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I. Shmagel, S. Vakulenko,
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"

Substantiation and choice of mathematical model structure for theoretical study of vibration resistance increasing problem of the lathe dynamic system during turning

The theoretical study of lathe's vibration resistance during turning process can be effectively realized by using modern means of mathematical modeling, which are characterized by a sufficient accuracy degree of correlation between input forces actions or disturbances and the machine tools dynamic response. An important requirement in creating a mathematical model of a machine tools dynamic system is providing ability to describe the physical characteristics of the studies object in a simple and convenient form and obtain the necessary, essential and reliable information about the properties of a real physical system. The theoretical study and analysis of dynamic processes of a potentially unstable lathe carriage system during turning is accompanied with a need in creation a calculation scheme of dynamic turning process and a mathematical model of studies lathe system. The implementation of this mathematical model will make it possible to determine the influence of the elastic and dynamic characteristics of special tool holder with an oriented center of rigidity on relative vibrations between work piece and cutter, and, in generally, on the main indicator of dynamic system quality of machine tools - vibration resistance.

In many cases, when studying the processes in the machine tools dynamic system during turning, it is sufficient to achieve reliable information using deterministic and linear mathematical models. The existing experience in the lathe vibration resistance study during cutting process indicates that the most important thing is to take into account in the mathematical model the coordinate interdependence [1] between the cutter's oscillation movement relatively workpiece surface and cutting forces value. Exactly this coordinate interdependence has the greatest effect on reducing the lathe vibration stability during cutting process and increases the possibility of specific sustained self-oscillations. So, the mathematical justification of cutting process vibro-stability losing is possible only taking into account the closedness of the investigated machine tool dynamic system with feedback through the dynamic cutting process.

The vibration resistance of the machine tools dynamic system during cutting depends mainly on the characteristics and parameters of its shape-forming machine tool units, such as stiffeners, the ratio of their parameter values and the relative orientation of the axes of maximum and minimum rigidity relative to the cutting force vectors direction. The lathe's carriage elastic system is a complex system with many degrees of freedom and the number of natural vibration modes. For each of these modes of vibration, it is possible to conditionally distinguish ellipses of elastic displacements, the directions of the main axes of which do not coincide with the general coordinate axes of the machine. The experience of the conducted theoretical research has revealed that intense self-oscillations are carried out at that frequency corresponding to the frequency of natural oscillations of the dominant elastic system, namely, to the oscillation frequency of that link or element of the lathe's elastic system, that has the largest displacement ellipse dimensions. Considering this fact, the scheme of carriages machine tool elastic subsystem and workpiece subsystem can be represented as a single-mass dynamic system with two degrees of freedom in the movement plane which is normal to machined surface. Such a simplification of the multi-mass machine tools dynamic system is permissible, because vibrations at other frequencies during cutting are not dominant and have insignificant effects of coordinate interdependence on the cutting process. A simplified single-mass mathematical model of a potentially unstable carriages dynamic system allows theoretical studies of dynamic systems stability according to the Nyquist criterion, with plotting Nyquist diagram of the open-loop system, consisting of the frequency (positive and negative) characteristics of each of the two normal vibration modes, crosses the negative part of the real axis.

The cutting process simulation is also carried out with taking into account its dynamic properties, such as the time constant of chip formation, time constants of rake and clearance angles of cutting process. However, when studying the occurrence of low-frequency and medium-frequency self-oscillations, the effect of changing rake and clearance angles almost does not change, and the time constants of rake and clearance angles are relatively small unchanged values, therefore, to simplify the dynamic characteristics of cutting process, these parameters are not taken into account. So, the dependence of cutting depth on the cutting force value can be linearized, while vibrations limiting of dynamic system only in the horizontal direction of Y axis.

A known solution [2,4] to the problem of vibration resistance increasing is use of special tool holder with an oriented position center of rigidity, which corrects the ellipse of vibration movement of the dominant carriage system at its main natural frequency, since these dynamic elements are partial and interconnected. Therefore, the mathematical model of lathes dynamic system should take into account the elastic and dynamic characteristics of tool holder's system, as an element of the tool holders partial subsystem, which is connected through feedback-loop of the cutting process with the workpieces partial subsystem and all together form a close-loop machine tool's dynamic system.

