Stability Analysis and Stabilization of a Class of Cutting Systems With Chatter Suppression

Hao-Fei Meng, Yu Kang, Zhiyong Chen, Yun-Bo Zhao, and Guo-Ping Liu

***Abstract*—In this paper, a new method for stability analysis of a single degree of freedom (SDOF) cutting system with sinusoidal spindle speed variation (SSSV) is proposed. Based on the approximately periodic property of the time delay in the turning process and the delay decomposition method, novel criteria of stability analysis for an SDOF cutting system are presented. Moreover, a state feedback controller is designed to stabilize the system and improve the steady-state response. Numerical simulation shows the effectiveness of the method.**

***Index Terms*—Chatter suppression, cutting systems, spindle speed variation (SSV), time-delay systems.**

I. Introduction

High-speed machines which are known to have high efficiency, high accuracy, and low cost also introduce various vibrations. Among these vibrations, the regenerative chatter between the workpiece and the cutting tool is most common and detrimental [1]. A tool generates a surface as material is removed, and any vibration of the tool is reflected on the surface. Since the surface generated by the previous pass becomes the upper surface of the chip on the subsequent pass and the cutting force depends on the current chip thickness, the cutting force fluctuates with the chip thickness which in turn leads to the vibration between the workpiece and the tool. This phenomenon, called regenerative chatter, deteriorates the stability of the cutting process. Therefore, chatter suppression has attracted a large number of attentions over the years [2]–[4].

Classical methods on mitigating regenerative chatter are based on modulating or optimizing the parameters of mechanical systems, including redesigning the structure of tools [5], [6], adding dampers, or damp absorbers [7]–[9], etc. However, accurate tuning of passive dampers is very difficult for good performance [10]. Spindle speed variation (SSV) as a well-known active technique to suppress regenerative chatter was investigated as early as 1974 by Inamura [11]. The literature on application of SSV in the turning process includes the work in [12]–[18]. In [12], SSV is used to suppress chatter in the noncircular process through theoretical computation and experiments. In [13], chatter suppression based on SSV in the turning process with tool wear is conducted by an experimental study. Since sinusoidal spindle speed variation (SSSV) is more easily tracked than other periodic functions, such as the triangular one, it is the most common form of SSV. Mathematical analysis and stability analysis for SSSV in turning are given in [14] and [15]. In [16], the authors program the spindle speed to suppress chatter for the minimum energy input by the cutting process. In [17], the authors use SSSV in the turning process with tool wear effect and select parameters of speed modulation by a genetic algorithm.

In this paper, we propose a technique to suppress chatter in the turning process by SSSV from another perspective. Using the state-space theory, we combine SSSV and the state feedback controller design. Taking the Lyapunov function as a special energy function, we construct Lyapunov functionals, based on Lyapunov–Krasovskii (L–K) theorem [19] to analyze the stability of the turning process under SSSV, and obtain stability criteria in the form of linear matrix inequalities (LMIs), which can be easily solved by MATLAB LMI toolbox. The delay decomposition method is introduced in the construction of Lyapunov functionals. In addition, since the selection of parameters of the spindle speed signal is often limited by the properties of the cutting system, SSSV may not be always effective to obtain an expected state response. Therefore, we design a state feedback controller to stabilize the cutting system. The numerical simulation illustrates the effectiveness of the approach.

II. System Modeling

The system for an orthogonal turning process is modeled as a single degree of freedom (SDOF) system [20]. The stability analysis and controller design approach for SDOF systems studied in this paper can be extended to multiple DOF systems by mode summation. The machine tool is described by a simple mass/damper/spring system as follows:

$$m\ddot{y}(t) + c\dot{y}(t) + ky(t) = k_c w_c[y(t-\tau(t)) - y(t)] \qquad (1)$$

with the mass of tool m, the damping coefficient c, and the spring stiffness k. The relative displacement of the tool from the reference position is denoted by $y(t)$. Let $\tau(t)$ be the time delay which is generated by the rotation of spindle and t denote the

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H.-F. Meng was with the Department of Automation, University of Science and Technology of China, Hefei 230026, China. She is now with the School of Electrical Engineering and Computer Science, University of Newcastle, Callaghan, N.S.W. 2308, Australia (e-mail: haofei.meng@uon.edu.au).

Y. Kang is with the Department of Automation, University of Science and Technology of China, Hefei 230026, China (e-mail: kangduyu@ustc.edu.cn).

Z. Chen is with the School of Electrical Engineering and Computer Science, University of Newcastle, Callaghan, N.S.W. 2308, Australia (e-mail: zhiyong.chen@newcastle.edu.au).

Y.-B. Zhao is with College of Information Engineering, Zhejiang University of Technology, Hangzhou 310023, China, and also with the CTGT Center, Harbin Institute of Technology, Harbin 150001, China (e-mail: yunbo.zhao@imperial.ac.uk).

