Estimation of the losses coefficient of the vibrational energy of the woodworking technological system

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Abstract. Domestic machine tool equipment is not worse than foreign analogues in terms of product processing accuracy, productivity and reliability. However, almost all machines (including woodworking ones) create sound pressure levels at the operator's workplaces that significantly exceed the maximum permissible values. Compliance of vibroacoustic characteristics of technological equipment with sanitary standards is not only one of the most important ergonomic criteria, but also largely determines the competitiveness of domestic equipment. The article developed methods of acoustic calculation of metal-cutting equipment, which take into account the coefficient of losses of the vibrational energy of the source, which is a frequency-dependent parameter. Experimental results and regression relationships were obtained for steel plates of various thicknesses, rolled products of multiple configurations, for transport machines and for glazing elements. For woodworking equipment, this data is obtained only for multilayer materials. For various types of wood, at present, such studies have not been carried out, which in fact determines the relevance of the materials in this article.

1. Introduction
Shield blanks and blanks such as beams from various materials, including multilayer materials, are processed on wide-belt grinding woodworking machines. The vibrational energy loss coefficients of these blanks depend on the wood species, its structure and their combinations. In addition, when installed and secured on the machine table, the workpiece becomes part of the machine's technological system, which also affects the value of the vibration energy loss factor.

The problem of measuring the losses of vibrational energy attracts the attention of many researchers due to the need to optimize and increase the efficiency of machines and mechanisms. In work 1, a device is developed based on the analysis of low-frequency vibration systems, and an energy collection device is presented in combination with a large magnetic impedance sensor. At the resonant frequency (10 Hz), the maximum electrical power of 1.4 mW at 0.5 g is generated. As a result of the periodic movement of the magnet, an amplitude-modulated signal was obtained, the amplitude of which is proportional to the amplitude (or acceleration) of mechanical vibrations.

Calculation of vibration speeds for closed systems with a low coefficient of vibrational energy loss is given in [2,3]. It is shown that the energy fluxes and sound power emitted by each element of the system can be reduced to a system of linear algebraic equations. This allowed us to offer a number of technical solutions that reduce the sound power when processing body elements.

The use of artificial neural networks and artificial intelligence algorithms for the classification of steel by vibration velocity signals is proposed in [4]. Experimental studies of the strength characteristics of various steel grades have been carried out, and a special device for impact testing
with an assessment of vibroacoustic parameters has been developed. The developed algorithm allows, with an average accuracy of more than 95%, to attribute the results to the corresponding steel grade.

A new method for determining the vibration sensitivity of discrete saws is proposed in [5]. The approach makes it possible to characterize oscillations and extract a behavioural model of saws during operation. Numerical optimization to reduce the vibration noise of the centrifugal fan volute is presented in [6]. The goal of optimization is determined by the minimum vibration-emitted sound power. The vibration noise control method for the volute included simulation of unsteady flow to the fan to generate a vibration noise source and low vibration noise optimization for the fan volute. The results showed that the method could effectively reduce the vibration noise of the fan, achieving a maximum noise reduction value of 7.3 dB.

Analysis of literature sources shows that for many production processes, the optimization of vibroacoustic characteristics is relevant, and it is necessary to take into account the value of the coefficient of losses of vibrational energy. Thus, the purpose of this work was an experimental analysis of the vibroacoustic characteristics of the equipment, as well as the noise at the operator's workplaces and the determination of the vibration energy loss factor when the workpiece is installed on the machine table.

2. Materials and methods
The article discusses wide-belt grinding woodworking machines on which panel blanks and blanks such as beams from various, including multilayer, wood materials are processed. The materials were pine, oak and birch blanks. The vibrational energy loss coefficients of these blanks depend on the wood species, its structure and their combinations. In addition, when installed and secured on the machine table, the workpiece becomes part of the machine's technological system, which also affects the value of the vibration energy loss factor.

To determine the coefficients of vibrational energy losses of blanks from various types of wood and multilayer materials, experimental studies were carried out on a special installation. Vibration excitation in both cases was carried out using a dynamometric hammer, and measurements with using a vibration sensor. The impact from a dynamometric hammer on the workpiece is a pulsed load, which actually excites vibrations in the entire spectrum of natural frequencies [7]. To calculate the vibroacoustic characteristics of the equipment, as well as noise, at the operator's workplaces, the value of the vibration energy loss factor was taken into account when the workpiece was installed on the machine table.

