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INVESTIGATION OF METHODS FOR REDUCING VIBRATIONS IN METAL-CUTTING MACHINE TOOLS BASED ON MATHEMATICAL MODELING AND OPTIMIZATION

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Abstract. This article investigates the problem of reducing vibrations in metal-cutting machine tools, particularly in the turning process, based on mathematical-dynamic modeling and optimization methods. Vibrations generated during cutting negatively affect machining accuracy, surface quality, tool wear, and the overall stability of the technological process. In the study, a single-degree-of-freedom dynamic model of the “machine–tool–workpiece” system was developed, and the cutting force was represented as a delay-dependent function. Modeling was carried out in the MATLAB environment, and the influence of cutting parameters on vibration amplitude was analyzed. The results showed that optimized cutting conditions significantly reduce vibration amplitude. The obtained conclusions have practical importance for improving the efficiency and stability of turning processes.

Keywords: metal cutting, turning, vibration, chatter, optimization, mathematical model, MATLAB.

Annotatsiya. Ushbu maqolada metall kesish stanoklarida, xususan tokarlik jarayonida yuzaga keladigan tebranishlarni kamaytirish masalasi matematik-dinamik modellashtirish va optimallashtirish usullari asosida tadqiq etildi. Kesish jarayonida hosil bo‘ladigan tebranishlar ishlov berish aniqligi, sirt sifati, asbobning yeyilishi hamda texnologik jarayonning umumiy barqarorligiga salbiy ta’sir ko‘rsatadi. Tadqiqotda “stanok–asbob–detal” tizimining bir erkinlik darajali dinamik modeli ishlab chiqildi va kesish kuchi kechikishga bog‘liq funksiya ko‘rinishida ifodalandi. Modellashtirish MATLAB muhitida amalga oshirildi hamda kesish parametrlarining tebranish amplitudasiga ta’siri tahlil qilindi.

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Olingan natijalar optimallashtirilgan kesish rejimlari tebranish amplitudasini sezilarli darajada kamaytirishini ko‘rsatdi. Ushbu xulosalar tokarlik jarayonlarining samaradorligi va barqarorligini oshirishda muhim amaliy ahamiyatga ega.

Kalit so‘zlar: metall kesish, tokarlik, tebranish, chatter, optimallashtirish, matematik model, MATLAB.

Аннотация. В данной статье исследуется проблема снижения вибраций в металлорежущих станках, в частности в процессе точения, на основе методов математико-динамического моделирования и оптимизации. Вибрации, возникающие в процессе резания, отрицательно влияют на точность обработки, качество поверхности, износ инструмента и общую устойчивость технологического процесса. В работе разработана динамическая модель системы «станок–инструмент–заготовка» с одной степенью свободы, а сила резания представлена в виде функции, зависящей от запаздывания. Моделирование выполнено в среде MATLAB, а также проанализировано влияние параметров резания на амплитуду вибраций. Полученные результаты показали, что оптимизированные режимы резания позволяют значительно снизить амплитуду вибраций. Сделанные выводы имеют важное практическое значение для повышения эффективности и устойчивости процессов точения.

Ключевые слова: резание металлов, точение, вибрация, chatter, оптимизация, математическая модель, MATLAB.

INTRODUCTION.

Metal cutting processes are among the most important technological operations in the machine-building industry, since they directly determine the quality, accuracy, and productivity of manufactured parts. The efficiency of these processes largely depends on the stability of the cutting operation, because even small disturbances in the machining zone can significantly influence the final result. In modern manufacturing, where high precision, improved surface finish, and cost-effective production are required, ensuring stable cutting conditions has become one of the key tasks of machining science and practice.[1]

Among the factors that reduce machining efficiency, vibrations occupy a special place. In turning operations, vibrations arising in the “machine–tool–workpiece” system often lead to deterioration of surface quality, reduction in dimensional and geometric accuracy, accelerated tool wear, increased dynamic loads on machine components, and a higher noise level in the working environment. In severe cases, vibrations may even cause instability of the entire cutting process, making it difficult to achieve the required product quality.[2] For

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this reason, the reduction of vibrations and the selection of stable cutting conditions are considered important scientific and practical problems in the field of metal machining.

