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METHODOLOGY OF ENSURING THE EFFICIENCY OF MECHANICAL PROCESSING DUE TO THE APPLICATION OF VIBRATION MONITORING AND VIBRATION PROTECTION MEANS

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The article describes the main causes and sources of impulse-vibration effects on the elements of the "machine tool – device - tool - detail" system. The paper deals with the development of methods for increasing the efficiency of machining due to the rational choice of technical solutions for vibration protection by design and technological methods with the use of vibration monitoring. A criterion for the efficiency of machining is given, which is determined by a matrix using scalar parameters, which are traditionally used for vibration diagnostics. A complex criterion for the quality of machining has been determined, which describes the indicators of the geometric accuracy of the machined surface. The block diagram of algorithms for selection and rational use of structural and technological methods of vibration protection of technological system elements is presented. Vibration and technological criteria for choosing solutions for vibration protection and monitoring are proposed. The implementation of the developed algorithms is considered on examples of machining and numerical estimates are given, confirming the high quality of the developed solutions.

Key words: vibration protection, vibration diagnostics, machining, monitoring, efficiency, reliability

INTRODUCTION

Ensuring the efficiency, reliability and safety of any technological, transport and power equipment requires the development and implementation of methods for studying processes that affect the technical condition of technical production facilities. Obviously, this is achieved by reducing the level of pulse-vibration effects by using vibration protection methods and devices, with an assessment of the technical condition based on the results of vibration monitoring, i.e. methods of test and functional diagnostics in order to identify equipment defects and control the permissible vibration level. The peculiarity of the requirements for vibration protection of technological equipment for machining is due not only to the requirements of reliability but also to the need for high efficiency of machining: quality, productivity, reducing energy consumption, ensuring the service life of its elements (tool durability), which are most significantly influenced by vibration effects. This specificity of the requirements lies in the fact that the technological system under consideration (Documental information search system - DISS) consists of the following elements: machine, fixture, tool, part (DISS), as well as vibration support installed on the foundation, the highly efficient operation of which is determined by many factors [1]. The main factors include the developed technological process, which includes the modes of machining, the geometry of the tool, and other parameters that are used depending on the required accuracy and productivity, the physical and mechanical properties of the part and the tool, the rigidity of the machine, the vibration activity of the above elements. An increased level of vibration not only reduces the service life and the reliability of its elements but also leads to a decrease in the quality of processing and a decrease in productivity, the efficiency of machining decreases, which is especially important in the machining of materials prone to hardening, such as titanium alloys, stainless steels, etc. The known methods of vibration monitoring using neural networks [2,3,4,5,6,7,8,9] have their limitations due to the complexity of physical and mechanical processes in the MDTD (machine-device-tool-detail) system (here it is necessary to decipher) during machining. The considered methods in the sources [10,11,12] to reduce the level of vibrations do not fully cover the arsenal of tools and methods. Developments in the field of vibration protection by "technological" methods are known by a number of authors [13,14,15,16], the disadvantages of these methods can also be noted in the complexity.

For the subsequent solution of vibration protection problems, we will single out two groups of such sources of pulse-vibration effects on the elements of the technological system, which reduce the reliability of operation and the efficiency of machining, which we will define by the terms: "external" and "internal" (Fig. 1).
The main causes and sources of impulse - vibration effects on MDTD elements

**Figure 1: The main causes and sources of impulse - vibration effects on MDTD elements**

**MATERIALS AND METHODS**

To solve these problems, the criteria for the effectiveness of machining and algorithms for its increase are considered, due to the implementation of design and technological methods of vibration protection from "external" and "internal" influences, as well as an algorithm for the reasonable choice of these methods of vibration protection. Difference from the existing approaches to the selection of criteria for the effectiveness of machining, based on the analysis of static parameters, the considered methodology includes the parameters of vibration function and test monitoring [17]. The generalized criterion required for highly efficient machining is fulfilled under the conditions:

\[ E_f = \left\{ K_d; \frac{1}{ZPTR_{to}}; t_{si}; 1/z_{to} \right\} \rightarrow \text{max} \]  

\[ K_d = \{ \delta_{lr}; \delta_{oup}; \delta_{form}; \delta_{wave}; \delta_r;HV_{det}; \text{hard} \} \]  

