https://doi.org/10.31891/2219-9365-2026-87-57
UDC 621.951.72: 621.9.08

PERPERI Liudmyla
Odesa Polytechnic National University
https://orcid.org/0000-0002-6840-0241
HOLOBORODKO Hanna
Odesa Polytechnic National University
https://orcid.org/0000-0002-2836-7221

EVALUATION OF THE VIBRATION STABILITY OF A TECHNOLOGICAL SYSTEM AS A PREREQUISITE FOR ENSURING THE ACCURACY OF PRECISION HOLE MACHINING

The article presents an evaluation of the vibration stability of a technological system for machining precision conical holes with unilateral cutting tools. The relevance of the study is linked to the influence of the system's dynamic state on the accuracy of hole-shape generation, form deviations, and the quality of the machined surface. Precision conical holes are considered as a representative object of investigation, since their geometry is sensitive to transverse tool displacements, variation in the actual uncut chip thickness, and cutting-force vibrations. The technological system is represented as the interaction of an equivalent elastic system and the cutting process. The cutting process is described by a first-order dynamic element, and the equivalent elastic system by a second-order oscillatory element. The frequency response of the conditionally open-loop system is obtained as the product of the corresponding characteristics. The computational-graphical procedure was implemented in the Scilab environment, which ensured automated determination of the real and imaginary components and construction of the corresponding hodographs. For different machining conditions and workpiece materials, amplitude-phase frequency characteristics were constructed. It was established that the cutting-process gain coefficient and the time constant affect the shape and scale of the hodographs. Evaluation of vibration stability via the Nyquist criterion for all considered conditions, the hodographs remain close to the origin of the complex plane and do not encircle the critical point (−1; i0), confirming the vibration-stable state of the system. From a metrological viewpoint, vibration stability is regarded as a prerequisite for stable formation of measured machining results: dimensional accuracy, conical profile, form deviations, and surface quality. The proposed approach can be used as a preliminary stage of analysis for determining the conditions that ensure the accuracy of precision hole machining.

Keywords: vibration stability; technological system; precision conical holes; cutting process; frequency response; Nyquist criterion.

ПЕРПЕРІ Людмила, ГОЛОБОРОДЬКО Ганна
Національний університет «Одеська політехніка»

ОЦІНЮВАННЯ ВІБРОСТІЙКОСТІ ТЕХНОЛОГІЧНОЇ СИСТЕМИ ЯК ПЕРЕДУМОВИ ЗАБЕЗПЕЧЕННЯ ТОЧНОСТІ ОБРОБКИ ПРЕЦИЗІЙНИХ ОТВОРІВ

Статтю присвячено оцінюванню віброcтійкості технологічної системи обробки прецизійних конічних отворів інструментами однобічного різання. Актуальність дослідження зумовлена тим, що динамічний стан системи впливає на стабільність формоутворення отвору, розмірну точність, відхилення форми та якість обробленої поверхні. У роботі технологічну систему подано як взаємодію еквівалентної пружної системи та процесу різання. Частотну характеристику умовно розімкнутої системи визначено як добуток відповідних частотних характеристик. Розрахунково-графічну процедуру реалізовано в середовищі Scilab, що забезпечило автоматизоване обчислення дійсної та уявної складових частотних характеристик і побудову годографів за єдиним алгоритмом. Для різних умов обробки побудовано амплітудно-фазові частотні характеристики процесу різання та умовно розімкнутої технологічної системи. За результатами аналізу діаграми Найквіста встановлено, що годографи не охоплюють критичну точку (−1; i0), що підтверджує віброcтійкий стан системи за прийнятих параметрів різання. З метрологічної точки зору віброcтійкість розглянуто як передумову стабільного формування параметрів точності обробки прецизійних отворів. Отримані результати можуть бути використані для попереднього аналізу умов забезпечення розмірної точності, форми та якості обробленої поверхні.

Ключові слова: віброcтійкість; технологічна система; прецизійні конічні отвори; процес різання; частотна характеристика; критерій Найквіста.