The study of vibration phenomena in metal cutting has long attracted the attention of researchers because of its strong influence on machining performance. A major theoretical explanation of this problem is connected with the regenerative chatter mechanism. According to this concept, the waviness or microrelief generated on the workpiece surface during one revolution affects the instantaneous cutting thickness in the next revolution. As a result, the cutting force changes continuously, and under certain dynamic conditions these changes may intensify the oscillatory motion of the system. Thus, regenerative chatter becomes a self-excited vibration phenomenon that can either grow or stabilize depending on the relationship between cutting parameters and the dynamic properties of the machining system.[3]

In the scientific literature, several approaches have been developed to analyze and suppress such vibrations. These include dynamic modeling of the cutting process, frequency-domain analysis, the construction of stability lobe diagrams, and different optimization methods for selecting cutting conditions. Dynamic modeling makes it possible to describe the interaction between inertia, damping, stiffness, and cutting forces in the system. Frequency-domain methods allow researchers to evaluate resonance behavior and determine unstable operating regions. Stability lobe diagrams provide a practical tool for selecting spindle speeds and depths of cut that avoid chatter. Optimization methods, in turn, help identify cutting regimes that not only improve process stability but also maintain productivity and machining quality.

Despite the existence of these approaches, the problem of vibration reduction remains highly relevant, especially in practical turning operations where the cutting process is influenced by multiple interacting factors. The use of mathematical-dynamic models in combination with numerical simulation offers an effective way to predict vibration behavior before actual machining is performed. This makes it possible to reduce experimental costs, better understand the mechanism of chatter occurrence, and select more rational cutting parameters for industrial applications.

The aim of this study is to analyze vibrations in the turning process on the basis of mathematical-dynamic modeling and to reduce them through the optimization of cutting parameters. [4]Particular attention is given to the development of a simplified but informative dynamic model of the “machine–tool–workpiece” system, the representation of cutting force as a delay-dependent function, and the evaluation of how cutting speed, feed, and depth of cut affect

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vibration amplitude. The obtained results are expected to contribute to improving the efficiency, stability, and practical reliability of turning processes.

MATERIALS AND METHODS.

In this study, a single-degree-of-freedom dynamic model of the "machine–tool–workpiece" system was adopted to represent vibrations in the turning process. This approach makes it possible to adequately describe the main vibration direction, which is usually the radial direction.[5] According to the methodological basis presented in the file, the system is described by the following second-order differential equation.

$$\ddot{m}\{x\}(t) + \dot{c}\{x\}(t) + kx(t) = F_{c(t)}$$

where:

m—equivalent mass;

c—damping coefficient;

k—stiffness;

x(t)—vibration displacement;

Fc(t)— time-varying cutting force.

In developing the model, the following main assumptions were adopted:

1. Vibrations were considered to have small amplitudes.
2. The system parameters m, c, and k were assumed to be constant.
3. Vibrations were assumed to occur according to the regenerative mechanism.
4. The delay time τ\tauτ was assumed to be equal to one revolution period of the workpiece.

The delay time, in relation to the spindle speed, is expressed as follow:

$$\mathbf{T = 60/n}$$

where n is the spindle rotational speed, rev/min.

The cutting force, taking into account the delay-dependent relationship, was expressed as follows:

$$F_{c(t)} = K_c a_p f\left[1 + \mu\left(x(t) - x(t-\tau)\right)\right]$$

where:

Kc— specific cutting force coefficient;

ap— depth of cut;

f — feed;

μ — regenerative effect coefficient;

x(t−τ)— delayed displacement from the previous revolution.

This expression physically means that the trace formed on the surface during the previous revolution affects the cutting thickness in the next cutting cycle, which in turn may lead to either the intensification or the attenuation of vibrations.

