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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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Key words: *vibration protection, vibration diagnostics, machining, monitoring, efficiency, reliability*
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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 efficien , 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 efficienc 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 efficien 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 efficienc 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 efficienc of machining, which we will define by the terms: "external" and "internal" (Fig. 1).

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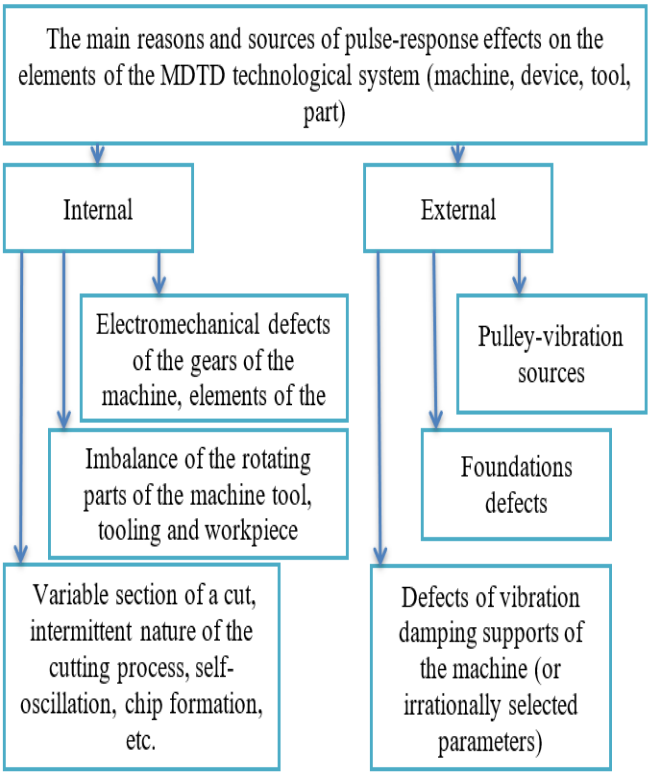

Figure 1: The main causes and sources of impulse - vibration effects on MDTD elements

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. Differ nce 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 efficien machining is fulfilled under the conditions:

$$E_f = \left\{K_d; Pr_{st}; \frac{1}{ZPTR_{to}}; t_{si}; 1/z_{to}\right\} \rightarrow \max \quad (1)$$

$$K_d = \left\{\delta_{ir}; \delta_{oup}; \delta_{form}; \delta_{wave}; \delta_r; HV_{det}; \Delta_{hard}; \ldots\right\} \quad (2)$$

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

- δ_{lr} - the linear dimensions tolerance;

- δ_{oup} - the tolerance to mutual positions (non-perpendicularity, non-parallelism, etc.);

- δ_{form} - the tolerance for shape error (non-flatness, out-of-roundness, etc.);

- δ_{wave} - the tolerance for waviness (for finishing operations of machining, grinding, honing, polishing);

- $\delta_r = R_z$ (R_a) is the roughness;

physical-mechanical - quality characteristics:

- HVdet - the microhardness;

-Δhard - the work hardening depth (μm), 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]:

$$P_m = \{P(n, s, t, B)\} \quad (3)$$

where n - spindle speed (rpm);

s - delivering (mm / tooth);

t - depth (mm);

B - milling width (mm).

Z_{to} - energy consumption during machining by the components of the cutting force Pz, Py, Px, the cutting moment Mz.

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

$$Z_{to} = \{(t_{tl}; G_t; HCR_d; \delta_d; HCR_d; C_d; C_t; \Omega_i^*; CF; TSM\} \quad (4)$$

where t_{lt} - tool life time (or the number of passes, parts) at which machining takes place with the required quality;

t - cutting depth;

Gt - cutting tool geometry;

HRCd - part hardness;

σd - tensile strength of the material of the part;

HRCt - the hardness of the cutting edges of the tool;

C_d - rigidity of the part;

C_t - tool stiffness;

Ω^*_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]:

$$t_{f=}\{(I; n; d; z; \alpha; \gamma; \omega)\} \quad (5)$$

where I is the vibration parameter;

n - number of revolutions;

d – cutter diameter;

z – number of tool teeth;

α – back angle;

ω – 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 ranges: reverse, cog, resonant elements MDTD), measured at the i-point in accordance with the integrated technological map of vibration control, shown in Fig.2. on the example of a milling machine [21].