STATEMENT OF THE PROBLEM IN GENERAL FORM AND ITS CONNECTION WITH IMPORTANT SCIENTIFIC OR PRACTICAL TASKS

Ensuring the accuracy of mechanical machining is one of the key tasks of modern machine-building production, particularly when manufacturing precision components that are characterised by heightened requirements for geometric accuracy, dimensional stability, and surface quality. For turning, facing, profiling, and other machining methods that use cutting tools, the achievement of specified accuracy parameters depends not only on tool geometry, cutting conditions, and workpiece material properties, but also on the dynamic state of the technological system [1–3]. The technological system "machine tool – fixture – tool – workpiece" is subjected to variable force loads that can cause elastic displacements, vibrations, and loss of forming stability. Such phenomena directly affect dimensional accuracy, form deviation, and surface quality. The dynamic stiffness of the technological system can be regarded as one of the necessary prerequisites for ensuring machining accuracy [2, 4].

This problem is especially critical when machining precision holes, since even slight tool vibrations can alter the actual chip thickness, destabilise the cutting force, and introduce additional machining errors [5, 6]. Therefore, the assessment of the technological system's vibration stability ought to be viewed not merely as a problem in cutting mechanics, but as a fundamental prerequisite for the stability of the measured accuracy parameters.

Existing approaches to assessing the dynamic behaviour of technological systems make extensive use of frequency-domain methods – in particular, constructing amplitude–phase frequency-response functions (FRFs) and applying the Nyquist criterion. The stability of the closed-loop system is assessed from the amplitude–phase frequency response of the notional open-loop system, which comprises the equivalent elastic system and the cutting process. In the case where the open-loop system possesses no unstable poles, the closed-loop system is stable provided its Nyquist plot does not encircle the critical point $(-1; i0)$ in the complex plane [7]. Nevertheless, most computational approaches focus primarily on the mechanical assessment of stability, while its link with the metrological assurance of machining accuracy often remains insufficiently emphasised. It is therefore pertinent to perform a frequency-domain evaluation of the technological system's vibration stability and subsequently interpret the results from the standpoint of the stable generation of dimensional and surface-quality parameters.

ANALYSIS OF RESEARCH AND PUBLICATIONS

In studies of machining processes, considerable attention is devoted to the problem of self-excited vibrations, since they are among the factors that limit cutting stability, tool life, and surface quality [2]. In contemporary research, vibration stability is regarded not only as a condition for safe operation of the technological system, but also as a factor determining whether a surface can be generated stably with the prescribed machining parameters [6]. A distinct line of inquiry concerns the dynamics of precision-hole machining – in particular, processes in which the cutting portion of the tool produces an asymmetric force distribution [5, 8].

Work [5] examines the issue of measuring the dynamic characteristics of a technological system. It is noted that the determination of natural frequencies, damping, and other parameters of the system's dynamic state is a necessary stage for constructing an adequate computational model. It is precisely experimentally determined or refined parameters that enable subsequent frequency-domain assessment of the technological system's stability.

Study [6] analysed the stability of machining processes with account for the dynamics of the technological system and the regenerative mechanism of vibration onset. Significant attention is devoted to the relationship between the system's dynamic characteristics, cutting parameters, and the conditions for the emergence of unstable regimes. Such an approach is essential for justifying the use of frequency-domain characteristics in vibration-stability assessment tasks.

Work [9] investigated the dynamics of hole-machining processes, in particular the influence of tool vibrations on the process kinematics and the formation of hole geometry. It is shown that during hole machining, vibrational displacements of the tool can alter the actual cutting conditions and affect the stability of shape formation. This is important for research related to the machining of precision holes and ensuring their geometric quality. Under such conditions, the transverse displacements of the tool, the variation in the actual uncut chip thickness, and the dynamic interaction between the cutting process and the elastic system of the machine tool acquire particular significance [3, 9].

This makes it possible to proceed from a description of the vibration process to a computational assessment of system stability. An analysis of studies and publications shows that the mechanisms of self-excited vibrations, dynamic modelling, and approaches to enhancing the vibration stability of cutting processes have been investigated quite extensively. At the same time, the linkage between the results of frequency analysis and the stability of the formation of measured accuracy parameters, shape, and surface quality remains insufficiently emphasised. It is precisely this aspect that forms the basis of the present work.