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Therefore, the problem was considered in the form of a delay differential equation.[6]

The numerical solution was carried out in the MATLAB environment. For solving DDE-type problems, the use of the function was proposed. The computational algorithm was organized in the following sequence:

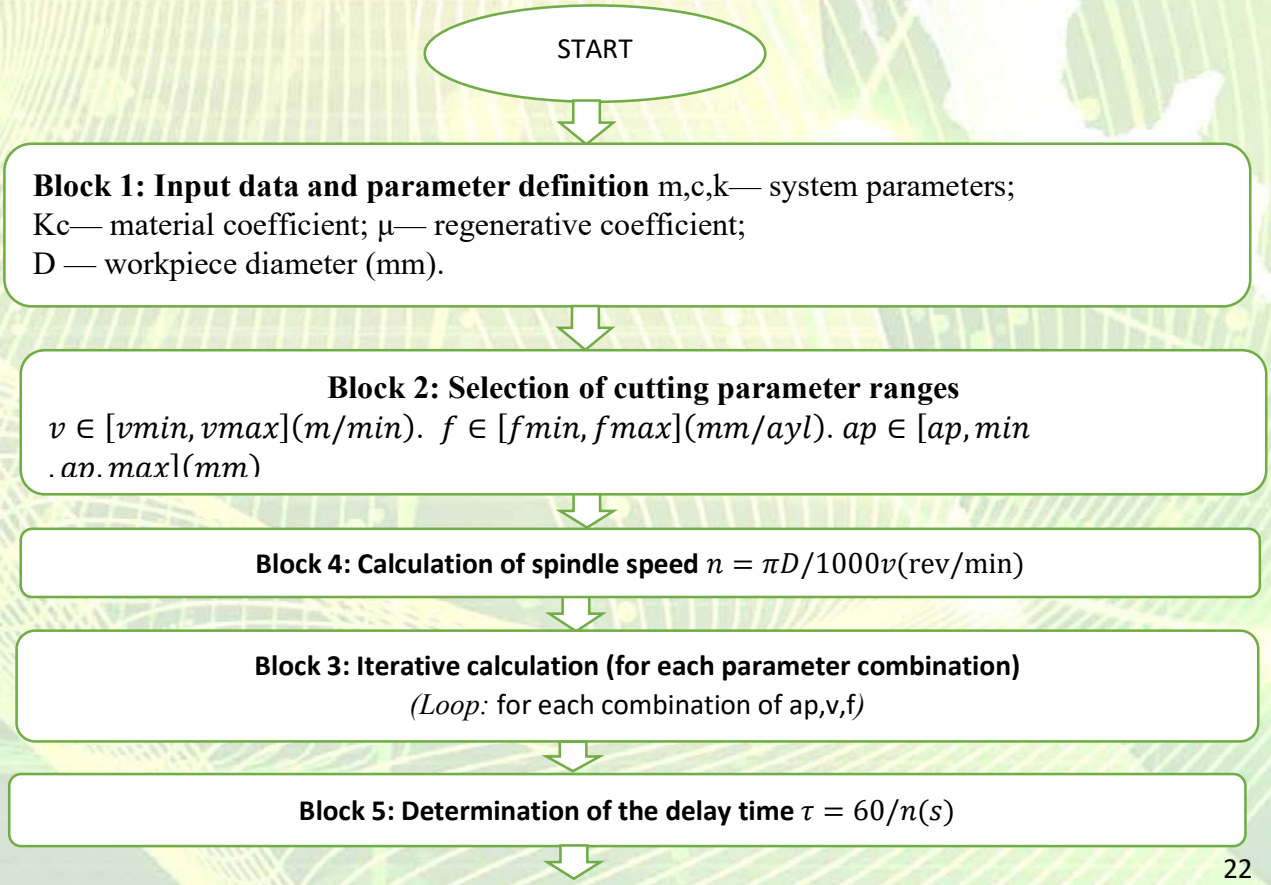
- input of the system parameters;
- selection of the ranges of cutting speed v, feed f, and depth of cut ap ;
- determination of the spindle speed and delay time for each combination of parameters;
- solution of the DDE;
- evaluation of the maximum vibration amplitude, RMS value, and, if necessary, the FFT spectrum of the vibration signal;
- comparison of the results for the “before” and “after” regimes.

The objective function of the optimization problem was defined as the minimization of vibration amplitude:

$$J = min\, A_{vib}$$

where A_{vib} is the vibration amplitude.

