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Revisiting the Provision of Nanoscale Precision of Cutting on the Basis of Dynamic Characteristics Modeling of Processing Equipment

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The article deals with the issues related to the development of the processing equipment providing nanoscale precision of cutting by means of turning and milling. Building of a machine dynamic model is carried out to solve of this task. This allows taking into account the dynamic characteristics of the existing or designed equipment and the errors of dynamic setting of the machine and this also allows providing processing precision in nanometer range.

Keywords: Nanoscale precision, Turning machine, Dynamic model, Cutting

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1. INTRODUCTION

Global high-tech production is already posing and solving the tasks of producing hardware, which are characterized by manufacturing errors with values less than 100 nm. For quite a long period of time there have been technologies, equipment, tools and instrumentation to achieve nanoscale precision, based on the implementation of honing, polishing, burnishing and additional pass finishing processes. Their use has allowed achieving the values of the roughness parameters *Ra* less than 2 nm. However, these processes are classified as finishing operations and basically do not allow controlling sizing errors and geometric form while processing. Widely known and used fine diamond turning processes, implemented using existing technologies, equipment and cutting tools, give an opportunity of precision only in the micrometer range. In this connection the issues related to the development of the processing equipment providing nanoscale precision of processing using turning and milling methods are of great interest and importance. The solution of these tasks is not possible without taking into account the dynamic characteristics of the existing or designed equipment and the errors of dynamic setting of a machine.

2. DESCRIPTION OF THE SUBJECT AND THE METHODS OF THE RESEARCH

As it is known, the generalized mathematical model of vibrations of cutting machine units can be represented in matrix form [1-6]

$$M\ddot{X} + H\dot{X} + CX = F, \qquad (1)$$

where M is the mass matrix of the machine units; H is the damping coefficient matrix; C is the machine stiffness matrix; $X, \dot{X}, \ddot{X}$ are the vectors of the vibratory displacement of the machine units and their first and second derivatives; F is the vector of vibro-perturbations.

Further arguments and conclusions are based on the analysis of the dynamic model of a turning machine (Fig. 1). To simplify the calculations, we assume that the machine consists of three units: a spindle unit with a fixed workpiece (unit 0); frame (unit 1) and cutting unit (unit 2).

With the same purpose we will consider vibrations of the machine units in the transverse direction, then the matrices M, H, C, the vectors and will take the form

$$M = \begin{bmatrix} m_0 & 0 & 0 \\ 0 & m_1 & 0 \\ 0 & 0 & m_2 \end{bmatrix}, H = \begin{bmatrix} h_0 & -h_0 & 0 \\ -h_0 & h_0 + h_1 + h_2 & -h_2 \\ 0 & -h_2 & h_2 \end{bmatrix},$$

$$C = \begin{bmatrix} c_0 & -c_0 & 0 \\ -c_0 & c_0 + c_1 + c_2 & -c_2 \\ 0 & -c_2 & c_2 \end{bmatrix}$$

$$X = \begin{bmatrix} x_0 \\ x_1 \\ x_2 \end{bmatrix}, \dot{X} = \begin{bmatrix} \dot{x}_0 \\ \dot{x}_1 \\ \dot{x}_2 \end{bmatrix}, \ddot{X} = \begin{bmatrix} \ddot{x}_0 \\ \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix},$$

$$F(t) = \begin{bmatrix} F_d + F_R \\ 0 \\ -F_R \end{bmatrix}, \qquad (2)$$

where m_i, h_i, c_i are the reduced mass, the damping coefficient, stiffness coefficients of i-th unit of the machine; $F_R(t)$ is the cutting force; $F_d(t)$ is the force caused by the presence of static imbalance of rotating workpiece

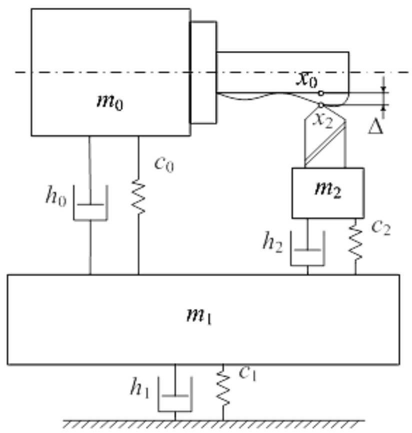

Fig. 1 – Generalized model of vibrations of turning machine units

$$F_d = m_z e \omega^2, \qquad (3)$$

where m_z is the workpiece mass; e is the specific static imbalance of the workpiece; ω is the spindle rotational speed.