1. The criterion of efficienc of machining Ef 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:

$$A_i = \begin{bmatrix} x_i & y_i & z_i \\ \dot{x}_i & \dot{y}_i & \dot{z}_i \\ \ddot{x}_i & \ddot{y}_i & \ddot{z}_i \end{bmatrix} = \begin{bmatrix} A_\Sigma \\ \dot{A}_\Sigma \\ \ddot{A}_\Sigma \end{bmatrix} \quad (6)$$

where:

$$A_{i\Sigma} = \left(A_{ix}^2 + A_{iy}^2 + A_{iz}^2\right)^{0,5};\ \dot{A}_{i\Sigma} = \left(\dot{A}_{ix}^2 + \dot{A}_{iy}^2 + \dot{A}_{iz}^2\right)^{0,5};\ \ddot{A}_{i\Sigma} = \left(\ddot{A}_{ix}^2 + \ddot{A}_{iy}^2 + \ddot{A}_{iz}^2\right)^{0,5} \quad (7)$$

where $A_{ix}, A_{iy}, A_{iz}; \dot{A}_{ix}, \dot{A}_{iy}, \dot{A}_{iz}; \ddot{A}_{ix}, \ddot{A}_{iy}, \ddot{A}_{iz}$; are respectively the measured values of the root-mean-square values of vibration displacement, vibration velocity and vibration acceleration along the X, Y, Z coordinates.

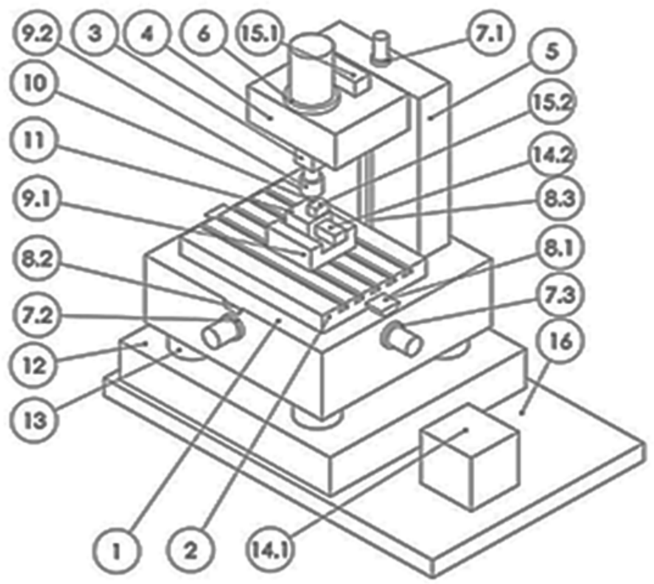

Figure 2: Comprehensive technological chart of vibration control of the vehicle and control points of vibration measurements along the technological axes X, Y, Z on the elements: machine

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, 14.2 - vibration damping devices; 15.1, 15.2 - test impact simulators; 16 - platform for installing the foundation (or vibration support) on the ground

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 [Bi]:

$$A_{pi\,\Sigma} < \left[A_{pi\,\Sigma}\right] \quad (8)$$

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]:

$$Pi \leq [Pi] \text{ or } \ldots Pi \rightarrow \min \quad (9)$$

The ratio of the peak value of the measured i-th vibration parameter PIKI 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:

$$PIKI \leq [PMSI] \text{ or } PIKI \rightarrow \min \quad (10)$$

$$P_i = \begin{bmatrix} P_{xi} & P_{yi} & P_{zi} \\ P_{\dot{x}_i} & P_{\dot{y}i} & P_{\dot{z}i} \\ P_{\ddot{x}i} & P_{\ddot{y}i} & P_{\ddot{z}i} \end{bmatrix} \quad (11)$$

3. The kurtosis matrix in the case under consideration is a statistical quantity that characterizes not only the Exi value but also the change ΔExch 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:

$$Exi = \mu 4/\sigma^4 - 3 \leq [Exch] \text{ or } Ex \rightarrow \min \quad (12)$$

where μ_4 is the fourth central point;

σ^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:

$$E_{xi} = \begin{bmatrix} E_{xi} & E_{yi} & E_{zi} \\ E_{\dot{x}_i} & E_{\dot{y}i} & E_{\dot{z}i} \\ E_{\ddot{x}i} & E_{\ddot{y}i} & E_{\ddot{z}i} \end{bmatrix} \quad (13)$$

