Method for the determination of the processing quality of repair parts of agricultural machinery

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Abstract. The dependence of the technological system state of repair equipment during its operation on the quality of repair of machine parts is revealed. The authors proposed a method to determine the quality of processing of repair parts, including ones of transfer function of the movable friction unit along the sliding guides of the metal-cutting machine under conditions of semi-fluid (mixed) friction in the form of an equivalent oscillatory link. The method is based on the integrated method for calculating and determining the technical state of a typical repair equipment based on the proposed integral criterion for the assessment of its vibration resistance. Using the theoretical developments and experimental data, the transfer functions of the machine support system for various designs were determined. The proposed complex method to calculate and determine the technical state of standard repair equipment will make it possible to develop new design solutions and re-equip the existing machine park of repair enterprises in agro-industrial complex.

1 Introduction

Modern agricultural machinery is a very high-technology product. Its repair at a high professional level and quality is a laborious and difficult task. For example, the quality of equipment repair is determined by the quality of repair equipment when restoring the parts of a equipment item[13].

In connection with the above-mentioned problem, there is the task to create new repair equipment or modernize existing one, including precision machines, corresponding in their technical level to foreign ones. The solution to this problem requires further research in the field of machine tool dynamics, the methods for the calculation and assessment of the dynamic state and subsequent optimization of dynamic characteristics for a number of limiting factors. In addition, it requires the development of reliable computational and experimental methods that allow consumers to give objective assessment of the technical level of structures of metal-cutting machines of a similar purpose, but different in engineering and technical performance with certain design features.

On the other hand, the modern trend in the development of machine tools, due to the continuously increasing requirements for them, is accompanied by a constant increase in the rotational speed of the main movement up to 4000-6000 rpm, the operating and idle run rates up to 0.5-3.0 and 10-20 m / min, respectively, by reducing the acceleration and deceleration time of the operating elements to 0.02 s at high requirements for the accuracy and roughness of the surfaces of the workpieces, etc. In this regard, the issues of further research of vibrations in machine tools are also of particular importance.

According to the above mentioned facts, the paper is devoted to the development of technological solutions in the process of creating a range of precision metal-cutting machines, equal to foreign machines in terms of their technical level, as well as methods for their calculation and study of quality, taking into account the specifics of the ratio of the limiting vibration characteristics when cutting in working space.

The quality of processing of agricultural machinery parts is determined according to various indicators, including: vibration resistance and productivity, accuracy, quality of repair operations performed. However, they are assessed as a set of dynamic processes, due to the increased requirements for the used parts of modern agricultural machinery [4 - 5]. Thereby, this aspect highlights the need to improve the performance of repair equipment and achieve their optimal dynamic characteristics.

2 Materials and methods

In order to achieve a high quality of repair of equipment, the system of repair can be considered as a single integral criterion that can be used to synthesize and optimize technological systems by comparing output

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*Corresponding author: hrasp29@yandex.ru parameters, as well as assessing the technical level of repair equipment [6].

The carrier system (CS) is formed by a set of machine elements through which the forces arising during cutting are closed. The CS elements include a spindle with supports, a bed and machine body parts. The choice of the optimal parameters of machine tool elements as a whole requires the solution of the problems of multicriteria optimization. However, the calculated dynamic characteristic of its CS is important among the limitations of machine tool performance in terms of vibration resistance. The productivity of a machine significantly depends on the construction arrangement of CS, as well as on the possibility of equipment with additional units, which allows realizing optimal cutting conditions, reducing the number of technological transitions and idle processing time [6].

Nowadays there are various design schemes, which are used for dynamic calculations of CS machine tools: rod (discrete) schemes; distributed parameter circuits. The basis of a number of existing schemes for structural analysis is the finite element method (FEM).

The main advantage of FEM is the fundamental possibility to describe the nature of the deformations of elements of real constructive forms rather than schematized. However, the application of FEM in the calculation of complex spatial structures leads to a number of difficulties caused by the need to represent structures in the design scheme with a large number of finite elements and, as a result, to process a large amount of input and reprocessable data, etc.

The authors of many works [6 - 10] note the practicability of modelling a procedure for the dynamic calculation of a machine tool consisting of two stages. Firstly, the calculation of natural frequencies and vibration modes is carried out and then the calculation of the frequency characteristics of an elastic system is performed taking into account damping at the second stage, revealing the nature changes in natural vibration modes. Then they propose to use a systematic approach to the design of machine tool layouts. It is a computational technique in which an elastic system is schematized with the help of so-called superelements subjected to automatic reduction (deflation) in a limited frequency range during the formation of matrices of a mathematical model, which significantly reduces the time for the calculation of dynamic characteristics.

