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MATHEMATICAL MODELING OF THE DYNAMIC CHARACTERISTICS OF TURNING CUTTERS WITH DAMPING ELEMENTS BASED ON THE COHERENCE FUNCTION

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Abstract. This article discusses the mathematical modeling and coherence-function-based analysis of the dynamic characteristics of a turning cutter equipped with a rod-and-spring damping element. Vibrations arising during the turning process negatively affect the quality of the machined surface, the service life of the tool, and the stability of the technological process. In the study, the "machine–tool–workpiece" system was considered as a single-degree-of-freedom delayed dynamic model, taking into account the influence of the damping element on the overall damping coefficient of the system. The results of numerical modeling carried out in the MATLAB environment were analyzed through vibration amplitude, frequency spectra, and the coherence function. The obtained results showed that the damped cutter is effective in reducing vibrations and that the coherence function is an important scientific tool for evaluating the relationship between vibrations and cutting force.

Keywords: turning cutter, damping element, rod and spring, vibration, coherence function, mathematical modeling, MATLAB.

Аннотация. В данной статье рассмотрены вопросы математического моделирования и анализа динамических характеристик токарного резца, оснащённого демпфирующим элементом в виде стержня и пружины, на основе функции когерентности. Вибрации, возникающие в процессе точения, оказывают отрицательное влияние на качество обработанной поверхности, срок службы инструмента и устойчивость технологического процесса. В исследовании система «станок–резец–деталь» принята в виде динамической модели с одной степенью свободы и запаздыванием, при этом учтено влияние

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демпфирующего элемента на общий коэффициент демпфирования системы. Результаты численного моделирования, выполненного в среде MATLAB, были проанализированы по амплитуде вибраций, частотным спектрам и функции когерентности. Полученные результаты показали, что резец с демпфированием эффективно снижает вибрации, а функция когерентности является важным научным инструментом для оценки связи между вибрациями и силой резания.

Ключевые слова: токарный резец, демпфирующий элемент, стержень и пружина, вибрация, функция когерентности, математическое моделирование, MATLAB.

Annotatsiya. Mazkur maqolada sterjen va prujinali dempferlash elementiga ega tokarlik kesgichining dinamik xususiyatlarini matematik modellashtirish hamda kogerentlik funksiyasi asosida tahlil qilish masalalari yoritilgan. Tokarlik jarayonida yuzaga keladigan vibratsiyalar ishlov berilgan sirt sifati, asbobning xizmat muddati va texnologik jarayon barqarorligiga salbiy ta’sir ko‘rsatadi. Tadqiqotda “dastgoh–kesgich–detal” tizimi bir erkinlik darajali kechikishli dinamik model sifatida qabul qilinib, dempferlash elementi tizimning umumiy dempferlash koeffitsientiga ta’siri hisobga olindi. MATLAB muhitida o‘tkazilgan raqamli modellashtirish natijalari vibratsiya amplitudasi, chastota spektrlari va kogerentlik funksiyasi orqali tahlil qilindi. Olingan natijalar dempferli kesgich vibratsiyalarni kamaytirishda samarali ekanligini hamda kogerentlik funksiyasi vibratsiyalarning kesish kuchi bilan bog‘liqligini baholashda muhim ilmiy vosita ekanligini ko‘rsatdi.

Kalit so‘zlar: tokarlik kesgichi, dempferlash elementi, sterjen va prujina, vibratsiya, kogerentlik funksiyasi, matematik modellashtirish, MATLAB.

INTRODUCTION.

In modern mechanical engineering and manufacturing industries, the efficiency, accuracy, and stability of metal cutting processes are among the main factors determining product quality and production competitiveness. In particular, the turning process remains one of the most widely used machining methods for producing cylindrical, conical, and shaped surfaces with the required dimensional accuracy and surface finish. However, despite the broad industrial application of turning, the process is often accompanied by dynamic phenomena, especially vibrations, which significantly reduce machining performance. These vibrations negatively affect the quality of the machined surface, accelerate tool wear, increase noise and energy consumption, and reduce the overall stability of the technological system. As a result, productivity decreases, tool replacement costs increase, and additional economic losses arise during production.

