Vibration stability criterion in assessing the dynamic quality and limiting capabilities of machine tools

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Abstract. The vibration resistance of the dynamic system of a cutting machine is considered as a criterion for assessing its dynamic quality and limiting capabilities. An example of diagnosing a group of machines of the same type by the criterion of vibration resistance with an assessment of their current state is given.

1. Introduction

Important factors affecting the accuracy of processing, durability are geometric and kinematic accuracy of the machine [1]. The design of machine tools and their most critical parts and mechanisms is largely subject to the criterion of accuracy. This criterion includes manufacturing accuracy, preservation of accuracy in operation (provided by the smallness of the given elastic, temperature deformations and vibration amplitudes, tuning accuracy) and preservation of accuracy over the established repair periods.

Geometric accuracy of machines is characterized by [1]:

a) the accuracy of the support surfaces for basing the tool and the workpiece;
b) the accuracy of the working bodies movement;
c) the accuracy of the relative position of the working bodies movement rails;
d) the accuracy of the location of the rails relative to the base surfaces.

Kinematic accuracy is characterized by the consistency of mutually related relative movements of the parts carrying the instrument and the workpiece.

The strength and durability of machines are also important factors affecting the performance. Wear greatly reduces accuracy, reduces vibration resistance and, as a result, performance. Therefore, the permissible wear of carrier and rail systems parts (guides, spindle bearings, tool seats and accessories, etc.) is determined by the criteria of accuracy and vibration resistance during machining [1, 2].

Increased requirements for dimensional accuracy and parts shape, the emergence of new hard-to-machine materials, the intensification of cutting conditions, as well as the widespread introduction of automation of technological processes and the creation of machines with control and regulation systems caused a sharp increase in the role of dynamic processes in machine tools. There are a number of dynamic processes during machining that have a significant impact on the quality of processing. This is the cutting process, friction processes, processes in engines [2–7].
A set of dynamic processes indicators in machine tools that determine the listed requirements of stability, accuracy, durability, etc. are united by the general concept of the machine dynamic quality \[2\]. The main indicators of the machine dynamic quality are the following:

a) stock and degree of stability;
b) deviations of the parameters of the dynamic system under external influences;
c) speed.

The stability margin determines the possibility of changing one or another parameter of the system without losing stability. The loss of stability by the system appears in vibrations or “undermining” of the instrument, in the uneven jump-like movement of the nodes or in their jamming. Thoroughly, vibration resistance is the most important indicator of the machine dynamic quality. It allows to determine the range of allowable modes and identify the machine limits.

2. Material and research methods

As the main criterion characteristic, which determines the limiting possibilities of the machine in assessing the dynamic quality, the boundary of the stability area was adopted \[8\] (figure 1). It divides two areas – the area of permissible modes, providing quiet cutting with a low vibration level, and the area of unacceptable modes with an increased vibration level. The stability boundary is built in the plane of the cutting process parameters.

![Figure 1. Stability area boundary of the machine when turning.](image)

The range of acceptable modes can be divided into three characteristic areas:

* the area of absolute stability, bounded by the axis of ordinates (cutting speed \(V\)) and a dotted line passing through the point of absolute stability \(A\);
* the area of stability at low cutting speeds, limited by the abscissa axis (cutting depth \(t\)) and the stability boundary below point \(A\);
* the area of stability at high cutting speeds, limited by the axis of ordinates (cutting speed \(V\)) and the stability boundary above point \(A\).

The change in the machine state is diagnosed by the displacement of the stability boundary, which can be characterized quantitatively. In this case, the characteristic features of each specific machine manifest themselves through the position of the stability boundary.

As an example, we can consider the dynamic manifestation of the technological system when processing by turning in the plane of parameters presented in Figure 1. We fix the depth of cut \(t = 4\) mm and choose three characteristic modes with cutting speeds respectively: \(V_1 = 20\) m / min, \(V_2 = 75\) m / min.
min and $V_3 = 110 \text{ m} / \text{min}$. Figure 2 shows diagrams of vibration displacement for the three modes. It can be seen from the diagrams that in modes 1 (figure 2, a) and 3 (figure 2, c) the average vibration amplitude level is $10 \mu\text{m}$, and in mode 2 (figure 2, b) it is $30 \mu\text{m}$. It turns out that when going beyond the boundary of the stability area, the vibration level increases threefold. Thus, we can conclude that the stability boundary defines the limiting machine capabilities and highlights the range of acceptable process conditions.