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The component error value of the workpiece in the transverse section (Δ) in this case will be determined by the expression (see Fig. 1)

$$\Delta = x_0 \text{-} x_2, \quad (4)$$

and includes sizing error, waviness and roughness of the machined surface.

Equation (1) using the Fourier integral transformation, can be reduced to the form

$$(-\omega^2 M + i\omega H + C)X(\omega) = F(\omega), \quad (5)$$

where i is the imaginary unit; $X(\omega)$, $F(\omega)$ are the complex amplitude spectra of vibration displacement and perturbation, respectively.

Expression $(-\omega^2 M + i\omega H + C)$ is the matrix of the dynamic stiffness of the machine. After the transformation of equation (5) we get the following expression

$$X(\omega) = (-\omega^2 M + i\omega H + C)^{-1} = F(\omega), \quad (6)$$

where the expression in brackets is the matrix of the dynamic compliance of the machine

$$W(\omega) = (-\omega^2 M + i\omega H + C)^{-1}. \quad (7)$$

Applying to equation (4) the Fourier integral transformation, we obtain

$$\Delta(\omega) = x_0(\omega) \text{-} x_2(\omega), \quad (8)$$

where $\Delta(\omega)$ is the complex amplitude spectrum of the component error value; $x_0(\omega)$ and $x_2(\omega)$ are the components of the vector $X(\omega)$.

Writing equation (8) with regard to the expression (6), we obtain

$$\Delta(\omega) = w_{11}[F_d(\omega) + F_R(\omega)] - \\ -w_{13}F_R(\omega) - w_{31}[F_d(\omega) + F_R(\omega)] + w_{33}F_R(\omega), \quad (9)$$

where w_{ij} is the dynamic compliance matrix components $W(\omega)$, i *is* the line number, j is the column number, respectively.

Rearranging the elements in expression (9) we finally get

$$\Delta(\omega) = (w_{11} - w_{13})F_d(\omega) + (w_{11} - w_{13} + w_{33} - w_{31})F_R(\omega). \quad (10)$$

The value $\Delta(\omega)$ is a complex one, and, therefore, for the estimation of the machined surface quality parameters it is enough to have the peak values of the component error elements.

It follows from the analysis of expression (8) that high precision of processing can only be achieved if there is no relative displacement of the cutting edge of the tool and the workpiece during vibration, i.e. if under the following condition

$$x_0(\omega) = x_2(\omega). \quad (11)$$

However, this condition cannot always be achievable in practice and determined from the linear model of vibrations (1). Then equality (11) can be replaced by

$$|x_0(\omega)–x_2(\omega)| \le \Delta_{max}, \text{ или } |\Delta(\omega)| \le \Delta_{max}, \quad (12)$$

where Δ_{max} is the required component error.

3. EXPERIMENTAL RESULTS AND DISCATIONS

Condition (12) may be implemented using various approaches. Let us consider some of them for specific dynamic characteristics of the system 'Machine, device, tool, workpiece' (MDTW) when component error Δ_{max} = 100 nm: m_z = 0,2 kg; m_0 = 10 kg; m_1 = 1000 kg; m_2 = 1 kg; $c_0 = 2{,}5 \cdot 10^6$ N/m; $c_1 = 6 \cdot 10^6$ N/m; $c_2 = 25 \cdot 10^6$ N/m; h_0 = 400 kg/f; h_1 = 4000 kg/f; h_2 = 400 kg/f.

The first approach involves setting the values of e and $|F_R(\omega)|$, then defining the rotational speed range ω for which (12) is fulfilled.

Thus, if e = 100nm and $|F_R(\omega)|$=10N, on the basis of expression (10) the required component error can be achieved at frequencies ω from 1477 to 1740 rad/s and more than 111,000 rad/s (Fig. 2), and, for example, component error less than 50 nm can be achieved at frequencies ω from 1,565 to 1,620 rad/s and more than 160,000 rad/s.