The comprehensive criterion for the quality of machining, including indicators of geometric accuracy:

- \( \delta_{lr} \) - the linear dimensions tolerance;
- \( \delta_{oup} \) - the tolerance to mutual positions (non-parallelism, non-parallelism, etc.);
- \( \delta_{form} \) - the tolerance for shape error (non-flatness, out-of-roundness, etc.); 
- \( \delta_{wave} \) - the tolerance for waviness (for finishing operations of machining, grinding, honing, polishing);
- \( \delta_r = R_0 \) is the roughness;
- physical-mechanical - quality characteristics:
  - HV_{det} - the microhardness;
- \( \Delta \text{hard} \) - the work hardening depth (\( \mu \text{m} \), etc.;

The productivity of machining, i.e. the volume of material removed per unit of time (revolution of the sizing tool or per tooth) [18]:

\[ P_m = \{ P(n, s, t, B) \} \]  

where \( n \) - spindle speed (rpm);
\( s \) - delivering (\( \text{mm} / \text{tooth} \));
\( t \) - depth (\( \text{mm} \));
\( B \) - milling width (\( \text{mm} \)).

\( Z_{to} \) - energy consumption during machining by the components of the cutting force \( P_z, P_y, P_x \), the cutting moment \( M_z \).

The costs of the adopted technical solutions of design and technological methods for reducing vibrations, expressed in time (hour) [19]:

\[ Z_{to} = \{ (t_{tl}; G_t; HCR_d; \delta_d; HCR_d; C_d; \Omega_i^*; CF; TSM) \} \]  

where \( t_{tl} \) - tool life time (or the number of passes, parts) at which machining takes place with the required quality;
\( t \) - cutting depth;
\( G_t \) - cutting tool geometry;
\( HCR_d \) - part hardness;
\( \sigma_d \) - tensile strength of the material of the part;
\( HCR_t \) - the hardness of the cutting edges of the tool;
\( C_d \) - tool stiffness;
\( C_t \) - rigidity of the part;
\( \Omega_i^* \) - resonant frequencies of the workpiece and tool;
\( CF \) - cutting fluid;
\( TSM \) - tool surface modifications.

The financial costs (rubels) for the adopted technical solutions of design and technological methods for reducing vibrations [20]:

\[ t_{f} = \{ (I; n; d; z; \alpha; \gamma; \omega) \} \]  

where \( I \) is the vibration parameter;
\( n \) - number of revolutions;
\( d \) – cutter diameter;
\( z \) – number of tool teeth;
\( \alpha \) – back angle;
\( \omega \) – helix angle.

Vibration monitoring parameters and criteria mean a set of data selected from a time signal in a steady state process using spectral masks (for example, in the frequency...
The criterion of efficiency of machining \( E_f \) is determined by the following criteria of vibration monitoring \( I \), given in matrices (by scalar parameters that are traditionally used for vibration diagnostics), characterizing dynamic processes in MDTD, from the analysis of which it can be concluded: repair is required or not required, replacement of MDTD element or technical solutions vibration protection. The data obtained during the measurement is entered into the database with the identifier corresponding to the given measurement.