![Figure 2. Vibration displacement diagrams: a – mode 1; b – mode 2; c – mode.](image)

To study stability, we consider the dynamic systems of machine tools when turning (figure 3, a, c) and milling (figure 3, b, d) [8].

The kinematics of formative movements during turning processing are presented in figure 3, a. The line of the cutting force action $P_z$ is aligned with the cutting speed $V$. To the cutter in this direction, the mass $m_z$, rigidity coefficients $c_z$ and damping $b_z$ are given. The force $P_y$ acts in the $y$ direction. The mass $m_y$, the coefficients of rigidity $c_y$ and damping $b_y$ are given to the cutter in this direction. The slice section consists of the thickness $a$ and the width $b$ of the slice, which are respectively equal to $b = \frac{t}{\sin \varphi}$; $a = S \sin \varphi$; $t$ is the depth of cut; $S$ is feed; $\varphi$ is the main angle in the plan.

As a model of minimum dimensionality, when machining by turning, a single-mass double-circuit flexural dynamic model with lumped parameters (figure 3, c) can be adopted, which is quite applicable for calculating machines stability [2].

With regard to the problem of dynamics in terms of the technological system stability, the normal contour ($OY$ axis) and the tangent contour ($OZ$ axis) are unequal:

- a normal contour determines the shaping accuracy, forms a vibration trace on the surface and makes a decisive contribution to the boundary formation of the stability area;
- The tangent contour improves the surface roughness, takes over a part of the energy generated during the cutting process and accordingly expands the stability area.

The exception in the model of the tangent contour $OZ$ narrows the stability area to approximately $10\%$ [9]. The transition admissibility to a single-dynamic model is confirmed by numerous dynamic tests of machine tools. But such a simplification of the dynamic system requires the periodic identification of parameters when conducting dynamic tests.
Figure 3. Kinematics of forming movements during machining by turning (a), by milling (b) and the model of a two-circuit dynamic system with machining turning (c), milling (d).
Consider the kinematics of shaping movements during contour milling (figure 3, b). Here the angle \( \alpha \) is the angle of the cutter position measured between the normal to the forming point \( A \) of the workpiece and the axis of the cutter rotation. The instantaneous thickness \( a_i \) and the slice width \( b_i \) are determined for the \( i \)-th tooth of the cutter; \( s_z \) is the working feed per tooth cutter; \( r \) is the cutter radius; \( \psi_i \) is the instantaneous angle of the cutter rotation; \( \psi_e \) is the cutting angle; \( \beta \) is the inclination angle of the screw helix of the tooth. The tangent, the radial \( P_{ti} \) and the axial \( P_{oci} \) components of the cutting force act on the \( i \)-th tooth of the milling cutter involved in the cutting.

Cutting force during milling is a periodic function, which complicates the solution of the stability problem and requires appropriate linearization. Analysis of the cutting forces nature change during milling showed [2, 8, 9] that while cutting with two or more milling teeth, the uneven milling with respect to the average value does not exceed 10%. Neglecting this value dramatically simplifies the calculation of cutting forces during milling. This is achieved by introducing average integral values of thickness \( a_m \), and width \( b_m \) of the slice. The model of the technological system for contour milling is presented in Figure 3, d. The same rules for shaping the surface can be applied to it as to the model during turning (Figure 3, b), i.e. it can be mathematically represented by a single-loop dynamic model in the direction of the \( OY \) axis.

