Simulation of dynamic processes when machining transition surfaces of stepped shafts

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Abstract. The paper addresses the characteristics of stepped surfaces of parts categorized as "solids of revolution". It is noted that in the conditions of transition modes during the switch to end surface machining, there is cutting with varied load intensity in the section of the cut layer, which leads to change in cutting force, onset of vibrations, an increase in surface layer roughness, a decrease of size precision, and increased wear of a tool's cutting edge. This work proposes a method that consists in developing a CNC program output code that allows one to process complex forms of stepped shafts with only one machine setup. The authors developed and justified a mathematical model of a technological system for mechanical processing with consideration for the resolution of tool movement at the stages of transition processes to assess the dynamical stability of a system in the process of manufacturing stepped surfaces of parts of "solid of revolution" type.

1. Introduction

Parts like shafts and axes are some of the most loaded parts of machines and mechanisms and are used in all areas of mechanical engineering. Coming from the strength requirement, it is rational to design shafts with variable cross-section that are similar in shape to bodies with uniform strength. A stepped shape is convenient in manufacturing and assembly, but the steps may come to take significant axial forces [1].

A particular feature of processing in the conditions of transition modes during the switch to end surface machining is cutting with varied load intensity in the section of the cut layer, which leads to change in cutting force, onset of vibrations, an increase in surface layer roughness, a decrease of size precision, and increased wear of a tool's cutting edge. This, in turn, reduces a tool's durability and facilitates gaps and backlash in the technological system.

The crucial condition for achieving high quality of machined surface is ensuring stability of the cutting process. Development of a self-oscillating process in a technological system of mechanical processing is also influenced by the processes of low-amplitude friction in a machine's support assembly, which is particularly important during transitional stages of processing.

2. Materials and methods

One of the promising methods of maintaining the necessary parameters of precision and quality of stepped shaft machining is the method of ensuring the dynamic stability of a technological system in transition modes during processing surfaces of "solid of revolution" parts by factoring in the processes of friction in CNC machine slideways.
The essence of this method lies in developing a CNC program output code that allows one to process complex forms of stepped shafts with only one machine setup. In this case, mode parameters are adjusted considering the factors that negatively affect the precision and quality of machining, such as vibrations caused by inconsistencies in tool movement conditioned by the nonlinearity of the characteristics of friction in a machine's slideways, and disturbance effects caused by the system's inertia in tool movement acceleration and stop regions along one of the axes.

An important moment in the process of simulating a technological system that describes interactions between the "tool" and "workpiece" subsystems in the conditions of mechanical stepping is the mathematical description of the processes of cutting and friction based on the set mode parameters [2].

It is also necessary to take into account the influence of change in processing direction; many parameters of a dynamic model assume new values, sometimes even another sign, which characterizes that not only the degree of this process' influence has changed, but even the nature of its effect on the development of the oscillating process.

The goal of this study is to design a model of a technological system for mechanical processing of "solid of revolution"-type parts on the basis of implementing algorithms of writing CNC output code taking into account changes in the system's stability in transition modes and the processes of low-amplitude friction in a turning machine's slideways during finish machining.

3. Discussion of research results
During processing of shaft's stepped surfaces, one can observe the alternating operation of feed drives, and the places where a tool cuts into the processed material, where the areas of the largest deviation of the points of the shaped surface from those in the blueprint are formed (Figure 1).

During the process of cutting a tool into the processed material (Figure 1 a, c) the observed jump in general vibration levels exceeds the level of established oscillations under constant processing parameters 1.7-2.2 times, which necessitates to start and stop work by rolling during such processing steps. When considering this process from the point of view of the mathematical model and adjusting CNC processing mode parameters, the depth of cut \( t \) is changed while other parameters are invariant [3-4].

Another thing observed during step machining is a jump in the general level of vibration within the immediate vicinity of the reference point that characterizes a vertex of an angle; however, the amplitude of the oscillating process exceeds the established oscillation level 1.3-1.5 times. This is conditioned by that, in this case, the tool does not leave the material of the workpiece, and the increase in the system's vibration level is conditioned by the disturbance effect of the processes that occur in the supports and feed drives, characterized by acceleration, deceleration, and friction. Magnitudes of these disturbance effects depend on the defined mode parameters, particularly initial and final linear feed velocities for every direction and acceleration. Adjusting these parameters can influence the intensity of the oscillating process in the areas of step processing. It should be borne in mind that the range of possible adjustments depends on which mode parameters are chosen to be invariant, as well as on the minimal values of feed \( S \) and cutting velocity \( V \) allowed for a particular tool.