Exok = Exich ± ΔExi (14)

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:

$$\Omega*_i = \begin{bmatrix} \Omega*_{xi} & \Omega*_{yi} & \Omega*_{zi} \\ \Omega*_{\dot{x}i} & \Omega*_{\dot{y}i} & \Omega*_{\dot{z}i} \\ \Omega*_{\ddot{x}i} & \Omega*_{\ddot{y}i} & \Omega*_{\ddot{z}i} \end{bmatrix} \quad (15)$$

$$\Omega*_i = ({}^{c_i}\!/_{m_i})^{0.5} \quad (16)$$

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):

$$\Omega*_i \neq \omega_i \quad (17)$$

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

5. Constant components of forces PO and moments arising during machining Mz, respectively, along the technological axes X, Y, Z:

Ff = {PO(n; s; t)Gt(d; z; α; γ; ω; CF; TSM} (18)

Ff = {Mz(n; s; t)Gt(d; z; α; γ; ω; CF; TSM} (19)

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

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

FΔz = ΔMz determines FΔM = {PO(n; s; t)Gt(d; z; α; γ; ω; CF; TSM} determines

ΔF = (ΔFx; ΔFy; ΔFz) (20)

FΔz = ΔMz determines FΔM = {PO(n; s; t)Gt(d; z; α; γ; ω; CF; TSM} (21)

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

$$[B_i] \equiv [A_i; \Omega_i^*; P_i; F_{nz}; \Delta M_{z*}] \quad (22)$$

where Ai – amplitude (formula 5);

$\Omega*_i$ - resonant frequencies of the workpiece and tool;

Pi – peak - factor;

Fnz – constant component of the cutting force;

ΔMz* - 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 Fm (j) and the parameters of vibration monitoring I:

FMo = {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:

FCF = {CF; Q; tCF; q} (24)

where CF – cutting fluid

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

tCF – temperature, ˚C;

q – thermal conductivity, W/(mK).

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

FG = {d; z; αt; γt; ωt} (25)

where d - cutter diameter (or workpiece);

z - number of teeth

γt - rake angle;

αt - back angle;

ωt - 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:

$$F_{ml} = \{t_{ml}; \sigma_{ml}\} \quad (26)$$

where t_{ml} - modified layer thickness

σml - physical and mechanical properties of the modifying material, etc. Dimensionless damping coefficien in the manufacture of elements of a technological system with increased damping properties by additive technologies:

$$\varepsilon_i = \frac{b_i}{\sqrt{2m_i \cdot c_i}} \quad (27)$$

where b_i – is the coefficien 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 elemen

Thus, due to the rational change of these factors, it is necessary that the value of the generalized criterion for highly efficien machining, expressed by dependence (1), be the maximum Ef → max at the minimum vibration level I → 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 efficien 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 I ≥ [Bi]:

1. I1=1 - repair (replacement) of an element of the technological system and the use of vibration protection methods are required (block 9);
2. I1 = 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 efficienc 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) I ≥ [Bi], 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];

I2=0 - it is necessary to control the "internal" influen - es, 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 lkelihood of taking, inadequate measures for the application of vibration protection methods, depending on the factors: - 13.1) required for the analysis of the signal and technical characteristics of the sensor (measurement of vibration acceleration, vibration