2. The matrix of RMS values can be represented as:

\[
A_i = \begin{bmatrix} x_i & y_i & z_i \\ \dot{x}_i & \dot{y}_i & \dot{z}_i \\ \ddot{x}_i & \ddot{y}_i & \ddot{z}_i \end{bmatrix} = \begin{bmatrix} A_x \Sigma \\ A_y \Sigma \\ A_z \Sigma \end{bmatrix}
\]

where:

\[
A_x \Sigma = (A_{x_1} + A_{x_2} + A_{x_3})^{\frac{1}{2}}; A_y \Sigma = (A_{y_1} + A_{y_2} + A_{y_3})^{\frac{1}{2}}; A_z \Sigma = (A_{z_1} + A_{z_2} + A_{z_3})^{\frac{1}{2}}
\]

The recorded values of the parameters are further compared with the permissible values, standardized by ISO 10816-3-2002 or the permissible values obtained by the experimental method for the considered technological operation of machining from the database \([B_i]\):

\[
A_{pi \Sigma} < \left[ A_{pi \Sigma} \right]
\]

It should also be noted that measurements of vibration displacement, vibration velocity or vibration acceleration are performed depending on the frequency range.

3. Peak Factor Matrix \([22]\):

\[
P_i \leq \left[ P_i \right] \text{ or } ... P_i \rightarrow \min \quad (9)
\]

The ratio of the peak value of the measured \( i \)-th vibration parameter \( PI_{Ki} \) to its root-mean-square value RMSI obtained by measuring the parameters of vibration displacement, vibration velocity and vibration acceleration along the \( X, Y, Z \) coordinates for subsequent comparison:

\[
PI_{Ki} \leq \left[ RMSI \right] \text{ or } PI_{Ki} \rightarrow \min \quad (10)
\]

3. The kurtosis matrix in the case under consideration is a statistical quantity that characterizes not only the \( Ex_i \) value but also the change \( \Delta Ex_{ch} \) of the probability density of vibration signal values from the normal distribution (vibration displacements, vibration velocities and vibration accelerations along the \( X, Y, Z \) coordinates) or a distribution characterizing the "serviceable" state of the Exok element technological system. Excess, determined by dependence:

\[
Ex_i = \mu_4/\sigma^4 - 3 \leq \left[ Ex_{ch} \right] \text{ or } Ex \rightarrow \min \quad (12)
\]

where \( \mu_4 \) is the fourth central point; \( \sigma^4 \) is the variance of a random variable.

By changing the values of the distribution of vibration parameters, it is also possible to determine the degree of development of the defect.

---

1 - bed and base; 2 - work table; 3 - spindle; 4 - support; 5 - column; 6 - main drive; 7.1, 7.2, 7.3 - drives with SHVP cable along technological axes \( X, Y, Z \); guides along the technological axes \( X, Y, Z \): 8.1, 8.2, 8.3; devices: 9.1-machine tool, 9.2-tool; 10 - tool; 11 - detail; 12 - foundation; 13 - vibration mountings of the machine; 14.1, 15.2 - test impact simulators; 16 - platform for installing the foundation (or vibration support) on the ground.

---

**Figure 2: Comprehensive technological chart of vibration control of the vehicle and control points of vibration measurements along the technological axes \( X, Y, Z \) on the elements: machine**
4. The matrix of natural frequencies of the system, determined from the integrated technological chart of vibration control of the technological system and control points of vibration measurements along the technological axes X, Y, Z:

\[ \Omega_i^* = \begin{bmatrix} \Omega_{x_i}^* & \Omega_{y_i}^* & \Omega_{z_i}^* \\ \Omega_{x_i}^* & \Omega_{y_i}^* & \Omega_{z_i}^* \\ \Omega_{x_i}^* & \Omega_{y_i}^* & \Omega_{z_i}^* \end{bmatrix} \]  

(15)

\[ \Omega_i^* = \left(\frac{c_i}{m_i}\right)^{0.5} \]  

(16)

natural frequencies of the i-th element (Fig. 2) (rad / s).

In this case, one of the conditions necessary to minimize vibration-impulse effects on the elements of MDTD (machine tool – device – tool - detail):

\[ \Omega_i^* \neq \omega_i \]  

(17)

where \( \omega_i \) - excitation frequencies due to external or internal causes (rad / s).