The second approach is to partition proportionally the value Δ_{max} between the components in the expression (10) $(w_{11} - w_{13})F_d(\omega)$ $(w_{11} - w_{13} + w_{33} - w_{31})F_R(\omega)$. Then the task of providing the precision of processing can be solved through comprehensive solution of the subtasks of providing the precision within the relevant components. Admitting, for example, that the first component is 10 % of Δ_{max}, and the second one is 90 %, from (12) we obtain two conditions

$$|w_{11} - w_{13}| \times |F_d(\omega)| \le 0{,}1\Delta_{max} \quad \text{and} \quad (13)$$

$$|w_{11} - w_{13} + w_{33} - w_{31}| \times |F_R(\omega)| \le 0{,}9\Delta_{max}. \quad (14)$$

On the basis of the first condition (13) it is possible to set an acceptable range of values of the specific imbalance of the workpiece for different rotational speed ranges

$$e \le \frac{0{,}1\Delta_{max}}{|w_{11}-w_{13}| m_z \omega^2}. \quad (15)$$

For example, on the basis of the second condition (14) for the specified value $|F_R(\omega)|$ = 10 N the component error less than $0{,}9\Delta_{max}$ = 90 nm can be achieved at frequencies ω from 1,487 to 1,723 rad/s and more than 12,050 rad/s (Fig. 3).

Based on the obtained rotational speed ranges, using (15) we get the restrictions to the maximum value of the specific imbalance of the workpiece (Fig. 4).

The acceleration of the machine to the running spindle rotational speed is associated with the passage of the resonant speed ω_r, which also imposes restrictions on the value of the specific imbalance of rotating workpiece. Based on the given value of the bearing clearance of the spindle unit Δ_p we get

$$e \le \frac{\Delta_p}{|w_{11}-w_{13}| m_z \omega_r^2}.$$

4. CONCLUSION

Thus, based on the modeling of the dynamic characteristics of a turning machine it is possible to solve comprehensively the task of providing the nanoscale precision while cutting.

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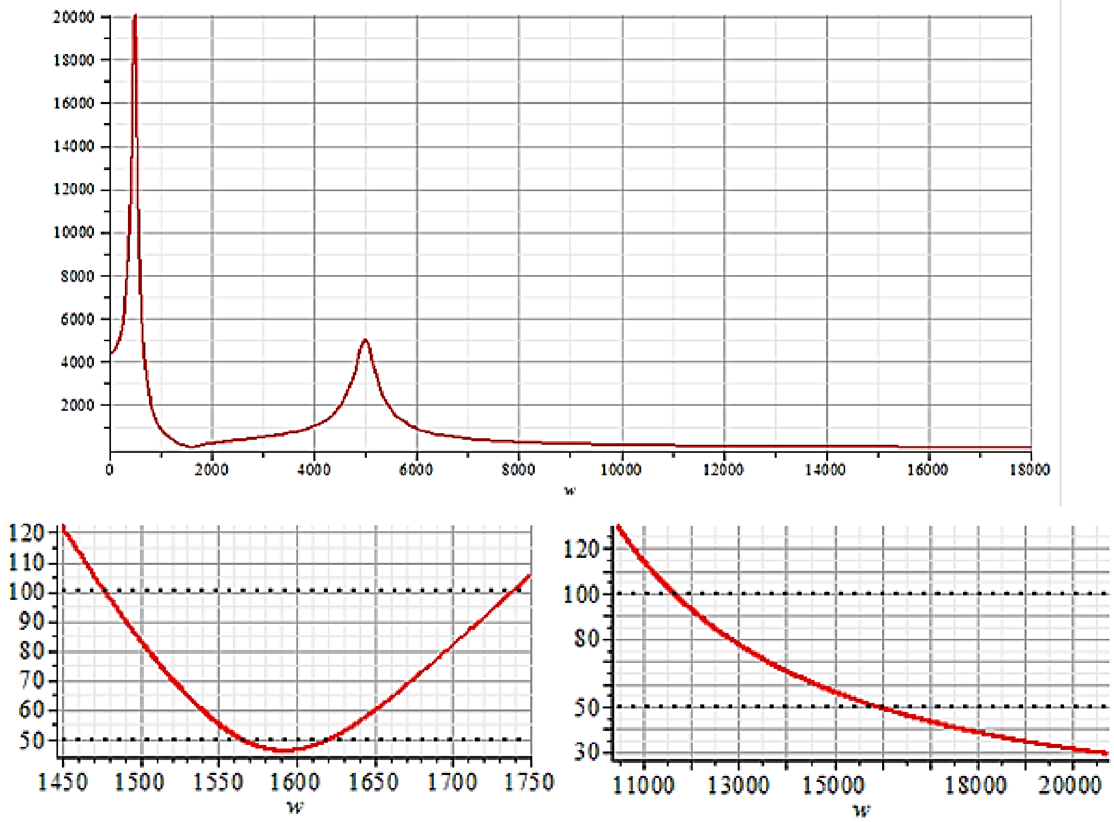