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The occurrence of vibrations in turning is mainly associated with the dynamic behavior of the “machine–tool–workpiece” system. This system possesses elastic, inertial, and damping properties, and under the action of variable cutting forces it may enter unstable oscillatory regimes. In many cases, vibrations are intensified due to the regenerative mechanism, in which waviness left on the previously machined surface affects the current chip thickness and leads to self-excited oscillations. Such a dynamic interaction makes the turning process highly sensitive to changes in spindle speed, feed rate, depth of cut, tool geometry, and stiffness of the technological system. Therefore, the study of vibration formation and suppression is one of the key scientific and practical tasks in machining theory and production engineering.[1]

To reduce the negative effects of vibrations, various technological and design-based solutions have been proposed in the literature and engineering practice. These include optimization of cutting parameters, improvement of tool geometry, enhancement of machine rigidity, application of advanced control methods, and use of damping devices. Among these approaches, cutting tools equipped with damping elements are of particular interest because they allow vibration energy to be dissipated directly in the tool structure. Such tools can improve dynamic stability without significantly changing the main kinematic parameters of the cutting process. In this respect, the introduction of damping elements in the form of rods and springs into the turning tool structure represents a promising engineering solution for vibration suppression.[2]

At the same time, for a more complete understanding of the dynamic behavior of damped turning tools, it is not sufficient to analyze only vibration amplitudes or frequency spectra. A deeper scientific assessment requires the study of the relationship between the excitation source and the system response. In this context, the coherence function is an important analytical tool. The coherence function makes it possible to determine the degree of frequency-domain correlation between the input signal, namely the cutting force, and the output signal, namely the vibration response of the cutting tool. This approach allows researchers to identify the frequency ranges in which tool vibrations are directly caused by the cutting process and to distinguish them from ranges dominated by external disturbances, measurement noise, or secondary structural effects. Therefore, the use of the coherence function provides broader opportunities for evaluating the real efficiency of damping elements in dynamic systems.[3]

Mathematical modeling plays an essential role in the study of machining vibrations because it makes it possible to investigate system behavior under different operating conditions without the need for expensive and time-consuming

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full-scale experiments. By constructing a dynamic model of the turning process, it becomes possible to evaluate the influence of stiffness, mass, damping coefficient, delay time, and cutting-force parameters on vibration stability. In particular, delayed dynamic models are widely used in turning studies because they reflect the regenerative nature of chatter vibrations. When a damping element is incorporated into such a model, its influence on the overall damping capacity of the system can be quantified more accurately, and the expected reduction in vibration level can be predicted under various cutting conditions.[4]

The scientific novelty of this study lies in the development of a mathematical-dynamic model of a turning cutter equipped with a rod-and-spring damping element and in the use of the coherence function as a tool for evaluating its vibration suppression capability. In the proposed approach, the "machine–tool–workpiece" system is considered as a single-degree-of-freedom delayed dynamic system, while the contribution of the damping element is introduced through the generalized damping coefficient. Numerical simulations performed in the MATLAB environment make it possible to analyze the vibration response of the system, identify the dominant frequency components, and evaluate the coherence between cutting force and tool vibration.

The practical significance of the research is determined by the possibility of applying the obtained results in the design of vibration-resistant turning tools and in improving the stability of machining processes in industrial conditions. The use of damped cutters can contribute to better surface quality, longer tool life, reduced noise levels, and increased machining reliability. In addition, coherence-based analysis can serve as a scientific basis for selecting rational damping parameters and for diagnosing unstable cutting conditions.

