Dynamic processes in technological systems of machining and the nature of their origin

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Abstract. The article describes the main causes of dynamic processes in technological systems, the types of vibrations that occur in machines, external sources that cause fluctuations in the machine bases. The article discusses the occurrence of self-oscillations in the machines. The authors proposed a mathematical model of a multi-mass technological system based on the example of a vertical drilling machine. The original multi-mass oscillatory system is replaced by a simplified three-mass model, which allows considering the low-frequency range of workloads and disturbing external influences.

1. Introduction
In modern engineering, the emerging dynamic processes in technological systems are divided into two classes associated with the implementation of the cutting process and not directly related to the cutting process. The drives of the main motion and feedrate are related to the machine nodes directly connected with the cutting process being implemented, and the arising dynamic processes in these nodes will affect the quality parameters of the machining.

In addition, an important role in the machining process is played by the carrier system of the machine, which is formed by a combination of different elements. Through this system, the forces arising in the process of cutting between the tool and the workpiece are closed. The elements of the carrier system include frame and body parts of machines, in which the executive bodies of the main drives and feed drives are located [1, 2]. Thus, the dynamic characteristics of the carrier system will have a fundamental effect on the stability of the technological system during machining, and determine the level of vibrational vibrations as a result of external disturbances.

Dynamic processes that are not directly related to the cutting process occur in various positioning systems, systems for fixing and securing tools and workpieces. The dynamic characteristics of such systems do not directly affect the cutting process, but they determine the operability and performance of the machine.

2. Materials and methods. Types of dynamic processes
In technological systems, stationary and non-stationary dynamic processes are also distinguished. A stationary process in a dynamical system is a process in which the variables describing its behavior do not change with time or are periodic functions of time (over a certain interval of its variation). Stationary processes can be divided into steady-state and quasi-static processes.

Dynamic processes are called non-stationary or transient when their condition cannot be characterized as steady. Transient processes in technological systems occur during the change in energy conditions...
during the transition from one steady state to another. Stationary modes include the modes of forced oscillations that occur during cutting with a multi-blade tool, during machining of regular profiles, and also when the rotary motion drive is operated with unbalanced parts, tools, workpieces, and rotors of motors.

Typical non-stationary modes are the run-up and run-down modes of the drives at idling speed, cutting and tool exit. Most of the dynamic processes in machine tools, which are related to weakly dissipative systems, have an oscillatory character. In technological systems, mechanical oscillations of practically all species are observed [3, 4].

3. Oscillations in technological systems
Distinguish free and forced oscillations of technological systems. Free oscillations - oscillations of parts and parts of the machine, occurring in the absence of disturbing effects and without energy from outside. Such oscillations arise due to the initially accumulated energy of the system due to the available initial displacements and velocities.

Free oscillations occur only in autonomous systems, are damped and do not have a significant effect on the indicators of dynamic quality. But the definition of natural frequencies and own modes of vibration of elastic machine systems is one of the main tasks of dynamic machine calculations [1, 3]. The identification of the own frequency spectra of machines is becoming important for eliminating resonant modes in forced oscillations. Knowing the spectra of the machine and its components, you can effectively solve the problems of vibration protection, control, etc.

Forced oscillations, characteristic of non-autonomous dynamical systems, are caused by variable perturbing external influences. Forced oscillations refer to the main types of oscillations, which have a significant effect on the indices of the dynamic quality of the technological system of machining. There are forced oscillations arising from internal sources - a working machine engine, a rotating tool, unbalanced workpieces. In the joints with reciprocating moving nodes, intense perturbation sources are the perturbations that arise when the angles are reversed [1, 5].

External sources that cause oscillations in the bases of machine tools include:
1. Oscillations transmitted by closely located equipment with unbalanced masses, with the impact nature of the processes being realized, etc. In these cases, the frequency of oscillations arising when cutting is the same or an integer multiple of the frequency of the exciting oscillations.
2. Oscillations caused by defects in machine gears. Incorrectly cut, poorly assembled or worn gears cause periodic forces transmitted to the bearings, and therefore to the spindle and machine bed, which under certain conditions is a frequent cause of vibration.
3. Oscillations caused by the elastic properties of soils, load-bearing structures of buildings (overlapping, common slabs, etc.). As the investigations [3] have shown, the method of setting up the machine has a significant effect on the stability during cutting, if the relative movements of the tool and workpiece in the cutting zone depend on the oscillations of the bearing systems.
4. Oscillations caused by an imbalance in the rapidly rotating parts of the machine or workpiece. In these cases, the centrifugal force changes direction, which causes oscillations.
5. Oscillations caused by the variable cross-section of the cut or by the intermittent nature of the cutting process.

Analyzing forced oscillations of elements of technological systems directly involved in the process of forming products (such as a spindle, calipers, racks, tables, etc.), it is possible to determine the frequency ranges of permissible operating conditions. Resonant modes, as the modes of the most intense oscillations, are generally considered in machines unacceptable. Therefore, one of the main tasks is the exclusion of operating modes of resonances. Since the level of resonant and near-resonance oscillations is determined to a large extent by the dissipative properties of the dynamic system of the machine, a reliable evaluation of these properties requires the execution of a set of special papers [5, 6].