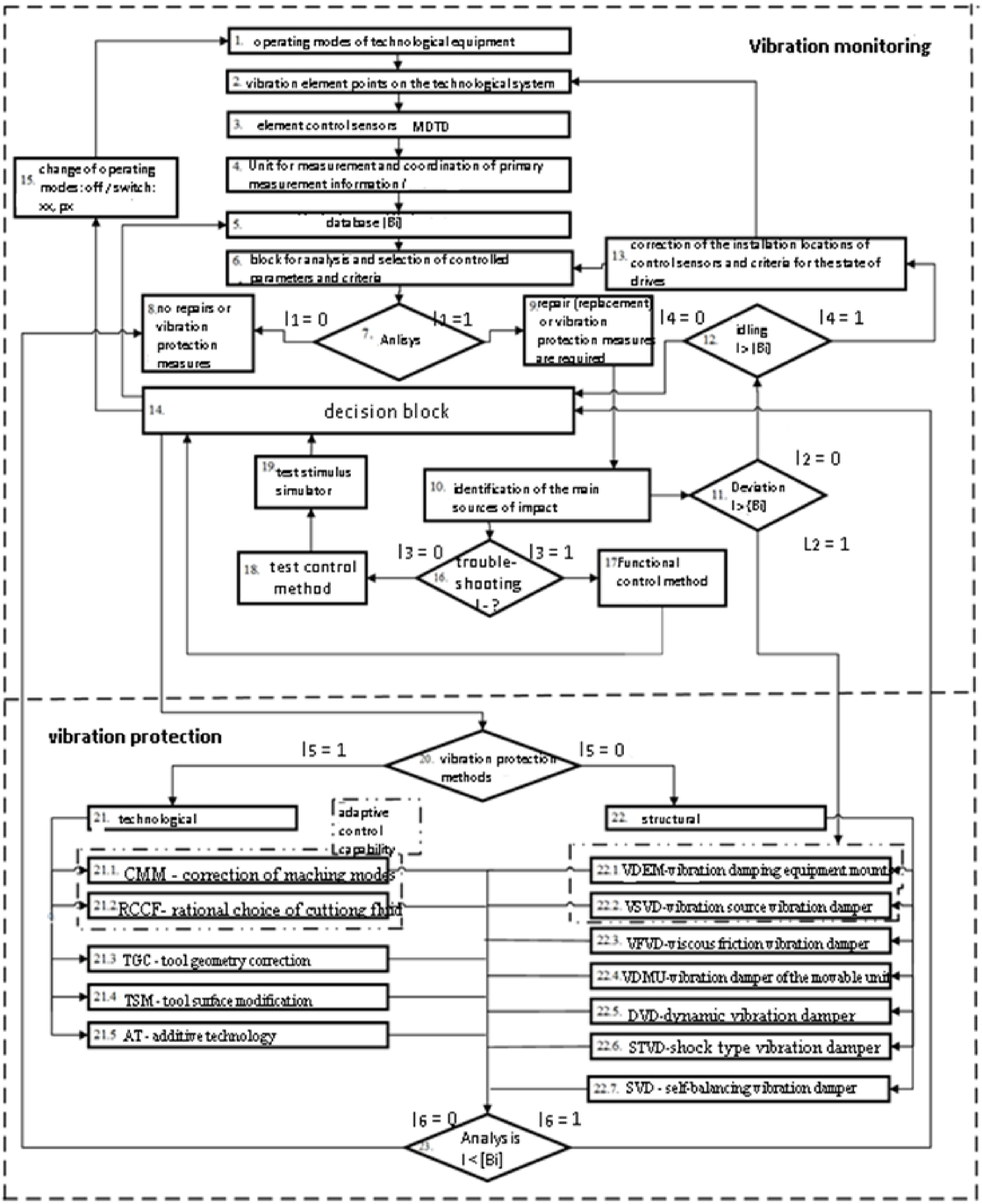

Figure 3: Block diagram of the algorithm for the selection and rational use of structural and technological methods of vibration protection of vehicle elements in order to increase the efficiency of machining based on the results of functional and test vibration monitoring (Ij-bits of information)

velocity, vibration displacement, etc.); - 13.2) changes in the sensor installation location along the measurement route; - 13.3) signal processing algorithms (such as fi - ters, extraction, rms values of the peak signal level, etc.);

- 13.4) requirements - useful signal / noise. A comparison of I ≥ [Bi] is made, based on of 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 MDTD system; 1-2) - idle; 1-3) - work in the specifie 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 ambiguous or contradictory information, on the basis of which decisions are made: - I2 = 1 - the sufficienc 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 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 MDTD 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 efficienc 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 constructional 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 effectivenes based on the results of vibration monitoring I ≤ [Bi]: - 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 ≤ [Bi], generalized technological criteria for the efficienc 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 reliabili .