The idea of superelements is based on the representation of a complex structure as a set of substructures, each of which is represented by a set of basic finite elements. Using this approach, each substructure is described in a convenient coordinate system selected for it and then calculated separately with fixed limits common with other substructures. The result of this calculation is to obtain the stiffness matrix of the substructure and the matrix of loads at its nodes. The substructures for which such matrices are defined we usually call a super element. Next, a system of equations for the constraints at the limits of super elements is created, expressing the equilibrium conditions of the entire structure as a set of super elements.

This system of equations has significantly less number of unknowns than the traditional system of equations. This completes the so-called direct course of calculation. In the reverse course of the calculation, each of the substructures is calculated for a given load and the displacements of its limit nodes found on the forward course. These calculations are performed without much difficulty, since substructures are always described by a system of low-order equations. From the standpoint of the classical displacement method, each substructure (super element) is a complex element of the main system of displacement method.

The paper [8] presents the calculation of static and dynamic characteristics of the spindle-bearing system using the method of structural modification. It is achieved when the initially accepted simple basic model (the spindle system together with the workpiece is approximated as a beam of constant diameter) due to the introduction of additional masses, springs (stiffnesses) and dampers is adjusted to the structure of the real system, which gives significant advantages in computation time in comparison with the finite element method. The deviations of the calculation results relative to the first three frequencies and modes of natural vibrations are insignificant.

For the description of CS, the authors of the paper [10] recommend using the simplest possible design scheme. For example, it may be an oscillatory system of rigid massive bodies, elastically interconnected. It means that the design scheme is composed of the dominant subsystems that are not known yet at the initial stage.

Such a calculation model is quite justified, for example, for boring machines with DNB = 320 mm and is practically unacceptable for heavy (milling, rotary, planing) gantry-type machines and spatial structures. More often, the most acceptable design scheme uses both concentrated masses and distributed parameters. However, the final development of the calculation model is associated with numerous experimental studies when they are compared to the results of calculation. Therefore, the most acceptable one is the calculation model used in this work [6] in the form of an arbitrary system of rigid bodies, connected in an arbitrary way by elastic elements with distributed parameters, taking into account energy dissipation in each structural element.

During the assessment of the vibration resistance of a machine tool, knowledge of the transfer function of CS is necessary in order to form the overall transfer function of a closed dynamic system.

3 Results and discussion

The key feature of the studied method [6 - 8] is its application in a complex that reflects very different dynamic phenomena in technological systems of the equipment, for example boring machines, and high requirements for dynamic processes (through a very wide range of changes in the parameters of the dynamic system of repair equipment - cutting speed, tool feed, dimensions, weight, configuration, materials, requirements for the accuracy of parts, etc.).

Taking into account the inconsistency and mutually exclusive nature of the considered initial values of the dynamic quality of equipment, such as accuracy and productivity, this method provides:

- The determination of the ultimate (integral) stability in the case of power conversion, which is used to calculate the productivity when roughing the base part;
- The assessment of accuracy during finishing.

The authors consider the first condition, when the operability of the dynamic technological system of boring machine is limited by its vibration resistance and the stiffnes of the part is taken in accordance with the work[8]. Productivity is quantified in the following order. First, the relative dimensions of the part in the plane of its processing and the integral dynamic characteristic of the equipment are determined in order to ensure vibration resistance, which consists of a number of constraints that together act in the technological system that determine the limit curve of the stable cutting t_{cal}.

Within the standard length of the workpiece:

$$t_v \ [8]; \ t_N = \frac{6120(N_{cal} - N_{x.x.})}{K_1 \cdot S^{0,75} \cdot V},$$

$$t_m = \frac{2000M}{K_1 \cdot S^{0,75} \cdot D}\ , \qquad (1)$$

Then, having determined the numerical value of the limiting integral criterion of vibration stability t_{integr} for cutting using this curve in a given coordinate system, the permissible (specific) metal removal rate is calculated from the expression:

$$Q = t_{integr} \cdot S \cdot V(1 - \frac{t_{interg}}{D}) \qquad (2)$$

where: t_{integr} – limiting integral characteristic of vibration resistance (integral cutting depth of block walls), obtained within the entire working space of the machine, mm; S – cutter feed, mm/rev.; V – cutting feed, m/min; D – workpiece diameter, mm.

Therefore, the maximum removal rate of the metal being removed is in direct proportion to the maximum allowable value of the depth of cutting for the studied repair equipment, taking into account the location of the cutter in its working space.

