Adaptive self-excited vibrations suppression during milling

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Abstract. The problem of the occurrence and rapid suppression of unstable self-excited vibrations arising in the process of milling is considered. It is assumed that tool (cutter) is connected with machine overarm by an elastic suspension, which is used for force sensation. The tool moves evenly along the work surface with a given pressure on it. Pressing of the cutter provides the necessary axial depth of cut. Uniform movement along the work surface provides the required tool feed. Unstable self-excited vibrations or chattering is a deterrent to increase productivity. In this paper we consider the possibility of promptly detecting the onset of unstable auto-oscillations from the amplitude spectrum of the sensor readings of the horizontal forces of interaction between the instrument and the working surface. The amplitude spectrum is obtained using the fast Fourier transform, which allows to determine the beginning of unstable processes in system. Timely change of the axial depth of cut allows to transfer the milling process into the stable zone.

1. Introduction
Metal machining is one of the main methods of parts manufacturing in mechanical engineering. The most common machining operation is the milling operation, which is currently carried out on machines with computer numerical control (CNC), as well as using robotic systems [1]. Due to the desire to expand the scope and increase productivity, optimization and intensification of the machining process are actual. The main limiting factor in improving milling performance is the possible loss of dynamic stability caused by tool vibrations [2]. Vibrations cause tool breakdowns, premature wear of the cutting edges, reduced quality and precision of machining. In practice, to minimize the probability of system stability losing, the parameters of the machining mode are consciously underestimated, which naturally leads to performance degradation.

One of the most characteristic problems in milling is the occurrence of regenerative self-excited vibrations (chattering). Currently, there are a number of hypotheses regarding the mechanism of the occurrence of regenerative self-excited vibrations, which can lead to milling process instability [3]. The most popular is the hypothesis of a delay between the change of cutting force and the change of the cutting chip thickness due to the relative displacement of the tool and the working surface. The articles by Tobias S. and Tlusty J.[4, 5] show that due to the modulation of the chip thickness the energy necessary for maintaining self-excited vibrations is introduced into the system.

Tool stiffness is limited and cutter have a finite number of teeth. So it can be argued that the cutting forces are intermittent, which can lead to the formation of a wavy cutting surface for each new cutter pass. In this case, the wavy surface left by the previous tooth is removed when the next tooth passes. And this tooth leaves the wavy surface too. This mechanism leads to the formation of waves on both
sides of the chip. The chip thickness depends on the phase shift between the passes of the current and previous cutter teeth. As a result, cutting forces can increase without limit.

Given that regenerative self-excited vibrations can lead to loss of stability, the operator must constantly monitor the processes in the system. Experimental and theoretical researches of many authors in most cases provide only a qualitative understanding of the processes. So, as a result of stability analysis, using nonlinear differential equations with delay, the stability lobe diagram can be obtained. This analytical diagram allow the operator to select the correct cutting parameters [6]. However, this procedure in practice does not always guarantee the stability of the process due to the approximation of mathematical models.

For turning and milling processes, Budak E. and Altintas Y. developed methods for determining the dynamic stability conditions of the system, allowing to relate the value of the axial depth of cut, feed and spindle speed, corresponding to a stable area. Further research by many authors has allowed us to develop a number of practical ways to reduce vibrations during milling. Today the most common ways of dealing with vibrations are offline (irregular cutters, speed modulators). The development of an adaptive control system for the milling process, which is capable to adjust the machining parameters in the online mode, remains actual. The articles [7, 8] describe methods of dealing with vibrations using active suspension with adjustment according to the spindle speed. The main focus is on the design features of CNC machines. This seriously limits the ability to quickly adjust the parameters of the machining in the online mode. From the point of view of the control system flexibility and the possibility of spatial processing of the arbitrary profile parts, the using of multi-axis robots with a tool installed in an elastic suspension is perspective. Elastic suspension provides a force sensation of the robot in at least three axes. This configuration allows to use the standard robot manipulator in the hybrid position-power control mode, in which robot moves taking into account the contact forces of interaction between the tool and the working surface. Installation the tool in an elastic suspension provides additional opportunities for organizing adaptation contours that can predict the possible loss of machining process stability and provide the necessary ratio of cutting parameters [9].

In this paper, we investigate the possibility of the axial depth of cut automatic correction when signs of dynamic stability loss appear. In this case, the corresponding time moment is detected using the amplitude spectrum of the horizontal cutting force. Amplitude spectrum is obtained using the fast Fourier transform (FFT). The results of computer simulation of the adaptation contour are presented.