5. Constant components of forces \( F_P \) and moments arising during machining \( M_z \), respectively, along the technological axes X, Y, Z:

\[ F_f = \{ P_O(n; s; t)G_t(d; z; \alpha; \gamma; \omega; CF; TSM) \} \]  

(18)

\[ F_f = \{ M_z(n; s; t)G_t(d; z; \alpha; \gamma; \omega; CF; TSM) \} \]  

(19)

The specified parameters in dependencies (18) and (19) in this case determine the energy consumption of \( Z_t \) per operation in the criteria for the efficiency of machining in (1).

6. Corresponding dynamic components of cutting forces or torque [22]:

\[ F_{\Delta z} = \Delta M_z \text{ determines } F_{\Delta M} = \{ P_O(n; s; t)G_t(d; z; \alpha; \gamma; \omega; CF; TSM) \} \text{ determines} \]  

\[ F_{\Delta F} = \{ \Delta F_x; \Delta F_y; \Delta F_z \} \]  

(20)

\[ F_{\Delta z} = \Delta M_z \text{ determines } F_{\Delta M} = \{ P_O(n; s; t)G_t(d; z; \alpha; \gamma; \omega; CF; TSM) \} \text{ determines} \]  

\[ F_{\Delta F} = \{ \Delta F_x; \Delta F_y; \Delta F_z \} \]  

(21)

All the above parameters I are entered into the database [B] with the corresponding identifiers:

\[ [B_i] \equiv [A_i; \Omega_i^*; P_i; F_{nz}; \Delta M_{z_i}^*] \]  

(22)

where \( A_i \) – amplitude (formula 5);

\[ \Omega_i^* \] - resonant frequencies of the workpiece and tool;

\[ P_i \] – peak - factor;

\( F_{nz} \) – constant component of the cutting force;

\( \Delta M_{z_i}^* \) - dynamic component of the moment.

To implement technological methods of vibration protection, it is necessary to experimentally reveal the correlation between the functional multifactorial dependences \( F_m(j) \) and the parameters of vibration monitoring \( I \):

\[ F_{Mo} = \{ n; sz; B; t \} \]  

(23)

where \( n \) is the number of revolutions of the spindle, rpm;

\( sz \) – feed, mm / tooth or - mm / rev;

\( B \) - milling width, mm;

\( t \) - cutting depth, mm, etc.

7. The parameters of the coolant, the method of supplying liquid (gas) to the cutting zone is determined by the formula:

\[ F_{CF} = \{ CF; Q; t_{CF}; q \} \]  

(24)

where \( CF \) – cutting fluid

\( Q \) – consumption of its physical parameters, (m3/s);

\( t_{CF} \) – temperature, °C;

\( q \) – thermal conductivity, W/(mK).

The geometric parameters of the tool are determined by the formula:

\[ F_G = \{ d; z; \alpha_t; \gamma_t; \omega_t \} \]  

(25)

where \( d \) - cutter diameter (or workpiece);

\( z \) - number of teeth

\( \gamma_t \) - rake angle;

\( \alpha_t \) - back angle;

\( \omega_t \) - the angle of ascent of the spiral cutter (or other tool).

Parameters of the modified surface of the tool, achieved by spraying or other methods:

\[ F_{ml} = \{ t_{ml}; \sigma_{ml} \} \]  

(26)

where \( t_{ml} \) - modified layer thickness

\( \sigma_{ml} \) - physical and mechanical properties of the modifying material, etc. Dimensionless damping coefficient in the manufacture of elements of a technological system with increased damping properties by additive technologies:

\[ \epsilon_i = \frac{b_i}{\sqrt{2m_i \cdot c_i}} \]  

(27)

where \( b_i \) – is the coefficient of friction of the i-th element;

\( m_i \) – is the reduced mass of the i-th element;