FORMULATION OF THE ARTICLE'S OBJECTIVES

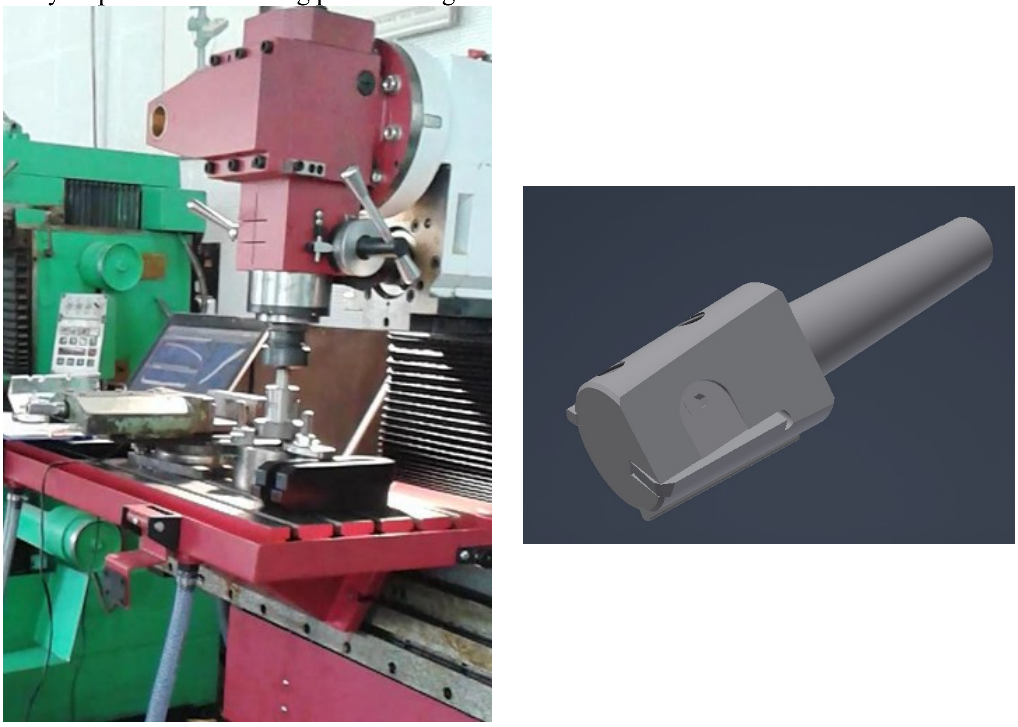
The aim of the work is to evaluate the vibration stability of a technological system for machining precision holes using unilateral cutting tools based on frequency analysis and to substantiate its role as a prerequisite for the stable formation of machining accuracy parameters. To achieve this aim, the following tasks must be solved:

– analyse the dynamic characteristics of the cutting process during the machining of precision holes with unilateral cutting tools;
– construct the frequency response functions of the cutting process and the conditionally open-loop technological system;
– develop a frequency-domain model of the system that combines the equivalent elastic system and the cutting process;
– assess the vibration stability of the technological system using the Nyquist criterion;
– interpret the obtained results from the standpoint of ensuring the machining accuracy of precision holes.

PRESENTATION OF THE MAIN MATERIAL

Ensuring the vibration stability of a technological system is critical for machining precision holes of various profiles, since dynamic tool displacements directly influence the formation of dimensional accuracy, form deviations, and surface quality. In this work, the machining of precision conical holes with unilateral cutting tools is considered as the object of the computational-graphical analysis. The choice of conical holes as the object of investigation is dictated by the fact that their accuracy is determined not only by dimensional parameters, but also by the stability of conical-profile formation, coaxiality, and form deviations. Under such conditions, even minor transverse vibratory displacements of the tool can alter the actual uncut chip thickness, induce cutting-force fluctuations, and affect the geometry of the machined surface. Therefore, the machining of precision conical holes serves as a representative example for evaluating the vibration stability of a technological system from the standpoint of ensuring the accuracy of precision holes.

