Modeling of contact interactions in lathe turning with accounts for rheology in the cutting zone

D V Vasilkov¹, V S Cherdakova¹ and M S Bundur²

¹ Baltic State Technical University VOENMEH, 1, 1st Krasnoarmejskaja street, St. Petersburg, 190005, Russia
² Peter the Great St. Petersburg Polytechnic University, 29, Polyteknicheskaya street, St. Petersburg, 195251, Russia

E-mail: vasilkovdv@mail.ru

Abstract. This article discusses the dynamic modeling of contact interactions in the technological system of machining in the turning process based on piecewise linear approximation. A feature of the model is that it differentiates between the conditions of contact interaction between the front surface of the tool and the coming off chips, as well as between the back surface of the tool and the workpiece being processed. The consideration is based on the two-term characteristic of friction, realized in the form of a sequence of sliding and adhesion phases. In this case, the process of contact interaction in each phase is described by a set of rheological models. The phase switching conditions are determined by the rate of relative contact interactions, as well as the contact pressures between the front surface of the tool and the chips, between the back surface of the tool and the workpiece. Differentiated description of contact interactions from the front and back surfaces of the tool made it possible to build a tool for studying the processes of self-regulation of contact interactions in dynamic contours and the connectivity between them, which allows us to determine the conditions for the formation of self-oscillations that the dynamic system imposes on itself. The performed experimental studies have shown the correspondence between the nature of the movements during modeling and real cutting.

1. Introduction

During mechanical tooling, issues arise in ensuring product quality (dimensions, micro and macro of surfaces, residual post-processing stresses). They may be efficiently resolved by studying dynamic properties of the tooling processing system, in particular, the contact interaction in the chip formation zone [1-6].

Analysis of processes taking place during the interaction between the chip and the frontal surface of a tool and between the processed surface and the back surface of the tool allows representing this process as a two-stage one, with a binding stage and a gliding stage [7-9].

Molecular processes taking place in the chip formation zone are represented as rheological models that link together a blank subsystem and a cutting tool subsystem [8-10]. In the model representation, the processes in question are reflected as a viscoelastic Voigt medium, an ideal Hooke's medium, an ideal viscose Newton's medium and an ideal plastic Saint-Venant medium (a trigger-shaped key) (Figures 1, 2), adapted to the problem in question. The modeled conditions include the interaction of
2. Materials and methods
Complex, refractory and aluminum alloys tend to form adhesive links at a broad range of cutting speeds. In [5], it has been confirmed that in the contact interaction area between the cutting tool and the blank there is a continuous formation (binding) and destruction gliding of adhesive links.

**Figure 1.** Rheological representations of force interactions in the cutting area

Conditions for transition between a gliding stage and a binding stage in interaction of the front and back surfaces of the tool with a chip and produced surface respectively are formed by the system itself, which is potentially auto-oscillating.

In Figure 1: \( R_{ZF}, R_{YF} \) is a group of rheological elements along the front surface in the direction of \( OZ, OY \) axes; \( R_{ZB}, R_{YB} \) is a group of rheological elements along the back surface in the direction of \( OZ, OY \) axes; \( z, y \) are generalized coordinated in the direction of \( OZ, OY \) axes, \( c_z, c_y \) are stiffness coefficients, \( b_z, b_y \) are dissipation factors.

In Figure 2: \( c_{f1}, c_{f2}, c_{v1}, c_{v2}, b_{f1}, b_{f2}, b_{v1}, b_{v2} \) are elasticity and dissipation factors of the rheological elements along the front surface of the tool in the direction of \( OZ, OY \) axes; \( c_{b1}, c_{b2}, c_{v1}, c_{v2}, b_{b1}, b_{b2}, b_{v1}, b_{v2} \) are elasticity and dissipation factors along the frontal surface of the tool in the direction of \( OZ, OY \) axes; \( Sv_{v1} \) and \( Sv_{v2} \) are Saint-Venant's tribological elements in the tangential outline along the back surface of the tool, \( Sv_{b1} \) and \( Sv_{b2} \) are Saint-Venant's tribological elements in the normal outline along the back surface of the tool; \( Sv_{f1} \) and \( Sv_{f2} \) are Saint-Venant's tribological elements in the tangential outline along the front surface of the tool, \( Sv_{v1} \) and \( Sv_{v2} \) are Saint-Venant's tribological elements in the normal outline along the frontal surface.

On the back surface of the tool, there is a viscoelastic interaction with the processed surface. Rheology of near-surface zone of the product material is modeled with the elements \( R_{YB} \) and \( R_{ZB} \) (Figure 1) [11]. From the frontal side of the tool, there is a viscoelastic interaction in the chip formation zone,
which is modeled with the elements $R_{yF}$ and $R_{ZF}$ (Figure 1). The rheological models of the force interactions in the cutting zone and at the back surface of the tool are in detail shown in Figure 2.