Often, noise levels need to be determined not only at geometric mean octave frequencies but also at intermediate (natural) frequencies. Therefore, on the basis of the values of the vibrational energy loss coefficients obtained as a result of experiments, it is necessary to determine an adequate analytical dependence of the loss coefficient as a function of frequency. The method of least squares was applied to determine the coefficients of various (non-linear and polynomial) functions. The choice of the most suitable function according to the principle of the least standard deviation was carried out.

3. Results
The results of experimental studies have shown that the values of the vibrational energy loss coefficients for various materials, even as part of the technological system of one machine tool, differ significantly. Therefore, below are the results of approximating the experimental data for each material separately.

Regression analysis is a relatively accurate method of studying the effect of a variable on a function. One of the primary techniques of regression analysis for estimating the parameters of regression models from sample data is the method of least squares (MLS). This method allows solving a wide range of problems, including approximating experimental data, determining initially unknown coefficients of the analytical dependence of a specific function. In this case, it is possible to determine not one, but several analytical dependencies and evaluate their adequacy using the sum of squares of deviations from experimental values. As a rule, the systematic relationships obtained using the least-
squares method are linear or polynomial. However, there are a number of non-linear functions that can be brought to a linear form (linearized) using simple mathematical transformations, and the coefficients of regression models can be determined using MLS.

For oak and birch wood, the experimental values of the loss coefficients were so close that they were combined into one group (Figure 1). The approximation by non-linear functions is presented in Table.1.

**Figure 1.** Oak and birch vibrational energy loss coefficients.

| Title                  | Equation                        | Standard deviation |
|------------------------|---------------------------------|--------------------|
| Exponential            | $\eta = 0.01e^{-0.30 \cdot f}$ | $4.03 \cdot 10^{-4}$ |
| Power                  | $\eta = 0.0116f^{-0.023}$      | $1.82 \cdot 10^{-4}$ |
| Hyperbolic 1 type      | $\eta = 0.0097 + 0.044 \cdot \frac{1}{f}$ | $1.40 \cdot 10^{-4}$ |
| Hyperbolic 2 type      | $\eta = \frac{1}{98.12 + 0.001f}$ | $4.01 \cdot 10^{-4}$ |
| Hyperbolic 3 type      | $\eta = \frac{f}{-420.08 + 102.9f}$ | $1.55 \cdot 10^{-4}$ |
| Logarithmic            | $\eta = 0.0115 - 2.4 \cdot 10^{-4} \ln f$ | $1.90 \cdot 10^{-4}$ |
| S-shaped               | $\eta = e^{-0.31 \cdot f}$     | $1.47 \cdot 10^{-4}$ |
| Reverse logarithmic    | $\eta = \frac{1}{85.6 + 2.31 \cdot \ln f}$ | $1.75 \cdot 10^{-4}$ |

Thus, the search algorithm for an adequate mathematical model is the determination of the regression coefficients of all possible analytical dependencies and the selection of the best one according to the principle of the minimum sum of squares of deviations. It should be noted that with the current level of computer technology and software, the implementation of this algorithm is not difficult, since the solution is reduced to finding the roots of systems of linear equations by one of the known methods. Since the found analytical dependences can be linear, non-linear functions, as well as polynomials of various degrees, the adequacy of the model must be assessed using a more rigorous parameter - the standard deviation (SD):
\[ \sigma = \sqrt{\frac{1}{(n-m)-1} \sum_{i=1}^{n} (y_i - \bar{y})^2} \]  

where \( n \) is the number of experiments; \( m \) is the degree of the polynomial; \( y_i \) - the value of the function in the test; \( \bar{y} \) is the calculated value from the model.

This parameter takes into account the average deviation not only from the number of measurements but also from the degree of the polynomial. As the experience of using the above algorithm shows, the maximum possible degree of the polynomial for a given number of experiments does not always adequately describe the experimental data; with an increase in the degree of the polynomial, the standard deviation sometimes increases.

Figure 2 shows the results of approximation of experimental data by various non-linear functions.

![Figure 2. Approximation by non-linear functions for oak and birch.](image)

The conducted experimental study of the coefficient of losses of vibrational energy on the example of products made of oak and birch showed that the curves of Hyperbolic type 1 and C-shaped function are best suited. It is advisable to compare the data obtained with other types of wood and data obtained by other researchers.

4. Discussion

Let us consider the obtained data on the coefficients of vibrational energy losses in comparison with different types of wood. In Figure 3 shows the dependence of losses on vibration frequency. The graph shows that there is a resonant increase in the coefficient in the zone of about 2000 Hz, which corresponds to the sound frequencies and adversely affects the health and productivity of the operator.