The investigation was carried out on a universal milling machine, model OMM64S, equipped with a Sinumerik 802 D CNC system (Figure 1). The evaluation of vibration stability was performed on the basis of frequency analysis. Within this approach, the technological system is regarded as a combination of the equivalent elastic system and the cutting process, which makes it possible to assess stability by means of the amplitude–phase frequency characteristics of the conditionally open-loop system. The main parameters used to construct the amplitude-phase frequency response of the cutting process are given in Table 1.



a) **b)**

Fig. 1. Universal measuring stand (a) based on the universal milling machine OMM64S, equipped with a Sinumerik 802 D CNC system and a conical unilateral reamer tool (b)

Table 1

Input parameters for plotting the amplitude-phase frequency response of the cutting process

Workpiece material	Hole parameters		Cutting conditions		T_P, s	K_P, N/m
	diameter *d*, m	length *l*, m	cutting speed *v*, m/s	feed rate *f*, m/rev		
Steel 45	0,03995	0,020	0,75	$5{,}0 \cdot 10^{-6}$	$2{,}6 \cdot 10^{-5}$	$2{,}0 \cdot 10^{5}$
Steel 45	0,03995	0,015	0,75	$1{,}0 \cdot 10^{-6}$	$5{,}3 \cdot 10^{-5}$	$3{,}0 \cdot 10^{5}$
Grey cast iron СЧ18	0,03995	0,020	0,75	$5{,}0 \cdot 10^{-6}$	$1{,}2 \cdot 10^{-5}$	$5{,}0 \cdot 10^{4}$
Grey cast iron СЧ18	0,03995	0,015	0,75	$1{,}0 \cdot 10^{-6}$	$1{,}2 \cdot 10^{-4}$	$7{,}5 \cdot 10^{4}$

The dynamic characteristic of the cutting process is presented in the form of a first-order aperiodic element:

$$W_P(j\omega) = \frac{K_P}{1 + j\omega T_P}, \quad (1)$$

where $W_P(j\omega)$ is the frequency response of the cutting process, N/m;
K_P is the transfer coefficient of the cutting process, N/m;
T_P is the time constant of the cutting process, s; ω is the angular frequency, s^{-1};
j is the imaginary unit.

Parameters K_P and T_P characterise the dynamic response of the cutting process to a change in the actual uncut chip thickness. The cutting-process gain coefficient K_P essentially shows how the cutting force changes when the deformation or the uncut chip thickness varies.

An increase in K_P raises the intensity of the process force response, while a change in T_P affects the phase shift between the perturbation and the cutting force. In order to establish the influence of the machining conditions on the dynamic behaviour of the cutting process, amplitude-phase frequency characteristics $W_P(j\omega)$ were constructed using the initial parameters given in Table 1. For each machining variant, the real *Re* and imaginary *Im* components of the frequency response $W_P(j\omega)$ were determined over a specified range of circular frequencies. The numerical designations next to the points on the curves correspond to the values of the circular frequency ω, c^{-1}. The results of the construction are presented in Figure 2.

The computational-graphical procedure was implemented in the Scilab environment, which ensured formalised calculation of the frequency-response components, construction of the hodographs by a single algorithm, and reproducibility of the obtained results. The appropriateness of using this environment for the automation of calculations, processing of measurement data, and graphical presentation of results was demonstrated in the authors' previous works [10–12].

The results obtained made it possible to compare the shapes of the cutting-process hodographs for steel 45 and grey cast iron СЧ18 з at different values of the width of cut, feed, gain coefficient K_P and time constant T_P.

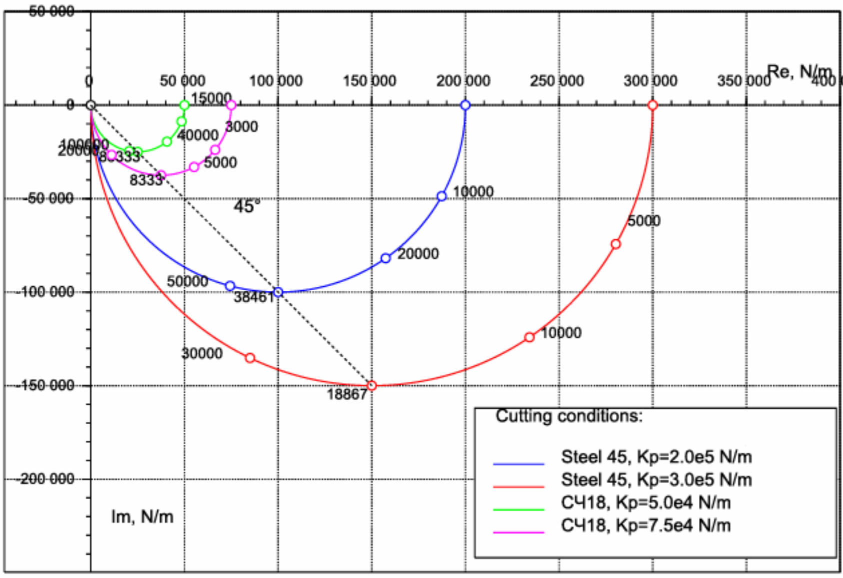


Fig. 2. Comparison of the amplitude-phase frequency response of the cutting process under different cutting conditions