Thus, the purpose of this study is to develop a mathematical dynamic model of a turning cutter with a rod-and-spring damping element and to scientifically evaluate, by means of the coherence function, the effectiveness of the damped cutter in reducing vibrations during the turning process.[5]

MATERIALS AND METHODS.

The research methodology was based on an integrated approach that included mathematical modeling, numerical computation, and signal processing methods. First, the dynamic parameters of both damped and non-damped cutting tools were determined, and the cutting conditions were varied within a specified range. In the MATLAB environment, the dde23 function was used to solve the delay differential equation describing the dynamic behavior of the system. The obtained time-domain signals were then analyzed in the time domain, frequency domain, and from the point of view of cause-and-effect relationships.

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DYNAMIC MODEL.

To evaluate the dynamic characteristics of a turning cutter equipped with a rod-and-spring damping element, the "machine–tool–workpiece" system was modeled as a single-degree-of-freedom delayed mechanical vibration system. The damping element introduces additional elastic and dissipative properties into the system, thereby enhancing the dissipation of vibration energy.

The equation of motion of the cutter vibration can be expressed as follows:

$$\ddot{m}\{x\}(t) + c \dot{+} c_d\{x\}(t) + (k + k_d)x(t) = F_{c(t)}$$

Here:

m — equivalent mass;

c — main damping coefficient;

c(d) — additional dissipation introduced by the damping element;

k — main stiffness;

k(d) — equivalent stiffness of the spring.

The cutting force, taking into account the regenerative mechanism, can be written as follows:

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

Here:

K(c) — specific cutting force coefficient;

a(p) — depth of cut;

f — feed;

μ — regenerative effect coefficient;

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

The delay time is expressed as follows:

$$T=60/n$$

Here,

n — spindle rotational speed, rpm.

Time-domain and frequency-domain analysis

In the time domain, the maximum vibration amplitude and the RMS value were evaluated. The RMS value is determined as follows:

$$x_{\{rms\}} = \sqrt{\left\{\backslash frac\{1\}\{T\} \int_0^T x^{2(t),dt}\right\}}$$

In the frequency domain, the spectral composition of the vibration signal was determined using FFT. The discrete Fourier transform is written as follows:

$$X(k) = \sum_{\{n=0\}}^{\{N-1\}x(n)e^{\left\{-\frac{j2\pi kn}{N}\right\}}}$$

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The spectral amplitude is evaluated as follows:

$$A(f)= | X(f) |$$

To provide a general evaluation of resonance- or chatter-related components, the spectral energy was also considered.

Coherence Function

As the main scientific novelty of this study, the coherence function was applied. It expresses the degree of frequency-domain relationship between the cutting force $\mathbf{F_(c)(t)}$ and the cutter vibration **x(t)**:

$$\gamma^{2(f)} =\backslash frac\left\{\left|G_{\{Fx\}(f)}\right|^2\right\}\left\{G_{\{FF\}(f)G_{\{xx\}(f)}}\right\}$$

Here:

$G_{\{FF\}(f)}$— auto-spectral density of the cutting force;;

$G_{xx(f)}$ — auto-spectral density of the cutter vibration;

$G_{\{Fx\}(f)}$ — cross-spectral density;

f — frequency.

The value of the coherence function ranges from 0 to 1. Values close to unity indicate that the vibrations are mainly deterministically related to the cutting process, whereas low values indicate that the vibrations are caused by random factors or external noise.[6]

RESULTS

1. Time-domain analysis

In the MATLAB environment, the delayed dynamic equation was solved and the vibration signal of the cutter tip, **x(t)**, was obtained. The maximum amplitude and RMS value were taken as the main quantitative indicators of vibration. The calculation results showed that, in the non-damped case, the maximum vibration amplitude was higher, the vibration signal was unstable over time, and periodic amplification was observed. This is a characteristic sign of the chatter phenomenon. In the damped case, however, the amplitude decreased, the vibration signal became smoother, and high-intensity oscillations were reduced.[7]

The degree of vibration reduction in percentage was evaluated as follows:

$$\eta_A = \frac{A_{max,0} - A_{max,d}}{A_{max,0}} \cdot 100\%$$

Here, $\mathbf{A_(max,0)}$ is the maximum amplitude in the non-damped case, and **$\mathbf{A_(max,d)}$** is the maximum amplitude in the damped case. In a typical case, this indicator was observed to lie within the range of 30–50%.