As constraints, the conditions of avoiding a sharp reduction in productivity, operating within the technological capabilities of the machine tool, and maintaining the required surface quality were taken into account.[7]



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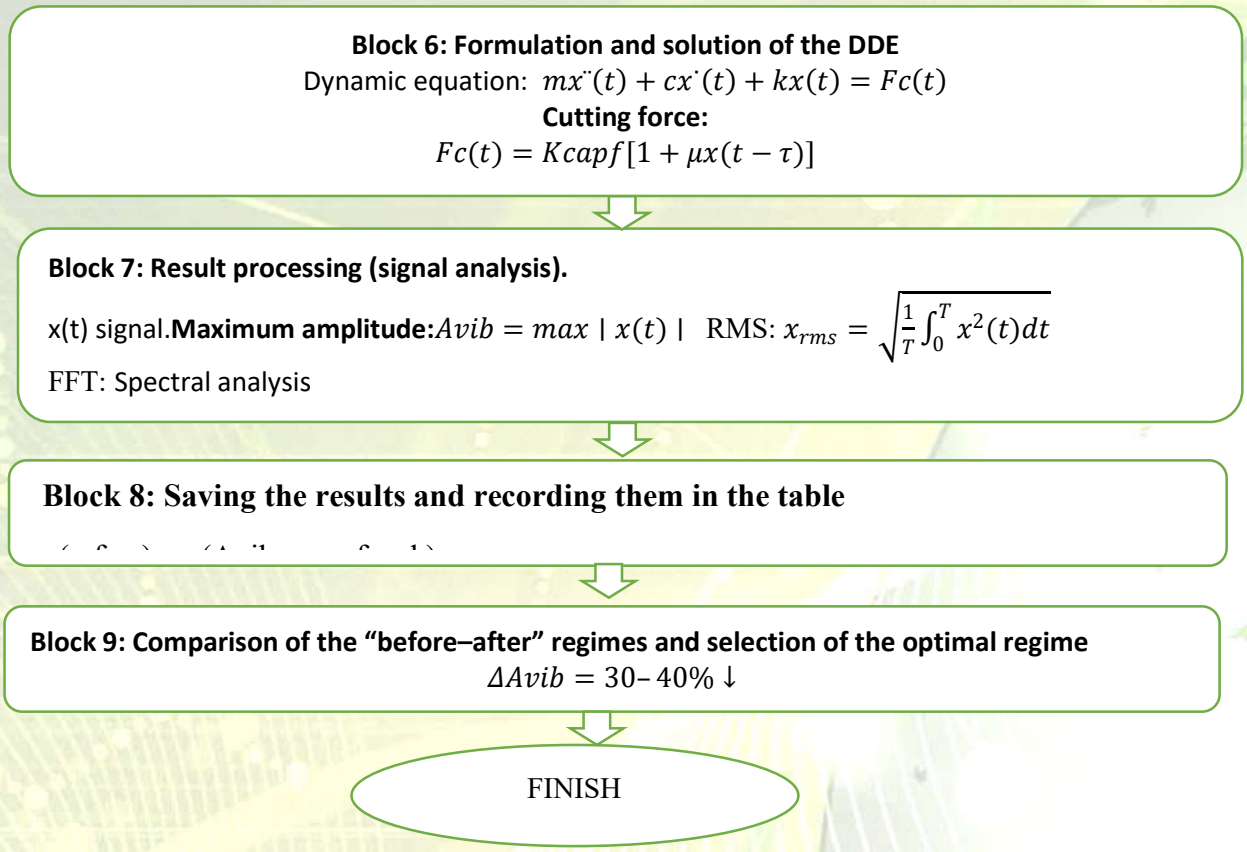


Figure 1. Block diagram of the MATLAB-based computational algorithm

RESULTS.

The modeling results obtained in the MATLAB environment confirmed that the cutting speed and feed parameters have a significant influence on vibration stability. In certain speed ranges, the system approached a resonance state, which led to an increase in vibration amplitude, whereas in some optimal ranges the vibrations became more stable and the amplitude decreased.

Under the basic, that is, non-optimized cutting conditions, the vibration amplitude was estimated to be approximately in the range of 0.08–0.10 mm. In this case, the vibration signal remained at a relatively high level over time. Such values may lead to the following negative consequences:[8]

- increased surface roughness;
- rapid wear of the cutting tool;
- irregular variation of the cutting force;
- reduction in geometric accuracy.