Fig. 2 – Dependence of the component error (nm) on the rotational speed ω (rad/s)

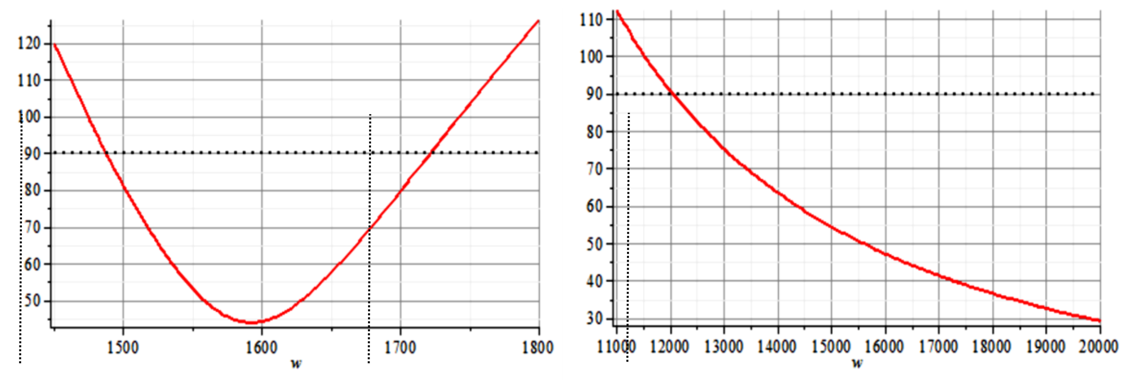

Fig. 3 – Dependence of $|w_{11} - w_{13} + w_{33} - w_{31}| \times |F_R(\omega)|$(nm) on the rotational speed ω (rad/s)

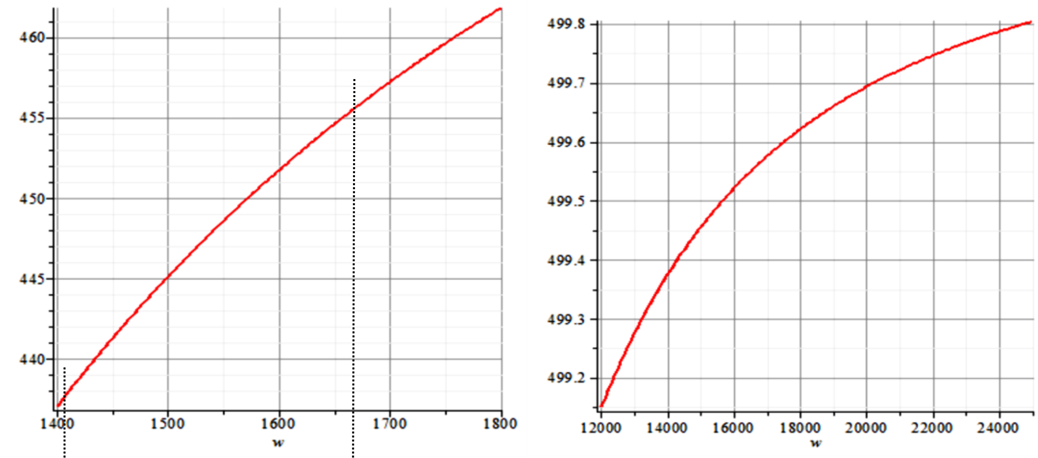

Fig. 4 – Dependence of the value of the maximum specific imbalance of the workpiece (nm) on the rotational speed ω (rad/s)

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