2. Mathematical model of regenerative self-excited vibrations

We assume that milling is carried out using the robot that is equipped with a cutter in an elastic suspension that provides a force sensing in the area of contact interaction between the cutter and the working surface[13]. According to the technological task, the robot must ensure the uniform movement of the cutter with a certain speed along the working surface with a given pressure to it. Altintas 2-DOF milling system is presented in figure 1 [1].

![Figure 1. Self-excited vibrations in 2-DOF milling system.](image-url)
2-DOF milling system describes the dynamic processes that occur during milling. The milling cutter has \( N \) teeth, tooth line inclination angle is taken as zero. Process parameters: \( a \) – axial depth of cut, \( f \) – feed, \( \Omega \) – spindle speed. The differential equations system describing the dynamics of the cutter is as follows.

\[
\begin{align*}
(m_x \ddot{x} + b_x \dot{x} + k_x x) &= F_x, \\
(m_y \ddot{y} + b_y \dot{y} + k_y y) &= F_y,
\end{align*}
\]  

(1)

where \( m_x, m_y \) – equivalent masses; \( b_x, b_y \) – damping coefficients; \( k_x, k_y \) – tool suspension stiffness; \( F_x, F_y \) – cutting forces in the x and y directions, respectively, which determine the nonlinear dynamics of the cutting process at the current time \( t \) and the preceding \( t - \tau \); \( \tau \) – delay (delay \( \tau \) takes into account the cutting effect "on track").

According to Al tintas Y., we define the expression for cutting forces. Two coordinate systems are introduced: global \( x, y \) and local \( u, v \), in which the cutter interacts with the work surface. The relationship between them is as follows

\[
\begin{align*}
v_j &= -x \sin \varphi_j - y \cos \varphi_j, \\
u_j &= -x \cos \varphi_j + y \sin \varphi_j,
\end{align*}
\]

(2)

(3)

where \( \varphi_j \) – current angle of tooth number \( j \) into material.

If the spindle speed is \( \Omega \), then \( \varphi_j = \Omega t \). Chip thickness consists of two components. Constant chip thickness \( (f \sin \varphi_j) \), associated with the movement of the cutter as a solid (feed), and dynamic thickness associated with tool vibrations in the present and previous tooth periods. Performing the appropriate transformations, we get

\[
h_j(\varphi_j) = (v_j(t - \tau) - v_j(t))g(\varphi_j) = (\Delta x \sin \varphi_j + \Delta y \cos \varphi_j)g(\varphi_j),
\]

(4)

where \( \Delta x = x(t) - x(t - \tau), \Delta y = y(t) - y(t - \tau), g(\varphi_j) \) – function that determines whether the mill tooth is in or out of cut

\[
g(\varphi_j) = \begin{cases} 
1, & \text{if } \varphi_{st} < \varphi_j < \varphi_{ex}, \\
0, & \text{if } \varphi_j < \varphi_{st} \text{ or } \varphi_j > \varphi_{ex}.
\end{cases}
\]

(5)

Here \( \varphi_{st} \) and \( \varphi_{ex} \) – the start and exit immersion angles of the cutter to and from the cut, respectively; \( x(t), y(t) \) and \( x(t - \tau), y(t - \tau) \) show the movement of the cutter in the present and the previous tooth periods.

Consider now the cutting force. Tangential \( F_{t,j} \) and radial \( F_{r,j} \) cutting forces arising on the \( j \)-th tooth are proportional to the axial depth of cut and chip thickness \( (h_j) \)

\[
\begin{align*}
F_{t,j} &= K_t a h_j(\varphi_j), \\
F_{r,j} &= K_r F_{t,j},
\end{align*}
\]

(6)

(7)

where \( K_t, K_r \) – cutting constants, determined for a particular material of the workpiece. Expressing the cutting forces in the x and y, directions, we get

\[
\begin{align*}
F_{x,j} &= -F_{t,j} \sin \varphi_j - F_{r,j} \cos \varphi_j, \\
F_{y,j} &= F_{t,j} \sin \varphi_j - F_{r,j} \cos \varphi_j.
\end{align*}
\]

(8)

(9)
Taking into account the number of cutting edges of the cutter $N$, we finally get

$$F_x = \sum_{j=0}^{N-1} F_{x,j}(\varphi_j); \quad F_y = \sum_{j=0}^{N-1} F_{y,j}(\varphi_j).$$