\( c_i \) - is reduced stiffness of the i-th element.
Thus, due to the rational change of these factors, it is necessary that the value of the generalized criterion for highly efficient machining, expressed by dependence (1), be the maximum $E_f \rightarrow \max$ at the minimum vibration level $l \rightarrow \min$. For the rational use and selection of methods for structural and technological methods of vibration protection of MDTD elements based on the results of functional and test vibration monitoring, an algorithm is needed that can significantly reduce the cost of implementing these technical solutions, for use in the development of a technical process or an adaptive control program with a CNC machine tool. The block diagram of the algorithm for the selection and rational use of structural and technological methods of vibration protection of the elements of the technological system is shown in Fig. 3 and has 2 sections:

1. section of vibration monitoring, which considers the sequence of actions for detecting the causes and places of occurrence, increased pulse-vibration effects on MDTD elements using the functional and test method;

2. section of vibration protection, which considers the sequence of actions for the justified use of structural and technological methods.

The vibration monitoring section displays an algorithm of actions for detecting the causes and places of occurrence, increased impulse-vibration effects on MDTD elements occur in sequence. On the operating modes of the technological equipment - the machine tool Block 1 determines the main operating modes of the technological equipment (machine tool): 1-1) with disconnected drives and other mechanisms - to detect the causes and sources of "external" impulse - vibration effects of parameters; 1-2) idle - without machining, to detect defects in bearings, ball screws, guides or other bearing elements of the machine, geometric and kinematic accuracy, etc. 1-3) work in specified modes of machining according to the experimental plan - for determination of rational modes in which the vibration level is minimal and (or) does not exceed the permissible, which meets the requirements of highly efficient machining, to detect the causes and other sources of "internal" impulse - vibration effects (Fig. 3). Block 2 is necessary for the implementation of vibration monitoring in accordance with the technological chart of vibration control of the technological system (see Fig. 3), i.e. determination of vibration measurement points along technological axes $X$, $Y$, $Z$. These are the places of installation of sensors on the elements of the vehicle, which are assigned depending on the tasks of the operational tasks of vibration monitoring. Elements of the technological system, the parameters of which are subject to control in static and dynamic modes using control sensors (block 3). These are vibration parameters, vibration acceleration, vibration velocity, vibration displacement, or static and dynamic components of force, moment, etc., which are measured by appropriate sensors. Block 4 of measurement and coordination of primary measurement information is used for data from sensors [23].

Block 5 database is required to store the received data. The database may also contain information on the permissible vibration levels, as well as permissible values, standardized by regulatory documents or accepted based on the results of experimental studies. In block 6 for analysis and selection of controlled criteria, the necessary algorithms for processing signals from sensors are set, i.e. what parameters or their combination should be analyzed to identify defects in the elements (nodes) of MDTD, which consists in the allocation of controlled frequency ranges and signal levels from sensors measuring different physical quantities and characteristics, as well as the possibility of expanding such criteria. In block 7, from the analysis of the information received and the selection of controlled criteria, on the basis of which decisions are made $l \geq [B]_i$:

1. $l_1 = 1$ - repair (replacement) of an element of the technological system and the use of vibration protection methods are required (block 9);

2. $l_1 = 0$ - no repair (replacement) of a technological system element or application of vibration protection methods is required (block 8).

Block 10 is required to determine the main sources of pulse-vibration effects that reduce the efficiency of machining, which may arise as a result of "internal" or "external" influences. In block 11, the selection of "internal" or "external" influences is carried out when the drives and other mechanisms of the MDTD system are disconnected - to detect the causes and sources of "external" impulse - vibration effects, i.e. not included in the MDTD system, but located in the immediate vicinity of the technological system (press, hammer, and other technological equipment operating in dynamic modes). - when the drives are switched off (mode 1-1) $l \geq [B]_i$, on the basis of which decisions are made: - it is necessary to control "external" influences, which are caused by sources of pulse-vibration, etc. (Fig. 3) and requires a mandatory (unconditional) transition to structural methods of vibration protection, the use of structural methods of vibration protection, consisting of:

1. in the application of vibration-damping supports of technological equipment (machine tools) or checking their defects or the foundation (VDEM block 22.1);