The most lathes vibration stability during turning is achieved when the action direction of the cutting force vector approaches the axis of maximum rigidity of carriage system; otherwise, in the machine tools dynamic system negative effect of coordinate interdependence on the relative oscillations level of cutter and workpiece is enhanced. The direction of the maximum rigidity axes of carriages elastic system passes through point on top of cutter tool to center of rigidity point. The main elastic deformations and displacement of carriage under the force action in this direction are determined by main axes of rigidity. If the force direction which acted on the carriage does not pass through the center of rigidity (fig.1), an additional elastic rotation occurs in the system around this point, so the rigidity in the direction perpendicular to the axis maximum rigidity will be minimal. The mathematical model of the machine tool dynamic system takes into account the elastic characteristics which reduced to the point of cutter top as the maximum and minimum stiffness coefficients of the carriages equivalent elastic subsystem and the angle of orientation in the direction of axes of rigidity.

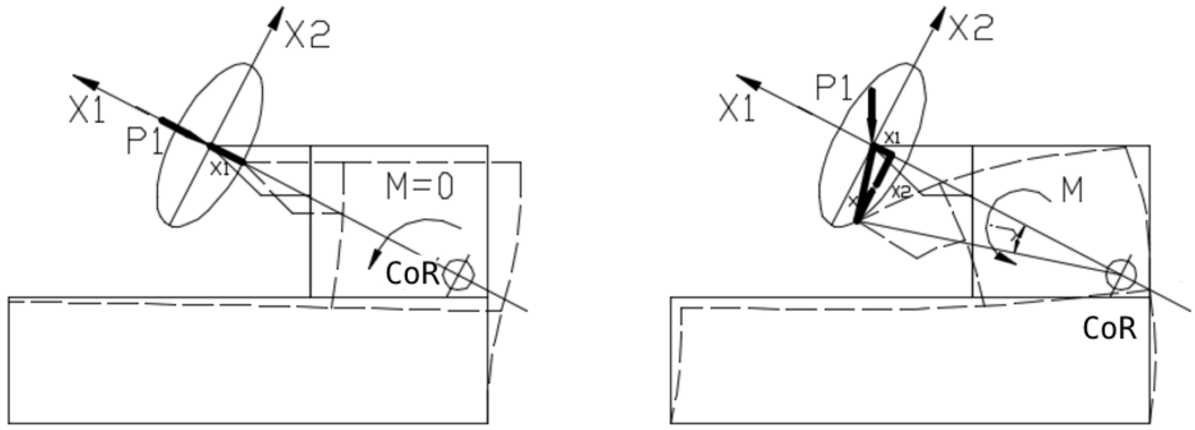

Fig. 1 The determining scheme the reduced elastic parameters of axes of rigidity depending on center of rigidity position of the machine tool carriage elastic system

Ensuring the optimal position of the center of rigidity carriage elastic system of real lathe structure is a difficult task, especially in the case of double-sided turning is impossible. Therefore, it is important to take into account in mathematical models, reduced stiffness coefficients of tool holder elastic subsystem, and orientation angle parameters of axes of rigidity, which differs from the orientation angle for carriage elastic subsystem.

The structure of a closed-loop lathe dynamic system with cutting process is shown in general form in fig. 2 and consists of an equivalent elastic subsystem (EPS) "tool holder", "carriage" and "workpiece", which interact with each other through negative feedback-loop of the cutting process. The open-loop lathe dynamic system has an input in the form of a time-varying thickness of the cut layer of the workpiece $\Delta y(t)$and a random component of the change in the part allowance $h(t)$. The output of an open-loop dynamic system is the total relative dynamic elastic displacement of the workpiece and the cutter along the y-axis under the cutting force action.