Table 1: Proposed vibration and technological criteria for choosing solutions for vibration protection and monitoring

<table>
<tr><td rowspan="4">The reason for the need for vibration protection (Fig.1)</td><td rowspan="4">Terms of use</td><td colspan="3">Verifiable criteria, monitoring and analysis methods</td><td rowspan="4">Achieved result</td><td rowspan="4">Recommended technical solution and vibration protection methods</td></tr>
<tr><td colspan="2">1.Vibration criteria I ≤ [Bi]
the effectiveness of v - bration protection based on the results of monitoring by dependencies</td><td>1.Technological criteria for the efficiency of - chining
Ef → max
by dependencies</td></tr>
<tr><td colspan="2">2. Vibration monitoring methods</td><td>2. Devices</td></tr>
<tr><td colspan="2">3. used by system software for analysis</td><td>3. System software</td></tr>
<tr><td rowspan="3">"External" influence</td><td rowspan="3">I1∩I2∩I6, where I1 = 1; I2 = 1; I6 = 1</td><td>1.</td><td>(5, 6, 7, 15)
number of formula</td><td>Cd; Tlt;
Zto→min;
If Zto {block 22.1VDEM<Z-to[block 22.2 VSVD]</td><td>Improving the quality of processing and tool life</td><td>Structural:
block 22.1.VDME
block 22.2VSVD</td></tr>
<tr><td>2.</td><td>Functional method</td><td>determination of geometric indicators of the quality of machining: material utilization rate</td><td rowspan="2"></td><td rowspan="2"></td></tr>
<tr><td>3.</td><td>System software: "Diamant", "VAST", "bearing", etc." K-5101+ System software: «Vibration recorder»; «LOGGER»</td><td>System software</td></tr>
<tr><td rowspan="3">"Internal" infl - ences caused by defects in machine elements</td><td rowspan="2">I1∩ I3 ∩ I5 ∩ I6, where I1 = 1; I2 =</td><td>1.</td><td>(5, 6, 7, 15)</td><td>Cd; tlt</td><td rowspan="2">Improved machining quality, productivity and tool life.</td><td rowspan="2">Replacement or repair of an item block 13 → Block 9</td></tr>
<tr><td>2.</td><td>Functional method</td><td>Determination of geometric indicators of the quality of machining</td></tr>
<tr><td>1;I5 =1; I6 = 1</td><td>3.</td><td>System software: "Diamant", "VAST", "bearing", etc. " Vibration recorder»</td><td>System software</td><td></td><td></td></tr>
</table>

Methods for test monitoring of technological system elements using a test stimulus simulator	I1∩ I3, where I1 = 1; I3 = 1	1.	(5, 6, 7, 15) number of formula		Revealing hidden defects that cannot be detected by a functional method.	Replacement or repair of MDTD element block 19 CTB → block 9
		2.	test monitoring			
		3.	System software: "Diamant", "VAST", programs "bearing", etc. K-5101+System software: "Vibration register-tor"; " LOGGER»			
"Internal" impacts due to machining	I1∩ I3 ∩ I5 ∩ I6, where I1 = 1; I2 = 1;I5 =1; I6 = 1	1.41	(23) formula	Cd; tlt	Improve machining quality, productivity and tool life while minimizing implementation costs Zto	technological methods: 1.41) block 21.1 CMM 1.42) block 21.2 RCCM
		1.42	(24) formula			
		1.43	(25) formula			
		1.44	(26) formula			
		1.45	(27) formula			
			Functional method	determination of geometric indicators and physical and mechanical characteristics of the quality of machining (HRC, HV, Ra)		
			Kistler dynamometer; K-5101+System software: "Vibration register", " LOGGER»	System software		1.42) block 21.2 RCCM
						1.43) block
						21.3 TGC
						1.44) block 21.4 TSM
						1.45) block 21.5 AT

<table>
<tr><td rowspan="8">"Internal" infl-ences caused by defects in machine elements</td><td rowspan="8">$I1 \cap I3 \cap I5 \cap I6$, where $I1 = 1$; $I2 = 1$; $I5 = 1$; $I6 = 1$</td><td>1.51</td><td>(5, 6, 7, 15) number of formula</td><td rowspan="5">Cd; tlt</td><td rowspan="8">Improving machining quality, productivity and tool life</td><td rowspan="5">constructional methods:
1.51) block 22.3.BBT</td></tr>
<tr><td>1.52</td><td>(5, 6, 7, 15) number of formula</td></tr>
<tr><td>1.53</td><td>(5, 6, 7, 15) number of formula</td></tr>
<tr><td>1.54</td><td>(5, 6, 7, 15) number of formula</td></tr>
<tr><td>1.55</td><td>(5, 6, 7, 15) number of formula</td></tr>
<tr><td></td><td rowspan="2">functional and test monitoring</td><td rowspan="2">determination of geometric indicators of the quality of machining: material utilization rate; physical and mechanical characteristics of the quality of mechanical processing Duramin-5 microhardness meter</td><td>1.52) block 22.4. VDMU the application requires an analysis of energy costs</td></tr>
<tr><td></td><td>1.53) block 22.5. VAB</td></tr>
<tr><td colspan="2">Kistler dynamometer; K-5101+System software: "Vibration register", " LOGGER»</td><td>System software</td><td>1.54) block 22.6. STDV</td></tr>
</table>