There are parametric oscillations of technological systems, which are caused by changes in the time parameters of the system. But such oscillations in machine tools are rare. Under certain conditions, they
arise in mechanisms with a nonlinear position function, which, for example, carry out reciprocating movement of the executive organs.

4. Self-oscillations in machine tools

Particular importance for identifying dynamic processes occurring in technological systems is the study of self-oscillations of machines. Self-oscillations (self-excited oscillations) arise and are maintained from a source of energy of an oscillatory property included in a nonlinear dynamical system. Self-oscillations in metal-cutting machines are the main type of vibrations that determine the features of the technological system of machining.

Self-oscillation as a global property of a dynamic system indicates a closed and non-linear dynamic system. Such understanding of these properties of the technological system allows us to correctly approach the construction of a dynamic model of the technological system, to study it, and to establish the tasks of controlling dynamic processes in the system [7, 8]. At the moment, the nature of the occurrence of self-oscillations in metal-cutting machines has not been fully revealed.

There are auto-oscillations arising during cutting and self-oscillation arising from friction. Since self-oscillations during cutting are, as a rule, excluded from the number of operating modes, one of the important problems of the dynamics of the technological machining system is the determination of the position of the boundary of the stability region in the parameter space of the system. Solving the problems of expanding the range of parameters with a regulated level of self-oscillations, it is extremely important to establish a relationship between the level of self-oscillations and tool resistance, with the formation of macro- and microgeometry of the processed surface of products, residual stresses in the surface layer, etc.

The problem of self-oscillations in friction was solved with reference to metal-cutting machines at first without connection with the same problem in friction, but in the future, bearing in mind the generality of approaches, is considered jointly [9, 10]. The self-oscillating frictional regimes arising from the movement of the moving machine units on the guide rails are characteristic both for operating modes and for the adjustment modes in the positioning process. Consequently, their influence significantly affects the characteristics of the dynamic quality of technological systems. The fact of occurrence of self-oscillations is important as well as their appearance: whether self-oscillations are close to harmonic or relaxation, or not.

5. Modeling of dynamic processes in technological systems

When studying the dynamic processes of vibrational multimass systems, the real mechanical system of the machine is replaced by a design scheme, i.e. a system with a finite number of degrees of freedom. The calculation scheme should be, on the one hand, equivalent to a real machine system with sufficient accuracy for practical application; on the other hand it is quite simple and reduced, to the extent possible, to a minimum amount of concentrated masses [1, 4].

The design scheme of a vertical drilling machine can be represented as a certain number of concentrated masses connected by weightless elastic and dissipative elements with linear characteristics.

This design scheme allows us to describe the dynamic processes occurring in the multi-mass mechanical system of the machine tool by a system of linear differential equations of the second order. Linear representation can be justified by the interference of the oscillating system by the cutting forces and the weight of the elements, and also by the relative small amplitude of their oscillations. The machine's mechanical system consists of the following main components: a spindle unit, a spindle head with an electric motor, a stand, a table and a machine base. Body parts are considered as absolutely rigid bodies, since their own deformations are substantially lower than the deformation of the joints.

The machine nodes are represented as concentrated masses \( m_i \) and moments of inertia \( J_i \), the stiffness of the contact areas determines the linear \( c_i \) and the angular \( K_i \) stiffness of the joint. The dissipative connections that determine the damping of the system's oscillations are represented as linear \( h_i \) or angular \( g_i \), depending on the shape of the oscillations.

Thus, the design scheme of the oscillatory system of a vertical drilling machine contains five concentrated masses, connected by elastic and dissipative bonds. Each mass in the general case has six
degrees of freedom, but the most interesting oscillations are those that are along the vertical axis of the
machine. In the case under consideration, the motion of each mass can be described by a second-order
differential equation, and, accordingly, the motion of the entire oscillatory system — by a system of such
equations. To describe the mathematical model of the vibrational one, one can use the d'Alembert
principle or the Lagrange equation of the second kind [4].

To compile a mathematical model of the oscillatory system of the machine, let us use the simplified
calculation model (Figures 1), which will be valid for the low-frequency range of the workloads and
external disturbances (0 ... 500 Hz); in this range, the vibration resistance of the machine is most often
observed. The diagram shows: a spindle head ($m_1$, $J_1$), a spindle knot ($m_2$) and a table ($m_3$). The stand, the
base of the machine and the joint between them are assumed to be absolutely rigid and fixed relative to
the foundation.

