built-in tuned mass dampers, which makes the boring process resistant to vibrations [3]. Shock absorbers are usually designed using classical analytical solutions, assuming a boring bar, which can be approximated by a system with one degree of freedom.

Such boring bars are produced by various companies, for example [4], but the specific selection of vibration damper parameters is always important. Dynamic Vibration Absorbers (DVA) are a common passive approach to dampening vibration in boring bars. Tuning is very important in DVAs to achieve the desired performance, and improper tuning can adversely affect their performance [5]. It is proposed to use a one-dimensional dynamic model of the boring process to predict stability, and the effectiveness of the solutions was confirmed by experimental stability lobes diagrams. This approach indicates the importance of applying mathematical methods to create an adequate model of the machining. The best results of applying passive methods using vibration absorbers were obtained with a two-mass model and frequency approaches using numerical methods [6].

Methods of active vibration suppression (ACC) involve the creation of automatic control systems with feedback. For example, machining Navi by Okuma uses a set of functions (software and hardware) that optimize cutting mode on a CNC machine directly in the process of machining [7] based on vibration signals. The hardware part consists of two independent modules (Fig. 2).
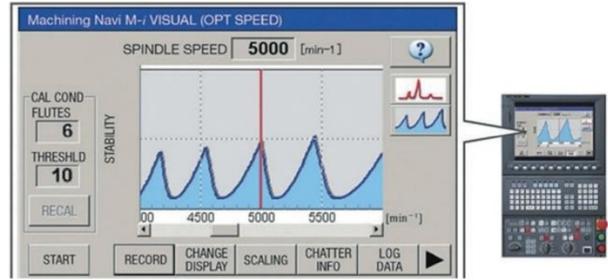
Fig. 2. Navi-Okuma Technology

In the case of an increase in the amplitude of self-oscillations, the system informs the operator about this and suggests specific changes in the value of the spindle speed. It can be seen that the solution is also based on the use of SLD, which is designed online from the measurement results and an a priori mathematical model of the dynamic system.

To implement active control methods, an automatic control system is proposed [8]. An offset signal measured in a direction orthogonal to the machined surface is used to generate a control action in the feed direction. A linear proportional control law is applied. To test the effectiveness of the proposed method and to find the best values of feedback gain, a mathematical model of the dynamics of the process of boring with control has been developed.

It is always important to understand the causes of vibrations in the machining system during cutting. Machine's vibrations occur due to the self-excitation mechanism during the formation of chip thickness during machining operations [9]. Always the root cause of the appearance of chatter is the force excitation of an elastic technological machining system. The wavy surface left during the previous pass is removed during the next pass and depending on the phase shift between two successive waves, the maximum chip thickness can increase exponentially when oscillating at a vibration frequency that is close to, but not equal to, the dominant structural mode in the system. That is explication of appearances of chatter in MS [9].

The presented review shows that in all chatter elimination methods it is important to create a mathematical model of the system using the function of delay argument because this is main cause of chatter appearance in cutting. In addition, the use of SLD makes it possible to reliably establish a stable cutting condition based on dynamic parameters of MS measurements online. Therefore, the problem of creating an adequate dynamic model of the boring process and an engineering software tool for reliable design SLD remains relevant.

3. The aim and objectives of the study

The purpose of this work is to create a new technique for designing a stability diagram in the "cutting depth – cutting speed" coordinates for boring processes, which is based on numerical methods for modeling the process in the frequency and time domain, which will allow you to

assign a cutting mode that provides maximum performance with minimum vibration.

To achieve the purpose, it is necessary to solve the following tasks:

– to create a mathematical model of the boring process, taking into account the two-mass dynamic system and the delay function;

– to develop a mathematical model in the application program for the operational design of the stability diagram of the cutting process;

– to conduct an experimental approbation of the developed method and check its effectiveness.