Analysis of Figure 2 shows that the shape and scale of the hodographs depend substantially on the cutting-process parameters. For conditions with a larger value of K_P the hodograph exhibits larger real and imaginary components, indicating higher sensitivity of the process to dynamic perturbations. Simultaneously, a change in T_P affects the frequency-position of the hodograph's characteristic points and determines the phase properties of the cutting process.

For the evaluation of the technological system's vibration stability, the frequency response of the cutting process was considered in conjunction with the characteristic of the equivalent elastic system.

Such an approach makes it possible to account not only for the dynamic response of the cutting process, but also for the elastic and damping properties of the technological system. The initial parameters of the equivalent elastic system are given in Table 2.

Table 2

Main Parameters of the Equivalent Dynamic Model of the Machining System

Parameter	Symbol	Value
Natural frequency	f_0	208 Hz
Natural angular frequency	ω_0	1306 rad/s
Machining system stiffness	*c*	$1{,}06 \cdot 10^7$ N/m
Static compliance of the machining system	$k=1/c$	$9{,}43 \cdot 10^{-8}$ m/N
Damping ratio	ξ	0,5
Characteristic time parameter	$T=1/\omega_0$	$7{,}66 \cdot 10^{-4}$ s

Taking the stated parameters into account, the frequency response of the equivalent elastic system is represented in the form of a second-order oscillatory element:

$$W_{EES}(j\omega) = \frac{k}{1 - T^2\omega^2 + j2\xi t\omega}, \quad (2)$$

where $W_{EES}(j\omega)$ is the frequency response of the equivalent elastic system, m/N;

The frequency response of the conditionally open-loop technological system is determined as the product of the characteristics of the equivalent elastic system and the cutting process:

$$W(j\omega) = W_{EES}(j\omega) \cdot W_P(j\omega), \quad (3)$$

Since $W_{EES}(j\omega)$ has the dimension m/N and $W_P(j\omega)$ has the dimension N/m, their product $W(j\omega)$ is a dimensionless quantity. This enables the application of the Nyquist criterion for assessing the stability of the technological system by the position of the hodograph on the complex plane. It is precisely this characteristic that is used for the subsequent evaluation of the system's vibration stability.

It is precisely this characteristic that is used for the subsequent evaluation of the system's vibration stability. At the first stage, amplitude–phase frequency characteristics of the conditionally open-loop technological system were constructed, which are shown in Figure 3. The detailed scale of the figure was used to analyse the shape of the hodographs, compare their positions for different machining conditions, and evaluate the influence of the cutting-process parameters on the frequency behaviour of the system. Such a scale makes it possible to analyse the shape of the hodographs, compare the influence of different machining conditions, and assess the nature of the variation in the real Re and imaginary Jm components of the characteristic $W(j\omega)$.