![Figure 1. Calculation scheme for vertical drilling machine.](image)

The mathematical model of the dynamic processes of the oscillatory system for this case will be
described by the following system of differential equations:

$$\begin{align*}
    m_2 \dddot{y}_2 + h_3 (\dot{y}_2 - \dot{y}_1) + c_2 (y_2 - y_1) &= P(t) \\
    m_1 \dddot{y}_1 + h_1 \dot{y}_1 + c_1 y_1 + h_2 (\dot{y}_1 - \dot{y}_2) + c_2 (y_1 - y_2) &= 0 \\
    J_1 \dddot{\phi}_1 + g_1 \phi_1 + K_1 \phi_1 + h_2 (\phi_1 R - \dot{y}_2) R + c_2 (\phi_1 R - y_2) R &= 0 \\
    m_3 \dddot{y}_3 + h_3 \dot{y}_3 + c_3 y_3 &= -P(t)
\end{align*}$$

where $y_1$, $y_2$, $y_3$, $\phi_1$ are the linear and angular deformations of the elements of the oscillatory system; $R$ —
spindle take-off or the action force of the cutting force $P(t)$ relative to the joint: the spindle headstock is
the stand.
Having transformed the system of differential equations by the Laplace method, and having grouped the coefficients with respect to the variables, one obtains a system of equations in the operator form of writing:

\[
\begin{align*}
\left( m_2 p^2 + h_2 p + c_2 \right) y_2 - \left( h_2 p + c_2 \right) y_1 &= P(p) \\
\left( m_1 p^2 + h_1 p + h_2 p + c_1 + c_2 \right) y_1 - \left( h_2 p + c_2 \right) y_2 &= 0 \\
\left( J_1 p^2 + g_1 p + h_2 R^2 p + K_1 + c_2 R^2 \right) \varphi_1 - \left( h_2 R p + c_2 R \right) y_2 &= 0 \\
\left( m_3 p^2 + h_2 p + c_3 \right) y_3 &= -P(p)
\end{align*}
\]  

(2)

Further from the obtained system of equations let us find the transfer function of the oscillatory system. The value of the transfer function is determined by the ratio of the Laplace images of the output and input parameters of the system. With respect to the oscillation system under consideration, the transfer function \( W_c(p) \) is the ratio of the tool and workpiece displacement \( y \) (output parameter) to the external force \( P \) corresponding to the cutting force (input parameter):

\[
W_c(p) = \frac{y(p)}{P(p)}.
\]  

(3)

The frequency characteristics of the oscillatory system can be determined from the transfer function \( W_c(p) \) by replacing the operator \( p \) by the complex variable \( i\omega \) (1). Having isolated the real and imaginary parts in the resulting expression, one can obtain a complex frequency response:

\[
W_c(i\omega) = \frac{y(i\omega)}{P(i\omega)}.
\]  

(4)

The amplitude-phase frequency characteristic of the oscillatory system will be a complex quantity and, after the transformation of the last expression, can be represented in the following two forms:

- in Cartesian coordinates

\[
W_c(i\omega) = Re_c(\omega) + i Im_c(\omega);
\]  

(5)

- in polar coordinates

\[
W_c(i\omega) = A_c(\omega) \cdot e^{i\varphi_c(\omega)},
\]  

(6)

where \( Re_c(\omega) \) is the real part; \( Im_c(\omega) \) is the imaginary part; \( A_c(\omega) \) is the amplitude equal to the ratio of the amplitude of the output parameter to the amplitude of the input; \( \varphi_c(\omega) \) is the phase between the oscillations of the output and input parameters.

The transition from Cartesian coordinates to polar coordinates is carried out as follows:

\[
A_c(\omega) = \sqrt{Re_c^2(\omega) + Im_c^2(\omega)}; \quad \varphi_c(\omega) = \arctg \frac{Im_c(\omega)}{Re_c(\omega)}.
\]  

(7)

Amplitude-phase frequency characteristics of the oscillatory system can be used to determine the natural frequencies of oscillations of the machine and to control the spectrum of the frequencies obtained during the detuning of the oscillatory system from the resonant frequencies. Also, the received frequency characteristics will be enough to determine the vibration level of the machine at idle speed, which is an important indicator of the dynamic quality of the machine. Determining the frequency characteristics of the oscillatory system is very important for the stability of the machine in different operating modes, i.e. in the process of cutting, positioning the working element, etc. [4, 9, 10, 11, 12].

6. Conclusion
At present, much attention is paid to the study of the causes of the emergence of dynamic processes in technological systems. The study of vibration resistance of machine tools, the causes of self-oscillation regimes and their interaction with forced oscillations, and measures and methods for their elimination are also proposed.

Since technological equipment is a complex oscillatory system with distributed inertial and elastic parameters, having an infinite number of degrees of freedom and an unlimited number of natural oscillation frequencies, the main difficulty in studying oscillatory processes in machine tools is the construction of an adequate and relatively simple mathematical model of dynamic processes.

The main parameters of the oscillatory system must be taken into account in calculations: the masses, the moments of inertia of the assemblies and parts, the rigidity of elastic elements, the forces of inelastic resistance (damping), the connections between mass displacements in a system with many degrees of freedom.

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