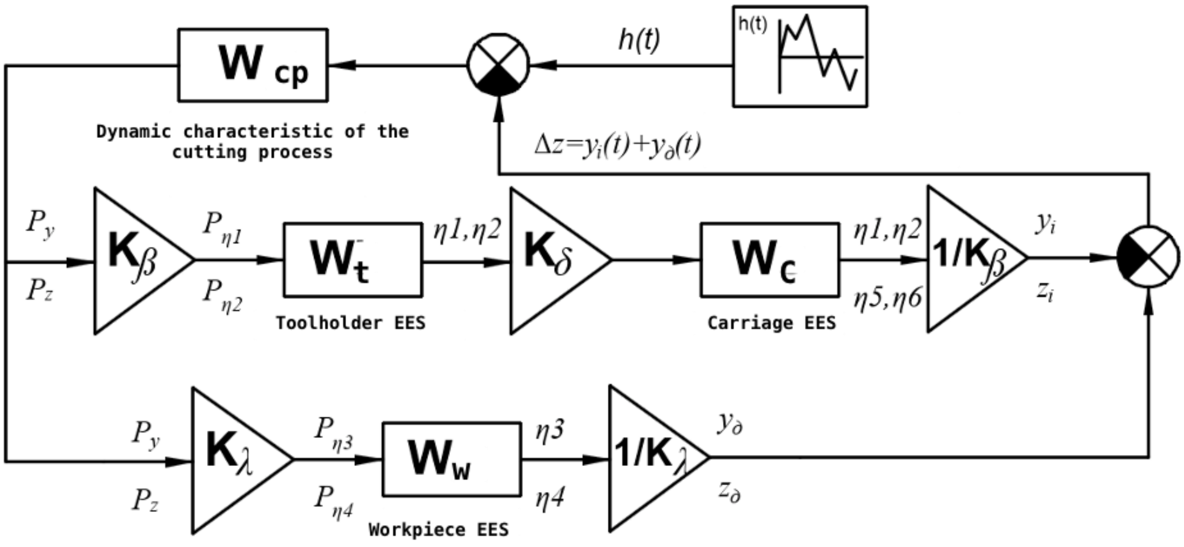

Fig. 2 Block scheme of a closed-loop machine tool dynamic system during cutting process

The machine tool equivalent elastic system (EES) is represented by blocks that reflect the response to the cutting force in the *y0z* plane. The general elastic system has a structure of two branches - the workpiece and cutter, which influence each other only through negative feedback-loop of the cutting process. Equivalent elastic system of machine tool, takes into account the elastic characteristics of the tool holder and carriage as two interconnected partial systems. The reactions of each of these elastic subsystems in the form of displacement along the given coordinate axes η_1, η_2, η_4, $\eta_5$form the total displacement of the cuttery_i. However, these elastic deformations, depending on their direction, have different effects on the given input actions. 183

The elastic displacements due to the deformation of the system of workpiece and cutter branches at the *y* coordinate directly affect the given cutting depth. However, the deformation at the *z* coordinate due to its small value $\Delta_z = z_i(t) + z_\partial(t)$ in comparison with the workpieces radius, and the small value of the instantaneous rate of deformation change $\frac{d\Delta_z}{dt}$ in comparison with the cutting speed, in a machine tool dynamic system is not taken into account. The mathematic model also has the direct and inverse transformation of the elastic displacements value in the general coordinate system *y0z* into the given $\eta_1 O \eta_2$, $\eta_3 O \eta_4$, $\eta_5 O \eta_6$through the matrix of coefficients K_β, K_γ, K_δ..These matrices have the values of the orientation angle of the reduced axes of the equivalent elastic system of the tool holder, carriage and workpiece.

Using the presented mathematical model of the EES of the machine tool, which consists a tool holder subsystem, a workpiece and carriage, it is possible to carry out a simulation analysis of working turning processes and evaluate the influence of the main parameters of stiffness and damping any of the subsystems, for example, a tool holder, on vibro-stability indicators general machine tool dynamic system during cutting process. Carrying out such theoretical analysis is possible using any modern programming languages which has integration function. However, it is convenient for such research tasks to use the professional tool for modeling dynamic systems like Matlab Simulink.

A general strategy for conducting simulating is recommended according to the following sequence of actions (fig. 3), according to which it is possible to theoretically determine the dependences of the changes in elastic characteristics influence such as the maximum and minimum stiffness parameters and the angle of orientation axes of rigidity for carriage and toolholder elastic systems on the vibration resistance during the cutting process.