4. The study materials and methods

The object of research is the process of boring holes on a CNC machine, where it is possible to select the cutting mode in a wide range. The cutting process is considered when it is implemented in a closed elastic system, taking into account machining along the trace. In the analysis of stability, a method was adopted based on a new criterion for the stability of systems with positive feedback, closed through a function of delay argument.

To develop a new methodology for assessing and predicting the stability of the cutting process, a system's approach was adopted, representing the MS by connecting individual blocks with signals between them. This makes it possible to obtain a mathematical model by means of differential equations in variable states adapted to modeling by numerical methods.

The adequacy of the proposed solutions and the convergence of the developed algorithm are confirmed by software as a result of simulation both the transient process and the frequency characteristics.

5. Results of designing cutting mode for holes boring

5.1. Mathematical model of machining for holes boring

The mathematical model of MS during boring should be built taking into account the concept of the operation (Fig. 3). The workpiece 1 is fixed in the chuck, and the cutting plate is at the end of the boring bar. The rotation of the workpiece provides the required cutting speed, and the boring bar is fixed in the turret and moves in the direction of boring with a certain feed. When boring, a cutting force arises and its component F_y causes an elastic displacement of MS, as a result of which the actual depth of cut H_a will differ from the specified one. In addition, during cutting, oscillations occur, which can only be described taking into account the dynamic properties of MS with loops feedback connections, when using a system's approach to representing the cutting process [6].
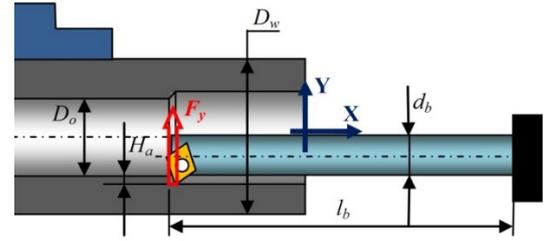
Fig. 3. Scheme of boring a hole

To compile a mathematical model, it is necessary to use a functional diagram (Fig. 4), which represents the closedness of the elastic MS through the loop feedback of elastic displacement with a given depth of cut. Therefore, the actual depth of cut is: $H_a = H_{cl} - \delta_{MS}$, where H_{cl} – commanded depth of cutting, δ_{MS} – elastic displacement (see fig. 4). The elastic displacement of MS consists of elastic displacements of the workpiece and the boring bar under the action of the normal component F_y of the cutting force. Machining along trace is represented by a delay argument function:

$$H_{cl} = H_c + \delta_{MS} e^{-\tau s}, \tag{1}$$

where H_c – commanded depth of cutting, τ – time of one tour of workpiece, s – Laplace operator.
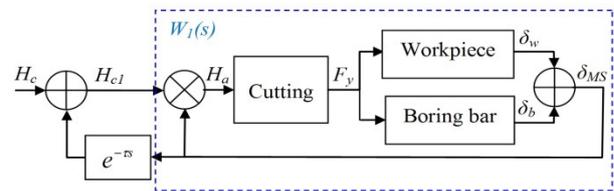
Fig. 4. Functional diagram of boring process

The workpiece and the boring bar in the first approximation are represented by single-mass dynamic models, which are under the action of force excitation. The transfer functions of such models are obtained from the equations of motion in the cutting zone, which describe the dependence of the elastic displacement on the cutting force in the direction of the Y coordinate.

For workpiece:

$$m_w \frac{d^2 \delta_w}{dt^2} + \lambda_w \frac{d\delta_w}{dt} + k_w \delta_w = F_y, \tag{2}$$

similar for boring bar

$$m_b \frac{d^2 \delta_b}{dt^2} + \lambda_b \frac{d\delta_b}{dt} + k_b \delta_b = F_y, \tag{3}$$

where m_w, m_b are the reduced masses of the workpiece and the boring bar, λ_w, λ_b are the coefficients of viscous friction in the systems of the workpiece and the boring bar, k_w, k_b are the stiffness of the workpiece and the boring bar in the cutting zone.