2. elimination of vibration in the source by installing a vibration damper (VSVD block 22.2) [23,24];

$I_2=0$ - it is necessary to control the "internal" influences, which requires a transition to block 12. Block 13 is required to determine the level of vibration at idle, i.e. caused by electromechanical defects in machine gears, device elements, tools, etc. (mode 1-2). Block 13 is necessary to correct the installation location of the control sensors and the criteria for determining the state of the drives and reduce the likelihood of taking, inadequate measures for the application of vibration protection methods, depending on the factors: - 13.1) for the analysis of the signal and technical characteristics of the sensor (measurement of vibration acceleration, vibration
Figure 3: Block diagram of the algorithm for the selection and rational use of structural and technological methods of vibration protection of vehicle elements in order to increase the efficiency of machining based on the results of functional and test vibration monitoring (lj-bits of information)
velocity, vibration displacement, etc.): - 13.2) changes in the sensor installation location along the measurement route; - 13.3) signal processing algorithms (such as filters, extraction, rms values of the peak signal level, etc.); - 13.4) requirements - useful signal / noise. A comparison of I ≥ [B_i] is made, based on which decisions are made: - I4 = 1 - it is necessary to correct the installation locations of the monitoring sensors and move to block 2; - I4 = 0 - it is necessary to go to block 6, analysis of monitored parameters and criteria for determining the defects of drives, bearings, ball-and-socket gear and other elements. Block 14-required for decision-making:
1. change of operating modes (block 15: 1-1) - with disconnected drives and other mechanisms of the MTD system; 1-2) - idle; 1-3) - work in the specific modes of machining according to the experimental plan;
2. entering information into the database (block 5);
3. making decisions on the method of vibration protection (block 20) [25].

Block 16 is used to eliminate accidental or contradictory information, on the basis of which decisions are made: - I2 = 1 - the sufficiency of information for the application of the method of functional vibration monitoring and the transition to the decision block 14; - I2 = 0 - a test vibration monitoring monitoring method is required (block 18); Block 17 is used as a functional vibration monitoring of vibration levels during machining (mode 1-3). Block 18 - test vibration monitoring is necessary to identify hidden defects that cannot be detected by a functional method. Block 19 is used to select the required test action simulator device for influencing the elements of the technological system of a test power or kinematic pulse-vibration excitation with specified parameters [25]. The vibration protection section displays an algorithm of actions to reduce the level of impulse-vibration effects on MTDT elements. Block 20 is used to determine vibration protection methods for making decisions: - I5 = 1 - application of the technological method, because according to the Zto criterion - the costs of the adopted technical solutions of design and technological methods of vibration reduction are minimal, see formula (1). An exception is a need for vibration isolation from "external" vibration sources. Technological methods are understood as technical solutions for vibration protection of a technological system, which consist in changing the dynamic parameters of forces caused by the cutting process to significantly reduce their level, to increase the efficiency of machining, which consists in applying the following measures:
1. correction of machining modes (CMM block 21.1);
2. rational choice of cutting fluid (RCCF block 21.2)
3. tool geometry correction (TGC block 21.3) [23];
4. modification of the surface of the tool, achieved by spraying or other methods (TSM block 21.4);
5. manufacturing of elements of a technological system by the method of additive technology (AT block 21.5) [23-25], which means the manufacture of tools, fixtures and other technological elements with increased damping properties, as well as other solutions.