When carrying out machine diagnostics, mass \( m_z \), rigidity coefficients \( c_z \) and damping \( b_z \) in dynamic circuits are given. To highlight the dominant dynamic contours of the machine dynamic system, we introduce into consideration the quality factor \( D \) of the oscillating system [10], which is determined by the formula

\[
D = \sqrt{\frac{m_y c_y}{b_y}} \quad (1)
\]

We will search for high-quality dynamic circuits by the amplitude spectrum of vibration displacements or vibration velocities in the frequency range 0 ... 1000 Hz based on the condition evaluation

\[
1 - 1/(2D_s) \leq f/\omega_s \leq 1 + 1/(2D_s), \quad (2)
\]

where \( \omega_s \) is the \( s \)-th natural frequency of the dynamic loop; \( f \) is the current frequency; \( D_s \) is the good quality of the \( s \)-th own form of oscillations.

For a high-quality contour, the reduced parameters are determined and a single-dynamic model is built [8]

\[
m_y \dddot{y} + b_y \ddot{y} + c_y y = P_y; \quad (3)
\]

\[
T_p \dddot{P}_y + P_y = -k^*_y y, \quad (4)
\]

where \( T_p \) is the lag time constant, \( T_p = l_p/V_s \); \( l_p \) is the path of chip formation equal to the length of the chip contact line with the front surface of the instrument; \( k^*_y \) is the contour transfer coefficient \( k^*_y = k_y \sin \varphi \), \( k_y \) is the coefficient of reducing the force \( P_y \) to the shear thickness \( a \).

The stability criterion of the dynamic machine system is calculated on the basis of the algebraic Hurwitz criterion [11] for the system of differential equations (3) - (4) defined by the inequality

\[
(T_p c_y + b_y)(T_p b_y + m_y) > T_p m_y (c_y + k^*_y) \quad (5)
\]

The construction of the stability boundary is carried out by step-by-step verification of the criterion (5) based on the D-partitioning method.

Table 1 shows the results of determining the for 7 machines of the same model.
Table 1. The results of determining the machines stability boundary.

| No. | Diagnostic results | Stability boundary |
|-----|--------------------|--------------------|
| 1   | Dominant node      | Spindle            |
|     | Frequency of dominant node, Hz | 131             |
|     | Damping parameter  | 56                 |
|     | Rigidity, kN / mm  | 55.5               |
|     | Analysis of test results: | The machine has high rigidity. The range of allowable cutting conditions is wide. The machine is in satisfactory technical condition. |

| 2   | Dominant node      | Spindle            |
|     | Frequency of dominant node, Hz | 136             |
|     | Damping parameter  | 32                 |
|     | Rigidity, kN / mm  | 25.0               |
|     | Analysis of test results: | The range of allowable cutting conditions is narrow. The machine requires inspection and determination of the type of repair. |

| 3   | Dominant node      | Tool holder        |
|     | Frequency of dominant node, Hz | 78              |
|     | Damping parameter  | 35                 |
|     | Rigidity, kN / mm  | 47.0               |
|     | Analysis of test results: | The machine has high rigidity. The range of allowable cutting conditions is wide. The machine is in satisfactory technical condition. |

| 4   | Dominant Node      | Support            |
|     | Frequency of dominant node, Hz | 43              |
|     | Damping parameter  | 25                 |
|     | Rigidity, kN / mm  | 25.5               |
|     | Analysis of test results: | The range of allowable cutting conditions is average. The machine requires preventive maintenance. |
Dominant Node Support
Frequency of dominant node, Hz 30
Damping parameter 35
Rigidity, kN / mm 24.0

Analysis of test results:
The machine has high rigidity. The range of allowable cutting conditions is wide. The machine is in satisfactory technical condition.

3. Discussion of research results
The studies of the machine dynamic system stability when machining with a blade tool on turning and milling operations showed the applicability of the general approach to determining the stability boundary area based on simplified models. The solutions obtained allow us to meet the requirements for the quality of manufacturing precision parts, taking into account the current state of the metal-cutting equipment.

The criterion of vibration resistance is an indicative tool for assessing the current state of the metal-cutting machine and its ultimate capabilities. From the test results shown in Table 1, it can be seen that different machines have different dynamic contours. In this case, the boundary line of the stability area depends directly on the state of the machine. In examples 1, 3, 5 the machines are in a satisfactory technical condition. In example 2 the machine has a narrow stability boundary, requires inspection and determination of the repair type. In example 4, the machine has a valid range of cutting conditions and requires preventive maintenance.

The results obtained indicate the practical applicability of the presented model solutions.

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