Thus, in the general case, the system of equations describing the milling process is a system of nonlinear differential equations with delay. Analysis of the system stability according to Altintas Y. allows us to build a stability lobe diagram in the space of the axial depth of cut and the spindle speed. In computer simulation of the milling process, the following parameter values were used:

$$m_x = 0.39 \text{ kg}; \quad m_y = 0.32 \text{ kg}; \quad K_t = 700 \cdot 10^6 \frac{\text{N}}{\text{m}^2}; \quad K_r = 0.07; \quad N = 4;$$

$$k_x = 5.6 \cdot 10^6 \frac{\text{N}}{\text{m}}; \quad k_y = 5.6 \cdot 10^6 \frac{\text{N}}{\text{m}}; \quad b_x = 115.3 \frac{\text{N} \cdot \text{s}}{\text{m}}; \quad b_y = 96 \frac{\text{N} \cdot \text{s}}{\text{m}}.$$  

The corresponding stability lobe diagram of the milling process is shown in figure 2.

![Stability lobe diagram](image.png)

**Figure 2.** Stability lobe diagram.

The shaded area corresponds to stability modes. Figure 2 shows the characteristic value of the axial depth of cut ($a_{critical}$) at which for any spindle speed the milling process remains stable. The upper region corresponds to the chatter phenomenon, in which the stability of the milling process is lost. The considered model of the milling process dynamics is in good agreement with the experiment [1].

3. **Detection of self-excited vibrations instability by the cutting forces amplitude spectrum**

It is proposed to perform automatic detection of regenerative self-excited vibrations based on the analysis of the amplitude spectra. Information about cutting forces is given by force sensors. Cutting force amplitude spectra obtained by FFT. Figure 5 shows the amplitude spectrum of the horizontal cutting force at $\Omega = 4500 \text{ rpm}$ and the value of the axial depth of cut within the shaded area of the stability lobe diagram (figure 2).

Increasing the axial depth of cut to the value from the chatter zone in figure 2 leads to unstable milling. Evidence of this is the evolution of amplitude spectra, shown in figure 3. At the frequency about 400 Hz the corresponding amplitude rapidly increases.
As a criterion for detecting unstable self-excited vibrations, we used the ratio of the detected harmonic amplitude at the chatter frequency $\omega_c$ to the amplitude of the first harmonic of the spectrum. In computer simulation, the threshold value is assumed to be 0.4.

4. Adaptive stabilization of unstable self-excited vibrations by changing the axial depth of cut

It is proposed to perform automatic detection of regenerative self-excited vibrations based on the analysis of the amplitude spectra. Information about cutting forces is given by force sensors. After detection milling process can be stabilized by choosing the axial depth of cut. This cutting parameter is the most critical for the milling process. The method is based on the fact that even a small decrease of the axial depth of cut about $(0.5 - 1)\%$ allows to prevent the unstable self-excited vibrations. Such a decrease of the axial depth of cut does not lead to violation of the established tolerances. Figure 4 shows the processes of horizontal cutting forces when using the system of automatic suppression of self-excited vibrations.

Figure 3. Unstable milling cutting forces spectrogram evolution.
Figure 4. Changing of the force sensor signal spectrum depending on the time in the presence of control system.

The simulation was carried out as follows. The axial cutting depth was chosen in the unstable zone near the stability boundary. Figure 1 shows that the increase of the vibration amplitude occurs up to the third second. After that the instability is detected by the amplitude spectrum and the axial depth of cut is reduced by 1% using robot position control system. The process quickly stabilizes. Figure 5 shows the evolution of the unstable milling spectrogram in the presence of control system.

Figure 5. The cutting force spectrogram evolution in the presence of control system.

5. Conclusion
In practice it is almost impossible to reconcile the desired cutting parameters by calculation with high precision. Analytical stability lobe diagrams can only be used like a reference point in the process of setting the parameters of machining. In addition, the cutting process may deviate from the calculated one. The developed control system allows, in the case of small deviations from the stable mode, almost instantaneously detect an increasing of vibrations and correct the cutting parameters without disturbing of the machining technology.
The introduction of robotic systems into the industry is an actual problem. From the point of view of control, the direction of adaptation contours intellectualization using the neural networks seems promising. Large amount of experimental and expert data provides an additional opportunity to adapt the control system to the potential loss of cutting stability. We can talk not only about establishing the fact of the process instability, but also about predicting the appearance of undesirable regimes, such as regenerative self-excited vibrations, which makes it possible to correct the machining parameters in real time. The introduction of such systems in production will make it possible in large batches to seriously reduce the scrap rate and increase productivity.

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