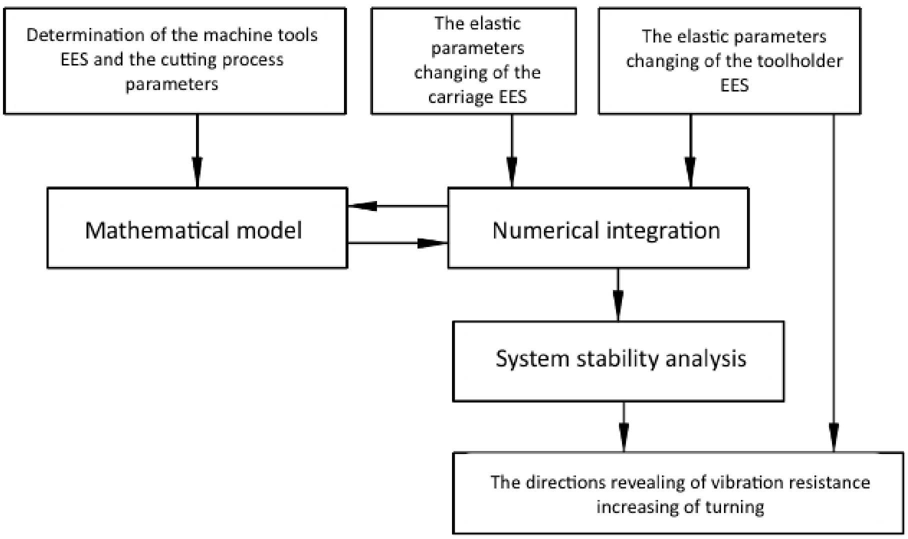

Fig. 3Algorithmoftheoreticalstudies

The vibration stability analysis and the relative oscillations level of the machine tools dynamic system is carried out according to the obtained by numerical integration of the Nyquist plot of the open-loop machine tool dynamic system and the temporal characteristics of the change in the cutter trajectory of closed-loop system. The obtained simulation results, especially those that indicate the positive effect of using turning toolholder with an oriented position center of rigidity, should be verified by experimental trying. To carry out simulating with adequate results, it is necessary to determine the parameters of dynamic model for cutting process: the cutting coefficient and the time constant of chip formation [3]. Since the study of changes in the parameters of the cutting process for dynamic system vibration resistance is not investigated, therefore, it is advisable to use the known experimental data. Determination of the reduced elastic parameters: the coefficient of maximum and minimum reduced stiffness and the reduced mass for the EES of the toolholder, carriage and workpieceare carried out experimentally. Sometimes, instead of conducting an experimental study of determining such parameters as the coefficient of reduced stiffness, frequency and form of natural oscillation, followed by the determination of reduced mass of machine structure units and elements, it is more convenient to simulate the spring-deformed state. System parameters characterizing internal friction or vibration damping coefficient are determined only from the analysis of experimental data.

Thus, mathematical models of the toolholder systems, workpiece, carriage and the dynamic system of cutting process are presented in aggregate to form a complex closed-loop machine tool dynamic model. The mathematical model makes it possible to carry out simulation studies of turning in order to determine the most rational design and dynamic parameters of special toolholder with an oriented position center of rigidity and to assess the effectiveness of its use. Such theoretical studies take into account the dynamic characteristics of a potentially unstable machine toolcarriage system during cutting process and will reveal the ratio between the maximum and minimum stiffness and the angle value of stiffness axes orientation of toolholder elastic system at which an increase in vibration resistance during turning is possible. The obtained simulation results as well as dynamic and elastic parameters must be taken into account when designing turning equipment for lathe.

REFERENCES

1. Kudinov V.A. Dinamika stankov (Dynamics of machines), Moscow: Mashinostroenie, 1967, 360 p.

2.Vakulenko S.V. Lathe tool holder with the oriented position of the center of rigidity // X International congress “Machines, Technologies, Materials”, vol.2, ISSN 1310-3946, - Scientific-technical union of mechanical engineering, Varna, Bulgaria 2013. p. 128-131.

3.Vakulenko S., Theoretical research of the cutting process dynamic characteristics // Zbiórartykułównaukowychrecenzowanych. "Science, Research, Development Technics and Technology." Z 40 - Warszawa, 2020. - 72 p. - p. 39-44. ISBN: 978-83-66401-53-2

4.Vakulenko S., Analysis of known design solutions of increasing turning vibration stability // Zbiórartykułównaukowychrecenzowanych. "Science, Research, Development Technics and Technology." Z 40 - Warszawa, 2020. - 72 p. - p. 30-36. ISBN: 978-83-66401-53-2.