In practice, it is difficult to determine the reduced masses and viscous friction coefficients of mechanical systems. Therefore, the representation of the equations of motion is used in terms of the natural frequencies of oscillations and damping coefficients of oscillations, for the identification of which known experimental methods are used [11]. Such methods are based on the use of special hammers, with the help of which the impulse response function (IRF)of the system is obtained. Then, using fast Fourier transforms [12], the amplitude-frequency characteristic of the system (spectrum) is obtained, which is approximated by the amplitude-frequency characteristic of a single-mass dynamic system.

Thus, using the representation of dynamic systems (2) and (3) in terms of natural frequencies and reducing to the standard notation, we have:
- for workpiece:

$$\frac{s^2 \delta_w}{\omega_w^2} + 2\xi_w \frac{s\delta_w}{\omega_w} + \delta_w = \frac{1}{k_w} F_y, \qquad (4)$$

- for boring bar:

$$\frac{s^2 \delta_b}{\omega_b^2} + 2\xi_b \frac{s\delta_b}{\omega_b} + \delta_b = \frac{1}{k_b} F_y, \qquad (5)$$

where ω_w, ω_b are the natural frequencies of the workpiece and the boring bar, ξ_w, ξ_b are the damping coefficients of the workpiece and boring bar vibrations.

The cutting process can be represented by a linearized model of the dependence of the cutting force component on the depth of cut:

$$F_y = k_F H_a, \qquad (6)$$

where $k_F = \left(\partial F_y / \partial H_a\right)_0$ – coefficient of the linearized dependence of the cutting force on the effective (actual) cutting depth H_a in the steady state region. Such coefficient can be obtained from the dependence of the cutting force component on the mode parameters [9]:

$$F_y = k_{yc} b H_a + k_{ye} b, \qquad (7)$$

where k_{yc}, k_{ye} are the coefficients of dependence of the normal cutting force on the cross-sectional area of the allowance cut per revolution and feed per revolution, b is the feed per revolution.

The values of such coefficients depend on the workpiece material and can be determined by the methods of statistical data processing presented, for example, in [13].

It is known that the best form of representation of a mathematical model is a block diagram, which is obtained from a functional diagram by replacing the names of the elements with their transfer functions (Fig. 5). This form makes it possible to obtain a mathematical model of the process of boring holes for use in further manipulations involving the design of a stability diagram in the coordinates "depth of cut - cutting speed". Since to solve the problem

it is necessary to perform numerical simulations in both the frequency and time domains, the best form of a mathematical model is its representation in state variables.
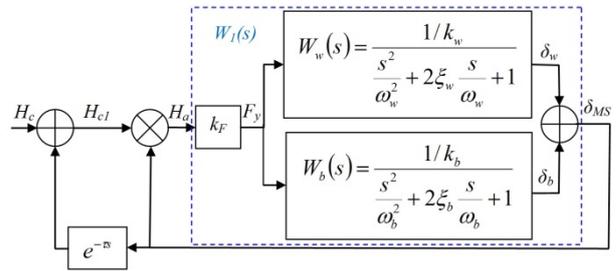
Fig. 5. Block diagram of boring

Using the rules for transforming block diagrams, it can get the transfer function of the direct channel of a closed system:

$$W_1(s) = k_F\left(W_w(s) + W_b(s)\right) = \frac{s^2 k_F T_1^2 + s k_F T_2 + k_F k}{s^4 T_3^4 + s^3 T_4^3 + s^2 T_5^2 + s T_6 + 1}, \qquad (8)$$

where, after simple algebraic transformations, it is possible to determine the time constants of the system:
- for the numerator:

$$T_1^2 = \frac{1}{\omega_b^2 k_w} + \frac{1}{\omega_w^2 k_b}, \quad T_2 = \frac{2\xi_b}{\omega_b k_w} + \frac{2\xi_w}{\omega_w k_b}, \quad k = \frac{1}{k_w} + \frac{1}{k_b},$$