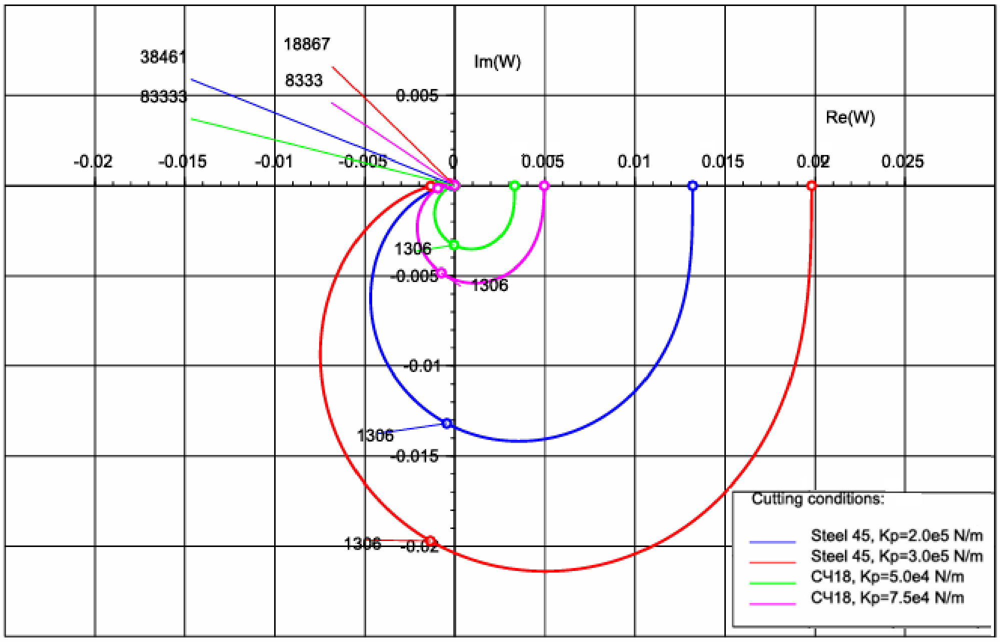


Fig. 3. Amplitude-phase frequency characteristics of the conditionally open-loop technological system

Figure 3 shows that the hodographs of the conditionally open-loop technological system are localised in a bounded region of the complex plane near the origin. The starting points of the hodographs, corresponding to $\omega = 0$, lie on the positive part of the real axis, and their coordinates are determined by the system's static gain $W(0) = kK_P$. As the circular frequency increases, the curves move into the lower half-plane and, as $\omega \to \infty$, tend towards the origin owing to the decrease in the modulus of the transfer function. The hodographs are marked with points corresponding to the natural circular frequency of the equivalent elastic system $\omega_0 = 1306\ s^{-1}$, as well as to characteristic frequencies of the cutting process $\frac{1}{T_P}$. The differences in the shape and size of the curves confirm the influence of the cutting-process parameters on the frequency behaviour of the technological system. With an increase in the static gain K_P, the hodograph moves farther from the origin, whereas the time constant T_P affects its shape and the position of its characteristic points. The largest hodograph by size was obtained for steel 45 at $K_P = 3{,}0 \cdot 10^5$ N/m, and the smallest – for СЧ18 at $K_P = 5{,}0 \cdot 10^4$ N/m N/m.

The absolute values of the real and imaginary components of $W(j\omega)$ are small, and the values of $Re(W)$ differ significantly from the coordinate -1 of the critical point (-1; $i0$). This preliminarily indicates a considerable remoteness of the hodographs from the critical region of stability loss. At the same time, a definitive stability assessment by the Nyquist criterion must be carried out using complete hodographs constructed for both positive and negative values of circular frequency.

At the second stage, the evaluation of vibration stability was performed by the Nyquist criterion. For this purpose, complete hodographs of the conditionally open-loop technological system were constructed from the calculated values of $W(j\omega)$, taking into account both positive and negative values of circular frequency; they are presented in Figure 4.

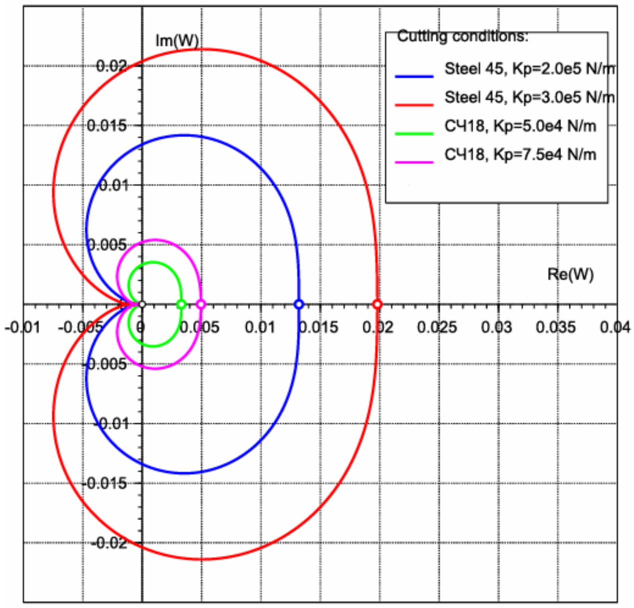


Fig. 4. Nyquist diagrams of the conditionally open-loop technological system for steel 45 and СЧ 18 under different cutting conditions

Figure 4 presents the complete Nyquist hodographs of the conditionally open-loop technological system. The branches corresponding to positive circular-frequency values are supplemented by complex-conjugate branches for negative frequencies. Owing to the fulfilment of the relation $W(-j\omega) = \overline{W(j\omega)}$, the resulting hodographs are symmetrical with respect to the real axis.