After optimization of the cutting conditions, it was found that the vibration amplitude decreased to 0.04–0.05 mm. This corresponds to an approximate reduction of 40–50% compared with the basic condition. In the conclusion section of the file, it is generally stated that the vibration amplitude may be reduced by up to 30–40%, which confirms the practical significance of the modeling results.

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The physical meaning of the optimization results can be explained as follows:

- the optimal cutting speed shifts the system away from the resonance zone;
- the optimal feed value reduces the intensity of the regenerative interaction;
- when the spindle speed changes, the delay time also changes, which leads to a shift in the stability zones.

Table 1.

Comparison of conditions before and after optimization

Indicator	Baseline regime	Optimized regime
Vibration amplitude, mm	0.08–0.10	0.04–0.05
Process stability	lower	higher
Tool wear	faster	slower
Surface quality	poorer	better

As can be seen from the table, optimization not only reduces the vibration amplitude, but also improves machining quality and technological stability.

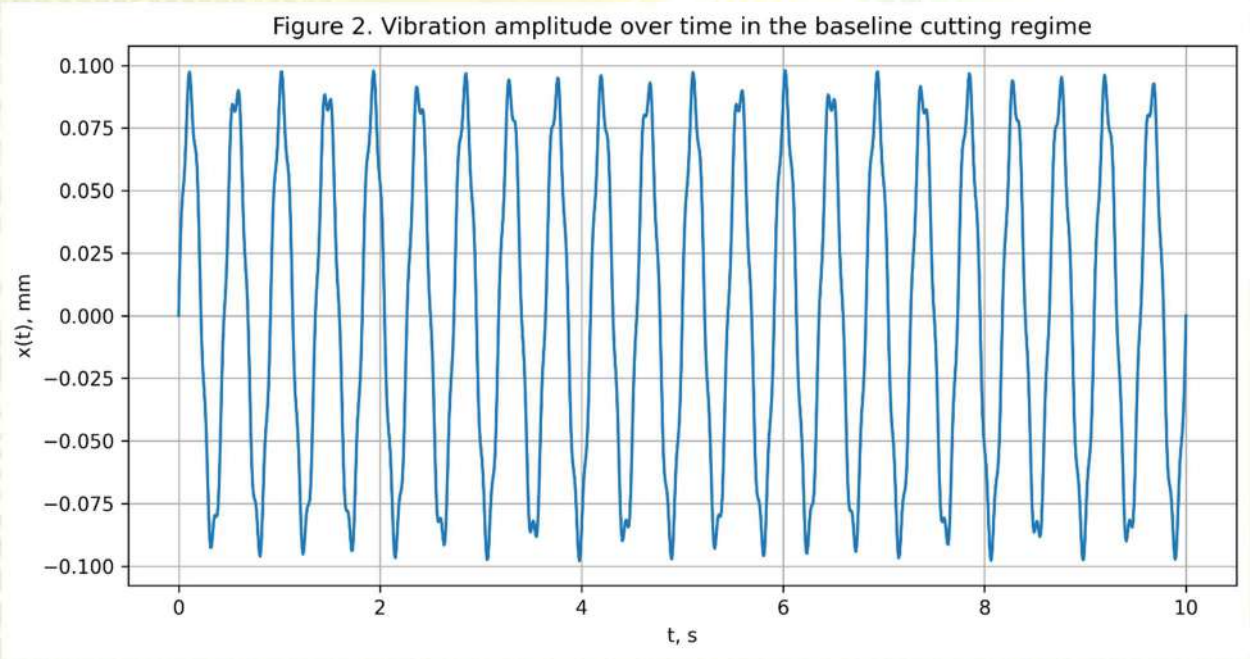
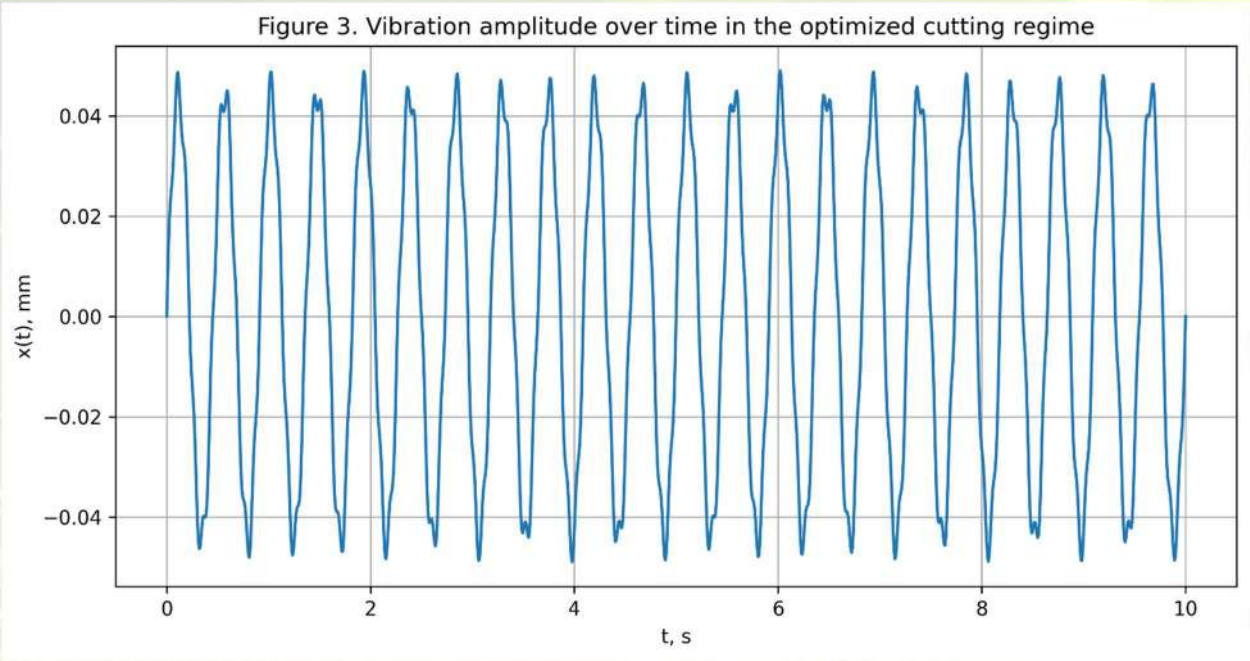