- for the denominator:

$$T_3^4 = \frac{1}{\omega_w^2 \omega_b^2}, \quad T_4^3 = \frac{2\xi_w}{\omega_b \omega_w^2} + \frac{2\xi_b}{\omega_w \omega_b^2},$$

$$T_5^2 = \frac{1}{\omega_b^2} + \frac{4\xi_b \xi_w}{\omega_b \omega_w} + \frac{1}{\omega_w^2}, \quad T_6 = \frac{2\xi_b}{\omega_b} + \frac{2\xi_w}{\omega_w}.$$

5.2. Mathematical model in the application program for operational design of the stability diagram of the cutting process

For further manipulations in order to determine the stability of MS in accordance with the new stability criterion proposed in [10], it is necessary to obtain the transfer function of a closed system (Fig. 6).
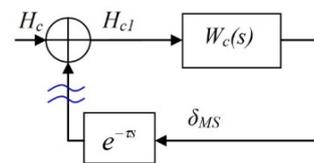
Fig.6. Block diagram for stability estimation

To assess the stability in accordance with the new criterion [10], the frequency method is used, based on the analysis of the Nyquist diagram of an open system with positive feedback through the delay function. The place of disconnection of the connection is shown in fig. 6, and the

transfer function $W_c(s)$ is determined from the block diagram in fig. 5 according to the conversion rules:

$$W_c(s) = \frac{W_1(s)}{1 + W_1(s)}. \qquad (9)$$

After substituting the values of the time constants of the transfer function $W_1(s)$ from (8) and reducing to the standard form, it is possible to obtain:

$$W_c(s) = \frac{s^2 Tc_0^2 + sTc_1 + kc}{s^4 Tm_0^4 + s^3 Tm_1^3 + s^2 Tm_2^2 + sTm_3 + 1}, \qquad (10)$$

where for the numerator: $Tc_0^2 = \dfrac{k_F T_1^2}{1 + k_F k}$,

$Tc_1 = \dfrac{k_F T_2}{1 + k_F k}$, $\quad kc = \dfrac{k_F k}{1 + k_F k}$,

for the denominator: $Tm_0^4 = \dfrac{T_3^4}{1 + k_F k}$, $\quad Tm_1^3 = \dfrac{T_4^3}{1 + k_F k}$,

$Tm_2^2 = \dfrac{T_5^2 + k_F T_1^2}{1 + k_F k}$, $\quad Tm_3 = \dfrac{T_6 + k_F T_2}{1 + k_F k}$.

To construct a system stability diagram, the program [10] uses a new criterion for the stability of systems with positive feedback through the function of the delay argument. A system is stable if the graph of its Nyquist diagram does not cover the point with coordinates [+1,0] in the complex plane. The algorithm performs an automatic search for the boundary depth of cut for each value of the cutting speed according to such a sign of the location of the graph of the Nyquist diagram of the transfer function $W_c(s)$. This is how a data array is formed, which determines the necessary stability diagram in the coordinates "depth of cut - cutting speed".

5.3. Approbation of results

To confirm the results obtained, experiments were performed for the machining system for boring a hole with the data presented in Table 1. Such data correspond as much as possible to the real parameters of the machining system when boring a hole.