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 efficienc of machining and the reliability of technological equipment [29].
2. The developed methods and algorithms for increasing the efficienc of machining due to the rational choice of technical solutions for vibration protection by technological methods. The proposed technical solutions allow: to significantly increase the efficiency of machining, by reducing the level of vibration-impulse effects on the elements of technological equipment, which increases productivity by 1.5 - 2 times, and also to reduce tool consumption by 30%.
3. The developed methods and algorithms for increasing the efficienc 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" influ nces "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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REFERENCES

1. Gavrilin, A., Moyzes, B., Zharkevich, O., (2015). Constructive and processing methods of reducing vibration level of the metalworking machinery elements. Journal of Vibroengineering, 17(7), 3495–35047.
2. Sinitsa, M.O., Komshin, A.S., (2020). Development of a control system for large-sized products to improve product quality in mechanical engineering // IOP Conference Series Materials Science and Engineering, 971:022057 DOI:10.1088/1757-899X/971/2/022057
3. F (2017). The use of measuring phase-chronometric systems in the production of cyclic aggregates of aircraft. MATEC Web of Conferences, 129, 01048. DOI: 10.1051/matecconf/201712901048
4. Kransutskaya, A., Syritskii A., Tumakova E., Boldasov D., (2019). The study on external influenc on the phasechronometric profile of asynchronous electric motors IOP Conf. Series: Materials Science and Engineering, 489, 012019 DOI:10.1088/1757-899X/489/1/012019
5. Pozdnyakova, E.D., Maslennikova, E.V., Komshin, A.S., Orlova, S.R. Measuring control of construction materials parameters in order to increase reliability of engineering objects. IOP Conference Series: Materials Science and Engineering, 2019, 489(1), 012008 DOI:10.1088/1757-899X/489/1/012008
6. Komshin A.S., Potapov K.G., Syritsky A.B., Fomin A.E., (2020). Monitoring system of hydro and wind power equipment based on intelligent measuring complexes and neurodiagnostics. IOP Conference Series Materials Science and Engineering, 971(2):022055 DOI:10.1088/1757-899X/971/2/022055
7. Boldasov, D.D., Drozdova, J.V., Komshin, A.S., Syritskii A.B., (2020). Neural Network Application for Phasechronometric Measurement Information Processing. Measurement Techniques, 63(9), 708–712. DOI:10.1007/s11018-021-01843-2
8. Azmi, A.I. (2015) Monitoring of tool wear using measured machining forces and neuro-fuzzy modelling approaches during machining of GFRP composites. Advances in Engineering Software, 82, 53-64. DOI:10.1016/j.advengsoft.2014.12.010
9. Proteau, A., Tahan, A., Thomas, M. (2019). Specifi cutting energy: a physical measurement for representing tool wear. International Journal of Advanced Manufacturing Technology, 103 (1-4), 101-110. DOI:10.1007/s00170-019-03533-4
10. Kaliński K., Stawicka-Morawska, N., Galewski M., Mazur, M., (2021). A method of predicting the best conditions for large-size workpiece clamping to reduce vibration in the face milling process. Scientifi Reports 11(1) DOI:10.1038/s41598-021-00128-6
11. Bolsunovsky S.A., Vermel V.D., Gubanov G.A., Kacharava I.N., Leontiev A.E., (2013). Computational and experimental evaluation of rational technological parameters of high-performance milling as part of an automated system for technological preparation of the production of aerodynamic models of aircraft. Izvestia of the Samara Scientific Center of the Russian Academy of Sciences, 11, 23 – 26.
12. Bolsunovsky, S.A., Vermel, V.D., (2009). Methodology and technical equipment for evaluating the vibration characteristics of the system "machine - device - tool- detail" in the process of high-speed milling // Scientific and technical report of TsAGI 2008: Sat. articles: Central Aerohydrodynamic Institute. Zhukovsky, 100.
13. Aleinikov D.P., Lukyanov A.V., (2017). Analysis of vibration parameters of end mills during their wear // Systems. Methods. Technologies, №4 (36), 71–77.
14. Aleinikov, D.P., Lukyanov, A.V., (2015). Investigation of the dynamics of fastening vibration sensors of the spindles of machining centers. Bulletin of the Irkutsk State Technical University, 2, 28 - 35.
15. Aleinikov, D.P., Lukyanov, A.V. Modeling of cutting forces and determination of vibrodiagnostic signs of defects in end mills. Systems. Methods. Technologies, 2017, 1 (33), 39 - 47.
16. Aleinikov D.P., Lukyanov A.V., (2016). Monitoring of the dynamic state of processing centers. Collection of articles of the VII All-Russian scientific-practica conference "Aircraft engineering and transport of Siberia", 197-200.
17. Nizhegorodov, A., Gavrilin, A., Moyzes, B., Zharkevich, O., Zhetesova G.S., Muravyov, O., Bets M., 2016, Stand for dynamic tests of technical products in the mode of amplitude-frequency modulation with hydrostatic vibratory drive, Journal of Vibroengineering, 18(6), pp. 3734 - 3742.
18. Eliseev, S., Livshitz, I., Lontsikh, P., Karasev, S., (2019). Specific modes of formation of dynamic states for robotic systems and their control systems, taking into account the connectivity of movements in two coordinates. Proceedings of the 2019 IEEE International Conference Quality Management, Transport and Information Security, Information Technologies IT and QM and IS, 333 - 338.
19. Eliseev S., Eliseev V., (2020). Reduced characteristics in assessing properties of mechanical oscillatory systems: generalized approaches in the construction of mathematical models. Studies in Systems, Decision and Control, 269-381.
20. Sandip, P., Shashikant, J., Asim, T., Suhas, S., (2014). Modelling and simulation of effect of ultrasonic vibrations on machining of Ti6Al4V, Affiliatio expand, 54(2), 694 - 705.