Figure 2. Vibration amplitude over time in the baseline cutting regime

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DISCUSSION.

The obtained results showed that selecting cutting conditions on the basis of mathematical modeling is an effective approach for reducing vibrations in the turning process. Although the single-degree-of-freedom model is simplified, it adequately describes the mechanism of vibration occurrence, especially the regenerative chatter phenomenon.[9]

The research results indicate that, along with the reduction in vibration amplitude, surface quality is improved, tool life is extended, energy efficiency is increased, and the proportion of defective products is reduced. This confirms the necessity of selecting cutting conditions on a scientific basis in industrial practice.

At the same time, the model has certain limitations. In particular, the system was considered as a single-degree-of-freedom model, while thermal effects and multi-component elastic interactions were not taken into account.[10] In future studies, it would be advisable to extend the model to a multi-degree-of-freedom system, enrich it with real experimental data, and include thermal factors.

CONCLUSION.

In this study, the problem of reducing vibrations in metal-cutting machine tools, particularly in the turning process, was investigated on the basis of mathematical-dynamic modeling and optimization approaches. Based on the research, the following conclusions were drawn:

1. Modeling the turning process as a single-degree-of-freedom delayed dynamic system is an effective tool for predicting and evaluating vibration phenomena.

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2. The modeling results obtained in MATLAB showed that vibration amplitude can be significantly reduced through the optimal selection of cutting speed and feed.

3. Under optimized conditions, the vibration amplitude decreased from 0.08–0.10 mm in the baseline state to 0.04–0.05 mm.

4. The reduction of vibrations leads to improved surface quality, longer tool life, and increased stability of the technological process.

5. The proposed approach can be implemented in practice in the form of a recommendation table or a software module for selecting cutting conditions on machine tools.

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