Approbation of the obtained results was carried out using a special program that allows you to calculate the response of the machining system in both time and frequency domains. When simulating in the time domain, a complete mathematical model of the system was used, taking into account positive feedback through the function of a delay argument, and when assessing stability according to the criterion [10], an open-loop system model was used (see Fig. 6). Modeling is carried out by a numerical method using the standard Runge-Kutta integration procedure of 4 order, and machining along the trace was taken into account through the recurrence relation:

$$H_{c1}[i] = H_c[i] + \delta_{MS}[i-1]. \qquad (11)$$

Table 1. Initial data

Workpiece		
Natural frequency	Hz	220
Stiffness	N/mm	2500
Hole Diameter	mm	36
Damping coefficient		0,05
Boring Bar		
Natural frequency	Hz	300
Stiffness	N/mm	500
Damping coefficient		0,05
Coefficient for cutting force (Steel 45)		
k_{yc}	N/mm^2	1400
k_{ye}	N/mm^2	35

According to the initial data in Table 1, using the mathematical model (10), (11) in the created application program, the stability diagram was designed (Fig. 7). As a result, the entire range of permissible values of the cutting mode was divided into two zones: above the graph – an unstable zone, below the graph – a zone of stable operation of the machining system.

Validity of the obtained results was checked by comparing the behavior of the system in the time domain and the location of the Nyquist diagram for the two cutting modes indicated in Fig. 7 by points 1 and 2. In fig. 8, is shows the transient response of the machining system in mode 1: depth of cut 0.4 mm, spindle speed 2150 rpm. It can be seen that the process is unstable – the amplitude of elastic displacement increases and over time will exceed the maximum allowable value.
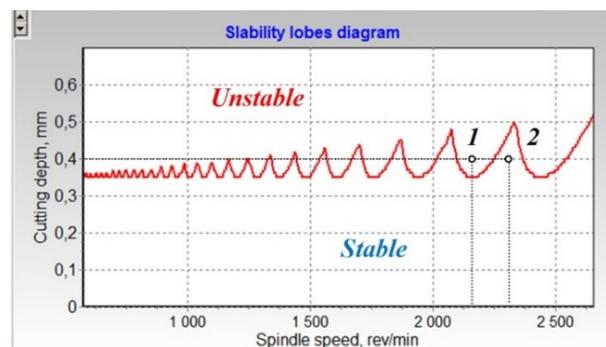
Fig. 7. Stability lobes diagram

Therefore, such a cutting mode is unacceptable and can lead to significant vibrations and even accidents. The graph of the Nyquist diagram for this mode of operation covers a point with coordinates [+1,0], which, according to the new stability criterion [10], leads to the loss of stability of the system with positive feedback through the function of the delay argument (Fig. 8, b).
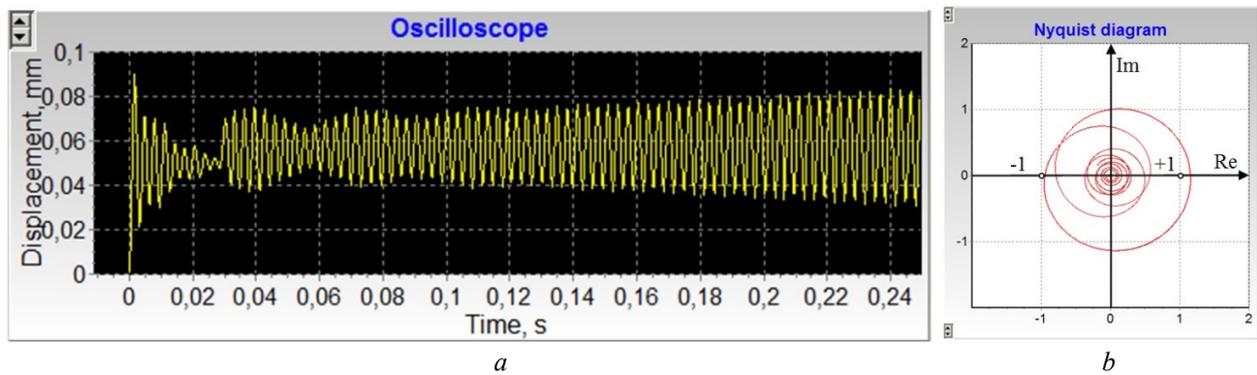
Fig. 8. The results of simulation of the functionning of the machining system at a cutting depth 0.4 mm, a spindle speed of 2150 rpm: *a* - transient response, *b* - Nyquist diagram
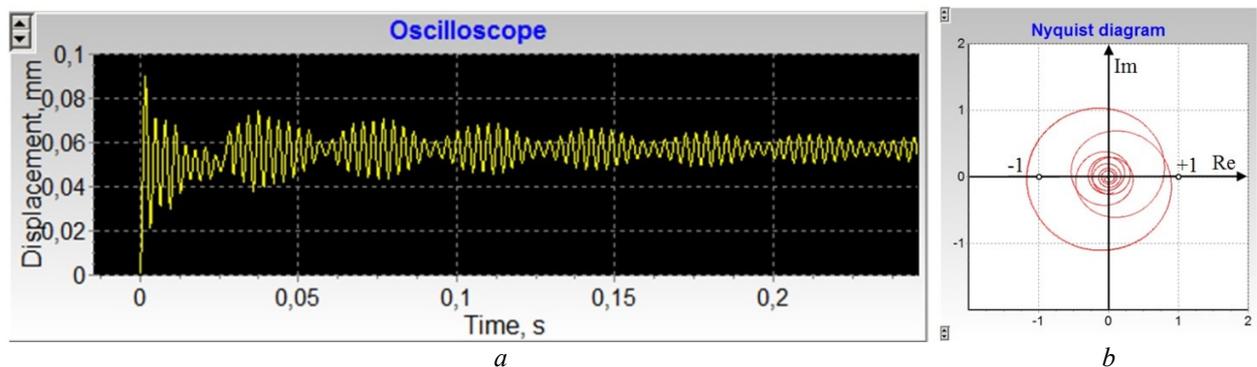
Fig. 9. The results of simulation the functioning of the machining system at a depth of cut of 0.4 mm, a spindle speed of 2320 rpm: *a* - transient response, *b* - Nyquist diagram