2. Frequency-domain analysis

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The FFT results made it possible to identify frequency components characteristic of chatter. In the non-damped case, the peaks corresponding to resonance and chatter were distinguished by high energy. In the damped case, however, the amplitudes of these same peaks decreased, indicating a reduction of vibration energy in the resonance range. The damping element acted as a mechanism for dissipating vibration energy in the system.

3. Analysis based on the coherence function

Although the time-domain and spectral analyses showed a reduction in vibration, the coherence function was applied to clarify whether the vibration was directly related to the cutting force or caused by other random factors. The calculations showed that, in the non-damped case, **$\gamma^2(f)$** had high values at the main frequencies corresponding to resonance and chatter. This indicates that the vibration signal was very strongly related to the cutting force and that the chatter mechanism was active. In the damped case, the coherence values in the same frequency ranges decreased, meaning that the deterministic component of the vibration associated with the cutting force was significantly reduced.

The reduction in deterministic coupling can be estimated in percentage as follows:

$$\eta_\gamma = \frac{\gamma_0^2(f) - \gamma_d^2(f)}{\gamma_0^2(f)} \cdot 100\%$$

This result shows that the damping element suppresses the chatter mechanism not only in terms of amplitude, but also in terms of the cutting force–vibration relationship. Thus, the coherence plot appears as the strongest scientific evidence of damping efficiency.

DISCUSSION.

The obtained results showed that, in the evaluation of vibrations during the turning process, relying only on amplitude or FFT analysis is not sufficient. This is because these methods show the magnitude of vibration, but they cannot fully reveal its source. The coherence function, however, makes it possible to identify the deterministic component of vibrations that is directly related to the cutting force. In this respect, the proposed approach is of great importance for deeper vibration diagnostics and for proving the actual effectiveness of the damping element.

It was found that the application of a rod-and-spring damping element increases the overall damping coefficient of the system and reduces the vibration amplitude as well as the spectral energy in the frequency ranges characteristic of

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resonance and chatter. This not only improves surface quality, but also extends tool life and increases the stability of the technological process.

This model also has certain limitations. In particular, the system was considered as a single-degree-of-freedom model, while thermal effects and multi-component elastic couplings were not taken into account. 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 more accurately determine the optimal values of $\mathbf{k_(d)}$ and $\mathbf{c_(d)}$ in the chatter range.

CONCLUSION

The results of the mathematical modeling and signal analysis showed that, in evaluating chatter vibrations during the turning process, it is not sufficient to rely only on amplitude and FFT analyses. The application of the coherence function makes it possible to identify the deterministic component of vibrations associated with the cutting force and to scientifically substantiate, at the cause-and-effect level, the actual effectiveness of the rod-and-spring damping element in reducing vibrations.

Based on the study, the following conclusions were drawn:

1. Representing the “machine–tool–workpiece” system as a single-degree-of-freedom delayed model is a sufficiently effective approach for evaluating vibrations in the turning process.

2. The rod-and-spring damping element improves the overall damping properties of the system and reduces both the vibration amplitude and the spectral components characteristic of chatter.

3. The coherence function is one of the most important scientific criteria for evaluating damping efficiency, since it makes it possible to identify the deterministic part of vibration related to the cutting force.

4. As a result of applying the damping element, the vibration amplitude was observed to decrease by up to 30–50% in typical cases.

5. Adapting the proposed model and analysis algorithm in MATLAB to production conditions and applying it in a predictive mode can contribute to increasing the stability of the turning process and extending tool life.

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