![Diagram of rheological elements](image_url)

**Figure 2.** Groups of rheological elements of force interactions in the cutting area

The main idea of the considered approach is a piece-wise linear approximation of the contact interaction in the processing system of machining directly during the cutting. It consists in analyzing the contact interaction during cutting as a sequence of states, each of which may be represented by its own set of rheological models. At that, the dynamic system itself forms the parameters of the switching function, determining transition from one stage to the other. The system of differential equations for the analyzed rheological model (Figures 1, 2) has the following form:

\[
m\ddot{z} + b_1 \dot{z} + c_1 z = R_{zf}^{(mol)} + R_{zf}^{(mec)} + R_{zb}^{(mol)} + R_{zb}^{(mec)};
\]

\[
m\ddot{y} + b_2 \dot{y} + c_2 y = R_{yf}^{(mol)} + R_{yf}^{(mec)} + R_{yb}^{(mol)} + R_{yb}^{(mec)};
\]
\[ T_{z}^{(mol)}(t) + R_{z}^{(mol)}(t) = -(b_{z}y + c_{z}) S_{v1}; \quad (3) \]
\[ T_{s}^{(mol)}(t) + R_{s}^{(mol)}(t) = -(b_{s}y + c_{s}) S_{v1}; \quad (4) \]
\[ T_{z}^{(mech)}(t) + R_{z}^{(mech)}(t) = -(b_{z}y + c_{z}) S_{v2}; \quad (5) \]
\[ T_{s}^{(mech)}(t) + R_{s}^{(mech)}(t) = -(b_{s}y + c_{s}) S_{v2}; \quad (6) \]
\[ T_{z}^{(mech)}(t) + R_{z}^{(mech)}(t) = -(b_{z}y + c_{z}) S_{v1}; \quad (7) \]
\[ T_{s}^{(mech)}(t) + R_{s}^{(mech)}(t) = -(b_{s}y + c_{s}) S_{v1}; \quad (8) \]
\[ T_{z}^{(mech)}(t) + R_{z}^{(mech)}(t) = -(b_{z}y + c_{z}) S_{v2}; \quad (9) \]
\[ T_{s}^{(mech)}(t) + R_{s}^{(mech)}(t) = -(b_{s}y + c_{s}) S_{v2}; \quad (10) \]

where \( T_{z}^{(mol)} , T_{s}^{(mol)} , T_{z}^{(mech)} , T_{s}^{(mech)} , T_{z}^{(mol)} , T_{s}^{(mol)} , T_{z}^{(mech)} , T_{s}^{(mech)} \) are time constants of the working processes in the direction of \( OY, OZ \) axes; \( R_{z}^{(mol)} , R_{s}^{(mol)} , R_{z}^{(mech)} , R_{s}^{(mech)} , R_{z}^{(mol)} , R_{s}^{(mol)} , R_{z}^{(mech)} , R_{s}^{(mech)} \) is a projection of the cutting force in the form of dynamic characteristics from the sides of the front and back surfaces of the tool in the direction of the \( OY, OZ \) axes.

During the contact interaction, transition from the binding stage to the gliding stage and back is modeled by movable Saint-Venant's tribological elements with characteristics of \( S_{v11}, S_{v12}, S_{v21}, S_{v22} \) in the tangential outline, and \( S_{v11}, S_{v12}, S_{v21}, S_{v22} \) in the normal outline. The switching function for transition between the gliding stage and the binding stage may be written down in the following form

\[ \begin{align*}
\text{when } S_{v11} & = S_{v11} = S_{v21} = S_{v21} = 0, S_{v12} = S_{v12} = S_{v22} = S_{v22} = 1 - \text{binding;} \\
\text{when } S_{v11} & = S_{v11} = S_{v21} = S_{v21} = 1, S_{v12} = S_{v12} = S_{v22} = S_{v22} = 0 - \text{gliding.}
\end{align*} \quad \text{(11)} \]

Characteristics of movable tribological elements \( S_{v} = 1 \) (correspondingly for outlines \( z \) and \( y \)) point to the fact that this movable tribological element is closed and its rheological unit is a perfectly solid body. It means that only one rheological unit participates in the contact interaction. The switching function (11), simultaneously with the system of differential equations (1)-(10) performs sequential switching of the tribological elements between the binding and gliding stages during the monitoring of kinematic characteristics of relative oscillations in the dynamic system in question.

A truly adhesive process, where binding happens, takes place when the following conditions hold:

\[ \delta_{cz} > \left[ \delta_{cz} \right], \quad \text{(12)} \]

where \( \delta_{cz} \) is a normal contact deformation; \( \left[ \delta_{cz} \right] \) is the value of the normal contact deformation after which an adhesive process starts, and

\[ V_{z} < \frac{V_{e}}{T_{sf}} = \left[ V_{z} \right], \quad \text{(13)} \]

where \( V_{z} \) is a relative tangential speed in the contact coupling; \( \left[ V_{z} \right] \) is the value of the relative tangential speed after which adhesive processes cease; \( l_{c} \) is the chip formation route.

The system of equations (1)-(10) with a broad variation of parameters was used as a foundation for modeling the processing system of tooling by lathe turning: The processed material was 20Kh13 steel, the tool material was R6M6 rapid tool steel, the cutting speed was from 15 to 200 m/min, a width of cut...
was 0.5 – 5 mm, the plan approach angle was 60 degrees, blank diameter was 60 mm. The results of separate comparative calculations and experimental studies are shown in Figure 3.

![Figure 3. Design (a) and experimental (b) oscillograph charts of vibrational motion during the lathe turning (V=30 m/min, the tool material – R6M5, the blank material – 20Kh13)](image)

In both design and experimental plots of vibrational motions along the normal to the formative point of the blank at a cutting speed of 30 m/min, there are typical pulse motions that may be interpreted as sequential transitions between the gliding and binding stages. Divergence between the design and the experimental data does not exceed 122 percent, which is satisfactory.

3. Conclusion
In this modeling representation, the processes in the cutting zone are considered on the basis of a rheological approach, allowing reflecting the interaction of elastic-dissipative and inertial characteristics of the processing system in the cutting zone within the framework of the general dynamic model. The obtained differential equations significantly simplify the method for determining the number of transitions between the gliding and binding stages in the area where self-sustained oscillations exist. The method allows largely determining the conditions under which the self-sustained oscillations form.

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