Simulation of the functioning of the machining system in the cutting mode corresponding to point 2 of the stability diagram shows that the process is stable. The transient process demonstrates a tendency to rapid attenuation (Fig. 9, *a*). The location of the graph of the Nyquist diagram also confirms the stability of the system with positive feedback through the function of the delay argument (Fig. 9, *b*).

The verification clearly demonstrates the practical relevance of the studies performed, especially in the field of high speeds of rotation of the part spindle. It is there that high processing productivity is achieved and at the same time the risk of falling into the area of unstable functioning increases.

6. Discussion about the purpose of the cutting mode when boring holes on a CNC machine

Hole boring is often a finishing operation where it is necessary to meet high demands on the accuracy and quality of the machined surface. Due to design limitations, boring is performed in a machining system of low rigidity, which imposes special requirements on the assignment of the cutting mode. Production experience and studies [1] prove the sensitivity of such operations to the assigned cutting conditions.

For the first time, the process of boring a hole is presented in the form of a mathematical model obtained from a block diagram (Fig. 5), which is compiled taking into account a two-mass dynamic machining system and the closedness of the cutting process through the normal coordinate (8). The main reason for the occurrence of regenerative oscillations in the system is also taken into account - machining along the trail. Such a process is represented by positive loop feedback through the function of the delay argument $e^{-\tau s}$, where τ is the time of one revolution of the workpiece, s is the Laplace operator.

To solve the problem, an application program was created, the interface of which allows you to enter all the system parameters necessary for modeling. The program uses an algorithm for searching for data arrays, the maximum depth of cut and spindle speed, which form a stability diagram of the machining system. The algorithm is based on a new criterion for the stability of systems with positive feedback loop through the function of the delay argument [10]. This is how the cutting process is presented, taking into account the machining along the trace, which is the main reason for the occurrence of regenerative oscillations in the machining system.

Previously [10], such an algorithm was used to assess the stability of the machining system, which is represented by a single-mass model. Successful application for

the two-mass model demonstrates the versatility of the new stability criterion and algorithms.