It can be seen in Figure 2 a) that the initial jump conditioned by the system's shift from friction to sliding friction, as well as the process of shifting from "jump-like" movement to moving in established oscillations correspond in a larger degree to the experimental data (Figure 2 b), obtained from processing a workpiece made from 40KHN steel in a CNC turning machine with different values set to the linear velocity of tool movement.

Furthermore, this research demonstrated that with the increase of the set velocity of the support stand movement, the nature of the resulting oscillating process changes substantially. With low sliding speeds up to 40 mm/min, the profile charts clearly showed the instances of the chafing surfaces "gripping", where the oscillating process consisted of relaxation self-oscillations caused by the jump-like movement of the support stand, and oscillations caused by the discrete nature of the movement of the drive's reference unit. As the velocity increases, chafing surfaces stop to "grip", and the oscillating
process represents a combination of self-oscillations caused by the nonlinearity of the process of friction, and the drive's reference input signals characterized by a higher eigen frequency. With the velocities of movement higher than 100 mm/min, the irregularities, caused by the nature of the reference unit's movement, are almost completely suppressed by the system's inertia, and the established oscillations become harmonic, characterized only by the friction process' nonlinearity.

![Diagram of the transition processes and vibration of a technological system in various sections during processing of a stepped shaft, where a, b are longitudinal machining, and c, d are end surface machining](image)

**Figure 1.** Diagram of the transition processes and vibration of a technological system in various sections during processing of a stepped shaft, where a, b are longitudinal machining, and c, d are end surface machining.

Analysis of the nature of movement of supports stands along the slideways, as well as the obtained values of vibration acceleration and vibration displacement amplitudes, allow one to identify the range of linear velocities and feed, under which the level of disturbance action on the technological system from the low-amplitude friction processes in the tool positioning devices will not lead to loss of stability of the dynamical system and can be recommended for the transitional processing mode parameters.
Figure 2. Comparison of the oscillations of the velocity values of the support stand's movement along the OZ axis with the speed defined to 1.67 mm/s: estimated (a) and experimental (b)

To determine the boundaries of a technological system's stability region, a mathematical model was designed, which is shown in Figure 3 in a simplified form.

Figure 3. A simplified structural layout of a technological system model that considers the disturbance effects of irregularities in feed drive movement $x_p(t)$ and $z_p(t)$

The obtained closed-loop system is fed with external disturbances that were pre-calculated under certain processing modes and nature of movement that describe the tool's movement trajectory deviation from the ideal one, implied by the CNC output code. At different processing stages, values of these disturbances will differ and, as a consequence, boundaries of the stability region will also differ. Operating the values of the set disturbances and knowing the mechanism of their appearance, for each section of the step of processing a stepped shaft it is possible to determine mode parameters and functional dependencies of their change to ensure the conditions of the machining process stability in the entire contour work processing step.

In this case, an adequate transition to a reduced-dimension model is performed based on the limits of the frequency range of the disturbance effects and low dissipative characteristics of the technological system. Simplification of the model is justified by the closeness of the spectral characteristics to the original model [2, 5 - 7].

The simplified and original models are equipotent if the following condition is met:
\[ \rho(W, W^m) \leq \varepsilon_m; \quad (1) \]
\[ \rho(W, W^m) = \min \rho(W, W^m), \quad (2) \]

where \( W, W^m \) is a matrix of frequency characteristics of the source and simplified models, \( \rho(W, W^m) \) is a metric that sets the distance between \( W \) and \( W^m \), \( \varepsilon_m \) is the set error value.

Meeting the conditions of the generalized and simplified models is ensured by the closeness of the phase and frequency-response characteristics.

In such case, the preliminary simplified model of a technological system for machining "solid of revolution"-type parts taking into account the closeness of the spectral and amplitude characteristics of the full model (1) and the simplified one (2) with the possibility of changing mode parameters and direction will take the form as shown in Figure 4. This model has four degrees of freedom: two of them characterize the "tool" subsystem and the other two characterize the "workpiece" subsystem, unified with each other through the process of machining and chip formation, having the purpose of introducing external disturbance effects coming from the support stands for lateral and crosswise movement of the tool, characterizing the processes of low-amplitude friction, and acting as a qualitative indicator of the processed stepped surfaces of a part.

![Figure 4](image)

**Figure 4.** A simplified dynamic model of a technological system for stepped shaft machining with four degrees of freedom, where a) is a model for lengthwise tool movement; b) is a model for the end surface processing process

4. **Conclusion**

As the result of this research, the authors developed and justified a mathematical model of a technological system for mechanical processing with consideration for the resolution of tool movement at the stages of transition processes to assess the dynamical stability of a system in the process of manufacturing stepped surfaces of parts of "solid of revolution" type.

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