Comparison with the data obtained for oak and birch shows (Figure 1) that such a surge is not observed and the dependence on frequency has a relatively smooth character. Although the relationship in Figure 1 has an upward trend in the 8000 Hz region, but this growth is insignificant.

Comparative analysis of tables 1 and 2 shows that a type 1 hyperbolic function describes the best approximation. The standard deviation in both cases is minimal and is equal to 1.40 \times 10^{-4} and 2.46 \times 10^{-4}, respectively. It can be seen that the curves almost coincide.

A similar technique was applied in [8] when modeling and calculating the hydraulic and mechanical parts of the original test bench design for plunger hydraulic cylinders with energy recovery. Noise phenomena of the stand hydraulic system were simulated, and a theoretical assessment of the vibration arising in the system elements was carried out. The level of the generated noise was assessed to select constructive measures to reduce it.
The durability of the cutting tool largely determines the technological and economic efficiency of the woodworking process. In work [9-11] it is shown that to increase the efficiency of woodworking and reduce the negative effect of vibrations, the means of wear of planning knives operating in conditions of dynamics and noise were investigated. For comparison, the results obtained can be interpreted in such a way that under conditions of increased tool dynamics and vibration of workpieces, it is possible to ensure the accuracy and efficiency of processing based on mathematical models linking the losses of vibrational energy and the characteristics of wood processing equipment.
Figure 4. Approximation by non-linear functions for pine.

Polynomial approximation creates an adequate mathematical model, provided the initial data is uniform. In our case, the range of frequencies has a geometric progression, so the maximum and minimum values differ from each other by two orders of magnitude. To align the original data, we will make the replacement $x = \lg(f)$. Since the measurements of the coefficient of losses of vibrational energy were carried out at 9 frequencies, the maximum degree of the approximating polynomial will be equal to 7. The results of the regression analysis by polynomials are presented in Table 3.

Table 3. Approximation by non-linear functions for pine.

| Degree | Equation                                      | SD       |
|--------|-----------------------------------------------|----------|
| 1      | $\eta = 0.012 - 0.0005(\lg f)$               | 4.78·10^{-4} |
| 2      | $\eta = 0.017 - 0.005(\lg f) + 0.0007(\lg f)^2$ | 1.81·10^{-4} |
| 3      | $\eta = 0.019 - 0.007(\lg f) + 0.0018(\lg f)^2 + 0.00013(\lg f)^3$ | 1.89·10^{-4} |
| 4      | $\eta = -0.006 + 0.034(\lg f) - 0.023(\lg f)^2 + 0.006(\lg f)^3 - 0.0006(\lg f)^4$ | 1.07·10^{-4} |
| 5      | $\eta = 0.024 - 0.028(\lg f) + 0.027(\lg f)^2 - 0.013(\lg f)^3 + 0.003(\lg f)^4 - 0.0003(\lg f)^5$ | 1.11·10^{-4} |
| 6      | $\eta = 0.104 - 0.228(\lg f) + 0.229(\lg f)^2 - 0.12(\lg f)^3 + 0.034(\lg f)^4 - 0.005(\lg f)^5 + 0.0003(\lg f)^6$ | 1.31·10^{-4} |
| 7      | $\eta = -0.951 + 2.816(\lg f) - 3.461(\lg f)^2 + 2.32(\lg f)^3 - 0.916(\lg f)^4 + 0.213(\lg f)^5 - 0.027(\lg f)^6 + 0.0014(\lg f)^7$ | 1.52·10^{-4} |

Since the smallest standard deviation of all functions has a fourth-degree polynomial, the regression dependence has the following form

$$\eta = -0.006 + 0.034(\lg f) - 0.023(\lg f)^2 + 0.006(\lg f)^3 - 0.0006(\lg f)^4$$

(2)

The obtained relationship allows using in engineering practice simple dependences of the vibrational energy loss coefficients depending on the frequency range of the woodworking machine.
5. Conclusions
The experimentally obtained vibroacoustic characteristics of technological equipment are not only one of the essential ergonomic criteria, but also largely determine the competitiveness of domestic equipment. The article developed methods of acoustic calculation of metal-cutting equipment, which take into account the coefficient of losses of the vibrational energy of the source, which is a frequency-dependent parameter. Experimental results and regression dependencies have been obtained for wood-based panels of various thicknesses, parts of multiple configurations, which makes it possible to propose technical solutions to reduce the loss factor across numerous frequency ranges.

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