The characteristic compact, loop-like shape of the hodographs is dictated by the structural layout of the unilateral reamer tool [13] (Fig. 1 b) The straight elements that contact the machined surface and perceive the radial component of the cutting force restrain transverse tool displacements, increase the effective stiffness of the system, and promote the dissipation of vibration energy. In the frequency domain, this manifests as the bounded size of the loops and the localisation of the hodographs near the origin. Such behaviour differs from that of a cantilever-type boring-bar arrangement, for which the lower transverse stiffness can lead to a greater spread of the hodograph in the complex plane.

All hodographs are localised near the origin and lie at a substantial distance from the Nyquist critical point $(-1; i0)$, which – because of its remoteness – is not shown in the chosen scale. None of the constructed hodographs encircles the critical point. Since the conditionally open-loop system has no unstable poles, the Nyquist criterion indicates that the closed-loop technological system is stable for all cutting conditions investigated.

Differences in the shape and size of the hodographs are due to the cutting-process parameters. An increase in the static gain K_P leads to an increase in the hodograph dimensions, while a change in the time constant T_P affects its shape and phase properties. The largest hodograph corresponds to the machining of steel 45 at $K_P = 3{,}0 \cdot 10^5$ N/m, and the smallest – to the machining of СЧ 18 at $K_P = 5{,}0 \cdot 10^4$ N/m.

The results obtained confirm that, under the machining conditions considered, the technological system with a unilateral reamer tool remains in a vibration-stable state. This has practical significance for the machining of precision conical holes, since the dynamic stability of the system reduces the likelihood of self-excited vibrations, cutting-force instability, and additional elastic tool displacements.

In a metrological context, vibration stability characterises not the quality of the finished hole directly, but the dynamic conditions governing the formation of its measured geometric and surface characteristics. A stable state of the technological system is an important prerequisite for the stable provision of dimensional accuracy, the specified conical profile, permissible form deviations, and the quality of the machined surface. Therefore, frequency-domain evaluation of dynamic stability should be regarded as a preliminary stage in the analysis of the conditions for ensuring the accuracy of precision hole machining. The construction of amplitude–phase frequency characteristics of the cutting process and the conditionally open-loop technological system, together with Nyquist diagrams, makes it possible to assess the system's vibration stability and substantiate its significance for the stability of machining results.

CONCLUSIONS FROM THIS STUDY AND PROSPECTS FOR FURTHER RESEARCH IN THIS DIRECTION

The present work performed an evaluation of the vibration stability of a technological system for machining precision conical holes with unilateral cutting tools, based on frequency analysis. The technological system was represented as the interplay between the equivalent elastic system and the cutting process, which made it possible to form the frequency response of the conditionally open-loop system.

The constructed amplitude-phase frequency characteristics of the cutting process demonstrated that variation of the gain coefficient K_P and the time constant T_P substantially affects the shape of the hodographs. This confirms the dependence of the cutting process's dynamic behaviour on the workpiece material and machining conditions.

Based on the construction of the hodographs of the conditionally open-loop technological system, it was established that the calculated curves lie near the origin and do not approach the critical point $(-1; i0)$. Analysis of the Nyquist diagram revealed the absence of encirclement of the critical point for all machining conditions considered, which testifies to the vibration-stable state of the technological system under the adopted cutting-process parameters.

The results obtained indicate that, under the machining conditions examined, the technological system remains in a vibration-stable state. This means that, within the adopted frequency model, no preconditions for the development of self-excited vibrations – which could cause additional elastic tool displacements, cutting-force instability, and deviations in the form and quality of the machined surface – were detected.

Further research should appropriately be directed towards expanding the range of experimental data on the dynamic characteristics of the technological system under different machining regimes, workpiece materials, and unilateral cutting tool designs. It would also be expedient to establish a quantitative relationship between the results of the frequency-domain vibration-stability evaluation and the actual quality parameters of the machined holes – in particular dimensional accuracy, form deviations, and surface roughness. This would allow the proposed approach to be extended from an assessment of the dynamic state of the system to a comprehensive analysis of the conditions for ensuring the accuracy of precision hole machining.

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