The correct functioning of the created program involves the use of a priori data about the system. Such data include, first of all, the stiffness and frequency of natural oscillations of the workpiece and the boring bar, as well as the coefficients of the cutting force formula. The coefficients depend on the material being machined and can be found in reference books [14], while the stiffness and natural frequencies require an online experiment to determine. Considering that such parameters tend to change during machining, Okuma's experience, NAVI technology [15] can be used to solve this problem. This technology, which is called "intelligent" by the firm, also uses a stability lobes diagram - compare fig. 2 and fig. 6 in this paper.

7. Conclusions

1. A mathematical model of the hole boring process has been developed in the representation of the machining system in the form of a two-mass dynamic model with negative feedback loop on the depth of cut and positive feedback through the function of the delay argument. This form of presentation is the most consistent with the real process of boring with the possibility of regenerative vibrations. The mathematical model in state variables allows using standard procedures of numerical integration and frequency numeric analysis. The delay argument function is implemented numerically through a recursive dependence.

2. The possibility of applying a new stability criterion for systems with positive feedback loop through the delay function is proved when they are represented in the form of fourth-order dynamic models. The developed application program allows you to automatically design a stability lobes diagram in the coordinates "depth of cut – spindle speed". Such a program is recommended for practical use when assigning a cutting mode for boring operations on CNC machines.

3. The importance of taking into account the results in the form of a stability diagram is shown, especially in the region of high speeds of the part spindle. Thus, according to the results of experiments, a change in speed by only 7% from 2150 rpm to 2320 rpm at the same depth of cut of 0.4 mm eliminates the risk of chatter in the processing system. The use of the created program when controlling the cutting mode online on a CNC machine is possible if it is equipped with vibration sensors and appropriate identification systems and will significantly increase the efficiency of the hole boring operation.

Conflict of interest. The authors declare that they have no conflict of interest in relation to this research, including financial, personal, authorship, or any other nature that could affect the research and its results presented in this article.

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Призначення режиму різання при розточуванні отворів на верстаті з ЧПК

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Анотація. *Процеси розточування отворів з причини конструктивних обмежень виконуються в обробній системі малої жорсткості, що зумовлює їх схильність до виникнення вібрацій. Стаття присвячена дослідженню процесу розточування отворів на верстатах з ЧПК, а предметом дослідження є вплив режиму різання на сталість процесу. Математична модель процесу представлена у вигляді двомасової динамічної системи, яка утворює замкнену структуру з від'ємним зворотним зв'язком за пружним зсувом. Крім того, урахований позитивний зворотний зв'язок через функцію запізнюючого аргументу, що представляє оброблення за слідом. Доведено, що саме такий процес і провокує виникнення регенеративних коливань в обробній системі. Застосування системного підходу дозволило отримати математичну модель у формі змінних стану, що є прийнятним для застосування чисельних методів моделювання як у часовому, так і в частотному просторі. Створена прикладна інженерна програма визначення діаграми стабільності в координатах "глибина різання – швидкість шпинделя". Програма використовує новий критерій сталості систем, замкнених через позитивний зворотний зв'язок з функцією запізнюючого аргументу. Вперше доведена валідність такого критерію для систем, що описуються диференціальними рівняннями четвертого порядку. Доведена важливість урахування результатів дослідження у вигляді діаграми стабільності при призначенні режиму різання, особливо в області високих швидкостей. Так, за результатами експериментів зміна швидкості всього на 7% з 2150 об/хв до 2320 об/хв при однаковій глибині різання 0,4 мм дозволяє перевести процес в стабільний. Використання створеної програми можливе в системі автоматичного управління режимом різання он-лайн при оснащенні верстату датчиками вібрацій з відповідними системами ідентифікації динамічних параметрів обробної системи, що значно підвищить ефективність оброблення.*

Ключові слова: *розточування отворів, діаграма стабільності, перехідні і частотні характеристики.*