It should be especially noted that the correction of the machining modes (CMM block 21.1) and the change of COTS (RCCF block 21.2) can be used not only in the development of the technical process, but also directly for the adaptive control of CNC machines. - I5 = 0 - application of the constructive method. Structural methods are understood as [25-27] technical solutions consisting in the use of vibration dampers that reduce the vibration activity of the elements of the technological system, the introduction of additional elements into its structure, through the use of the following devices. Vibration protection devices from "external" influences, (VDEM block 22.1) or (VSVD block 22.2), the use of which was discussed earlier [27]; vibration dampers of viscous friction (lunettes) (VFVD block 22.3); vibration dampers for the movable unit of the machine tool (VPU block 22.4) dynamic vibration dampers (DVD block 22.5) shock vibration dampers (STVD block 22.6) [28]; vibration dampers autobalancing (SVD block22.7) If necessary, it is possible to use combined methods - technical solutions, which consist in a combination of technological and structural methods of vibration protection. Block 23 is used to analyze vibration levels after applying the selected technical solution and its effectiveness based on the results of vibration monitoring I ≤ [B_i]: - I6 = 1 - the application of the selected technical solution turned out to be effective and (measures for vibration protection are no longer required transition to block 8); - I6 = 0 - the application of the selected technical solution turned out to be ineffective and a transition to block 15 is required (block for making decisions on changing the vibration protection method or technical solution, as well as stopping when the tool is worn out (broken) and replacing it.

**FINDINGS**

Aggregates of vibration I ≤ [B_i], generalized technological criteria for the efficiency of machining Ef → max and decisions made for vibration protection methods based on the results of test or functional vibration monitoring, which are introduced as additional ones in the design of the technological process and the operation of technological equipment. Algorithms or logical conditions for the analysis of the set of technical and technological criteria for decisions made and the choice of rational methods of vibration protection are given in Table 1. Thus, the methodology in the field of improving the methods of vibration protection of the elements for the technological system is considered, it makes it possible to apply design and technological methods of vibration protection based on the results of test and functional vibration monitoring according to scientifically grounded criteria, which ensures an increase in the efficiency of machining and reliability.
Table 1: Proposed vibration and technological criteria for choosing solutions for vibration protection and monitoring

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<td>3. System software</td>
<td>System software</td>
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<td>(5, 6, 7, 15) number of formula</td>
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<td>$l_1 \cap l_2 \cap l_6$, where $l_1 = 1; l_2 = 1; l_6 = 1$</td>
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<td>2.</td>
<td>test monitoring</td>
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<table>
<thead>
<tr>
<th>&quot;Internal&quot; impacts due to machining</th>
<th>1.41</th>
<th>(23) formula</th>
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<tbody>
<tr>
<td></td>
<td>1.42</td>
<td>(24) formula</td>
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<td>1.43</td>
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<td>1.44</td>
<td>(26) formula</td>
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<td>1.45</td>
<td>(27) formula</td>
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<tr>
<th>Functional method</th>
<th>determination of geometric indicators and physical and mechanical characteristics of the quality of machining (HRC, HV, Ra)</th>
<th>Improve machining quality, productivity and tool life while minimizing implementation costs Zto</th>
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<tbody>
<tr>
<td>Kistler dynamometer; K-5101+System software: &quot;Vibration register-lor&quot;, &quot;LOGGER&quot;</td>
<td>System software</td>
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</table>

| 1.41 | block 21.1 CMM |
| 1.42 | block 21.2 RCCM |
| 1.43 | block |
| 21.3 TGC |
| 1.44 | block 21.4 TSM |
| 1.45 | block 21.5 AT |
### CONCLUSIONS

The implementation of the developed algorithms is considered on examples of machining and numerical estimates are given, confirming the high quality of the developed solutions.

1. The implementation of the software made it possible to create a method for selecting the optimal machining modes to reduce the vibration of parts, as well as a method for selecting the optimal tool geometry, which increases productivity by at least 1.5 times, i.e., increasing the efficiency of machining and the reliability of technological equipment [29].

2. The developed methods and algorithms for increasing the efficiency of machining due to the rational choice of structural methods of vibration protection, achieved by using vibration dampers with elastic-inertial and dissipative parameters, based on the results of monitoring in a wide range of "external" and "internal" influences and devices for their implementation. The use of these devices made it possible to: - reduce tool consumption by 30%; - reduce the level of vibrations on the workpiece by 36 dB and thereby increased the quality of processing and the tool life time by 1.25 - 1.3 times.

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