The technical level of metal-cutting equipment is determined by such a multifactor indicator as productivity [7], calculating the processing cycle time for a conventional product:

$$T = \frac{V_c}{Q} + \frac{L}{S_{d.m.}} + \frac{T_t \cdot n}{60} + \frac{T_d}{60},$$

where: □ – product processing time, min; Q – Permissible metal removal rate at maximum permissible processing with a depth of cutting t_{integr}, cm^3/min; $S_{d.m.}$ – displacement movement speed, mm/min; V_c – chip volume per cycle, cm^3; L – Total length of displacement movements, mm; □$_t$ – tool position change time, s; n- Number of repair equipment tools; □$_d$ – device position change time, s.

The limit values of dynamic stability can be determined both by calculating all limit values and by calculating the test results of computational models and their experimental use. It allows taking into account the following factors [8]:

- the design characteristics of the main assembly units, control models of repair equipment, their location, drive structure, spindle torque and effective cutting characteristics;
- the possibility to obtain an objectively differentiated assessment of the dynamic state of equipment by calculation or calculation with the experimental use of digital technologies;
- the change in the position of the tool in the working space of the repair equipment, the material and geometry of the tool, the material of the parts, the flexibility of technological system.

Another assessment parameter that is used to assess the repair effects is the roughness of the treated surface during finish processing [9].

The stable formation of the maximum surface quality of the part during processing with the supply of directed regular surface microreliefs depends on the problem statement: the choice of a number of limiting factors and the acceptance of limit conditions.

The impact of the cutter feed on the surface roughness of the workpiece during sharpening can be determined by the Chebyshev formula:

$$R_z = \frac{S^2}{8 \cdot r} \cdot 1000\,, \qquad (3)$$

where: R_z – roughness height of the profile at ten points, mcm; R_z = 4 R□; S- feed value, mm/rev; r – cutter radius, mm.

In order to obtain optimal surface finish, the tool feed during finish processing is set in the range from 0.01 to 0.2 mm/rev. In this case, additional calculations of the cutter feed should be carried out according to the refined formula, determined by the roughness of the workpiece:

$$S_{rough} \le \frac{k_0 \cdot R_a^{k_1} \cdot V^{k_2} \cdot r^{k_3} HB^{k_4}}{t^{k_5} \cdot \varphi^{k_6} \cdot \varphi_1^{k_7}}\,, \qquad (4)$$

where: k_0, k_1,... k_7 – coefficients characterizing the processed and tool material (they are given in reference books for various brands of processed and tool materials); t – Cutting depth (it is taken in the range 0,05 – 0,1 mm); R_a – Arithmetic mean deviation of roughness profile; r – Leading edge radius; □ and □$_1$ – the main and auxiliary angles of the tool in the plan, respectively; □□ –Brinell hardness of the material of the repaired part.

From the formula (4) and the established nominal mode during the finish processing of medium-carbon steels and cast irons, for example, by sharpening with VK8 cutters, the value of the Ra parameter can be determined by the formula (5):

$$R_a = 0{,}85 \frac{t^{0,31} \cdot S^{0,58} \cdot \varphi^{0,4} \cdot \varphi_1^{0,4}}{V^{0,06} \cdot r^{0,66} \cdot HB^{0,05}} \qquad (5)$$

Additionally, the calculation of the tool feed is performed, taking into account the permissible stiffness and accuracy of the part:

$$S_{stiff} \le \sqrt[Xp_z]{\frac{\varepsilon JEf^1}{1{,}1C_{pz} \cdot l^3 \cdot t^{yp_z}}}\,, \qquad (6)$$

where: f –the change in the geometric straightness of the part during processing; l – the distance between the bases of the equipment or the offset of the part when it is fastened only in the chuck); J = the moment of inertia of the section of the part (for round solid parts); □ – modulus of elasticity of the workpiece material; J= 0,05d, where d –diameter of the circle of the treated surface; □ – the stiffness coefficient depending on the method of fixing the part on the machine: □ = 3 (when mounted in a holder), □ = 48 (when mounted in centers),
□ =96 (mounted in holder using boring table).