21. Gavrilin, A., Moises, B., Cherkasov, A., (2013). Constructive methods of increasing the vibration resistance of metal-cutting equipment. Diagnostics, 13, 82 - 87.
22. Gavrilin A., (2015). Modeling of dynamic processes in mechanical processing, Basic research, 2-20, 4403 - 4407.
23. Gavrilin, A., Kladiev, S., Glazyrin, A., Bolovin, E., Polishchuk, V., (2019). Identification of parameters of vibration electromagnetic activator mechanical system using limiting nearresonance frequency. Bulletin of the Tomsk Polytechnic University, Geo Assets Engineering, 330(4), 158 - 177.
24. Gavrilin A., Moyzes B., Kuvshinov K., Vedyashkin M., Surzhikova O., (2019). Determination of optimal milling modes by means of shock-vibration load reduction on tool and peak-factor equipment. Materials Science Forum, 942, 87–96. DOI:10.4028/www.scientific.net/MS .942.87
25. Gavrilin, A., Bolovin, E., Glazyrin, A., Kladiev, S., Polishchuk, V., (2019). Resonant oscillations with a limiting amplitude in a vibration electromagnetic activator, Bulletin of the Tomsk Polytechnic University, Geo Assets Engineering, 330(1), 201–213.
26. Gavrilin A., Cherkasov A., Khrenovsky A. Shock-type vibration dampener. Patent for a utility model of the Russian Federation No. 145093 dated 10.09.2014.
27. Gavrilin A., Cherkasov A. Vibration dampener for the mobile unit of the machine. Patent for a utility model of the Russian Federation No. 171245 dated 25.05.2017
28. Gavrilin A., Moises B., Kuvshinov K. Device for determining the dynamic stiffness of bearing elements of metal-cutting machines. Patent for the invention of the Russian Federation No. 2687341, dated 13.05.2019.
29. Nikonova T., Zhetessova G., Yurchenko V., 2018, Mathematical modeling of vibroburnishing of the hole of cylinder, Journal of Applied Engineering Science, 16(1), 5–10 DOI:10.5937/jaes16-13860

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