During finish processing, the speed of the processing of a part is determined by the known cutting conditions, taking into account the required depth of cutting and the feed rate of the tool. There is no chip formation at the cutting edge during processing. In addition, it is possible to apply the empirical equation [6] in order to find the Ra parameter for finishing conditions:

$$R_a = K \frac{S^{k_1} (90^0 + \gamma)^{k_4}}{r^{k_2} \cdot V^{k_3}} \qquad (7)$$

After setting the optimal cutting conditions for finishing: V, S, t, evaluating the stiffness of the technological system, it is necessary to determine the specific productivity of the repair equipment (processing time 1 dm^2 = 10000 mm^2 of the surface area of the base part) by the following formula:

$$T_m = \frac{10}{VS} \qquad (8)$$

From the cutting theory it is known that:

$$V = \frac{C_V}{t^x \cdot S^y} \qquad (9)$$

Therefore, substituting the values of formula (9) into (8), we obtain:

$$T_m = \frac{10t^x \cdot S^y}{C_V \cdot S} = \frac{10t^x}{C_V \cdot S^{(1-y)}} \qquad (10)$$

The stiffness of the technological system is determined by:

$$j = K_y \cdot C_p \cdot S^{0,75} \cdot \frac{\Delta_w}{\Delta_p} \qquad (11)$$

From here it follows that:

$$S^{0,75} = j\frac{1}{K_y \cdot C_p} \cdot \frac{\Delta_p}{\Delta_w} \text{ or}$$

$$S = (j\frac{1}{K_y \cdot C_p} \cdot \frac{\Delta_p}{\Delta_w})^{4/3}, \quad (12)$$

where: □p – error in the geometric shape of the part after production; □w – the error of the workpiece before its processing.

As a result, we get the following expression:

$$T_m = \frac{10t^x}{C_V}(\frac{K_y \cdot C_p \cdot \Delta_w}{j\Delta_p})^{\frac{4}{3}(1-y)} \qquad (13)$$

When finishing, the exponent 4/3 (1-y) = 1, therefore it is advisable to use the following expression when determining productivity:

$$T_m = \frac{10t^x}{C_V}(\frac{K_y \cdot C_p \cdot \Delta_w}{j\Delta_p}) \qquad (14)$$

These revealed dependencies allow determining the specified surface quality of the workpiece and the parameters of the repair process and the geometry of the cutting tool at the assigned values of the surface quality.

During the process of repair of a part, primary spontaneous vibrations in the technological system are transformed into secondary (regenerative) vibrations, which significantly worsens the quality indicators of the repair technological process. Regenerative spontaneous vibrations in a closed technological system are the result of defects that determine its roughness on the surface of the workpiece obtained from the previous roughing pass of the tool.

In order to obtain the optimal values of the assessment parameter of the surface quality during the study, various technical solutions were developed that allow, for example, in the simulation mode, controlling the vibration level of the technical system of the equipment for repair, as well as ensuring the automatic balancing of critical units of the machine during its direct operation in accordance with surface quality. The technical solutions offered throughout the finishing process in the technological system support dynamic fixed self-regulation, which allows the system to establish internal resonance and provide higher repair accuracy [10-11].

Thus, the studied indicators of reliability and durability of the repair equipment are assigned during their direct testing, for example, by information technology products, which play the important role in the prediction of the changes in the output-standardized parameter of repair equipment.

Nowadays, the problems of the provision of the dynamic stability and accuracy of movements of the movable units of the repair equipment are not fully solved. Continuously increasing technological requirements repeatedly set a designer the task of the development of new technical solutions that provide high-performance processing of parts with increased requirements for accuracy and roughness of the processed surface at minimal cost.

In order to solve the tasks set in this paper, it is necessary:

1. To study technical information, including inventions, aimed at the improvement of the smoothness of movement of the working parts of the machine and its vibration resistance.
2. To summarize the long-term national experience in the production and design of metal-cutting machine tools.
3. To perform multivariate development of the main units of the machine.
4. To propose promising designs based on the results of theoretical and experimental studies.

Many studies accentuate the great influence of numerous factors on the nature of the movement of working bodies such as:

- the configurations of guides and materials of rubbing pairs;
- the presence of grease and additives in its composition;
- the amount of feed on the guides;
- the symmetry of the drive and the presence of additional connections;
- drive rigidity;
- the damping conditions in structural elements, the presence of vibration dampers, etc.

Most of these factors are theoretically justified in the proposed mathematical model of the CS of a metal-cutting machine on sliding guides under conditions of semi-fluid friction.

In order to reduce the level of vibrations, it is possible to use a number of structures that will improve the dynamic characteristics of the CS of the machine.

4 Conclusion

As a result of the research the integrated method for the calculation and determination of the technical state of a standard repair equipment was developed on the basis of the proposed integral criterion for the assessment of self-oscillations, taking into account a set of factors that limit the dynamic state of the technological system.

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