G.-P. Liu is with the School of Engineering, University of South Wales, Pontypridd, CF37 1DL, U.K., and also with the CTGT Center, Harbin Institute of Technology, Harbin 150001, China (e-mail: guoping.liu@southwales.ac.uk).

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time period between the current and the previous tool passes. The constants k_c and w_c are the cutting force coefficient and the width of cut, respectively.

In a turning process, the time delay $\tau(t)$ is an intrinsic property of the system. The spindle speed is denoted by $\Omega(t)$. When $\Omega(t)$ is constant, i.e., $\Omega(t) = \Omega_0$, the time delay $\tau(t)$ satisfies $\tau(t) = \tau_0 = 60/\Omega_0$. When the spindle speed is time varying, $\Omega(t)$ and $\tau(t)$ satisfy $\int_{t-\tau(t)}^{t} \Omega(s)/60 \ \mathrm{ds} = 1$. For SSSV, the spindle speed has the form

$$\Omega(t) = \Omega_0[1 + \varepsilon \sin(2\pi f t)]$$

where ε denotes the small amplitude ratio and $T = 1/f$ the period of the spindle speed signal. Therefore, the time delay in system (1) can be expressed approximately as [15]

$$\tau(t) = \tau_0[1 - \varepsilon \sin(2\pi f t)]. \tag{2}$$

Let τ_1 and τ_2 denote the lower and upper bounds of the time delay, respectively. It is easy to see that

$$\begin{cases} \tau_1 = \tau_0(1-\varepsilon),\ \tau_2 = \tau_0(1+\varepsilon) \\ \dot{\tau}(t) \le 2\pi f \varepsilon \tau_0 = \mu. \end{cases} \tag{3}$$

Furthermore, the model (1) with the periodic time delay (2) implies the state-space equation, with $x(t) = [y(t) \quad \dot{y}(t)]^T$

$$\dot{x}(t) = Ax(t) + A_d x\left(t - \tau(t)\right) \tag{4}$$

where

$$A = \begin{bmatrix} 0 & 1 \\ -(k + k_c w_c)/m & -c/m \end{bmatrix},\ A_d = \begin{bmatrix} 0 & 0 \\ k_c w_c/m & 0 \end{bmatrix}.$$

III. Stability Analysis

In this section, we use L–K theorem to analyze the stability property of system (4). Before constructing the Lyapunov functionals, we will make use of the sinusoidal form of the spindle speed to design novel stability criteria. Specifically, we decompose the time-delay interval $[\tau_1, \tau_2]$ into two equal subintervals $[\tau_1, \tau]$ and $[\tau, \tau_2]$,where $\tau = (\tau_1 + \tau_2)/2 = \tau_0$. Define time fields

$$\Delta_1 \triangleq \{t | \tau(t) \in [\tau_1, \tau)\},\ \Delta_2 \triangleq \{t | \tau(t) \in [\tau, \tau_2]\}.$$

When $t \in \Delta_i$, $i \in \{1, 2\}$, we construct the following Lyapunov functionals:

$$V_i(t, x_t) = \sum_{r=1}^{8} V_{ri}(t, x_t) \tag{5}$$

where $x_t \triangleq x(t+\theta)$ with $\theta \in [-\tau, 0]$ mapping the interval $[-\tau, 0]$ to $\mathbb{R}^2$ and

$$V_{1i}(t, x_t) = x^T(t) P_i x(t)$$

$$V_{2i}(t, x_t) = \int_{t-\tau_1}^{t} e^{\alpha(s-t)} x^T(s) Q_{1i} x(s) ds$$

$$V_{3i}(t, x_t) = \int_{t-\tau}^{t-\tau_1} e^{\alpha(s-t)} x^T(s) Q_{2i} x(s) ds$$

$$V_{4i}(t, x_t) = \int_{t-\tau_2}^{t-\tau} e^{\alpha(s-t)} x^T(s) Q_{3i} x(s) ds$$

$$V_{5i}(t, x_t) = \int_{t-\tau(t)}^{t-\tau_1} e^{\alpha(s-t)} x^T(s) Q_{4i} x(s) ds$$

$$V_{6i}(t, x_t) = \tau_1 \int_{-\tau_1}^{0} \int_{t+\theta}^{t} e^{\alpha(s-t)} \dot{x}^T(s) R_{1i} \dot{x}(s) ds d\theta$$

$$V_{7i}(t, x_t) = (\tau - \tau_1) \int_{-\tau}^{-\tau_1} \int_{t+\theta}^{t} e^{\alpha(s-t)} \dot{x}^T(s) R_{2i} \dot{x}(s) ds d\theta$$

$$V_{8i}(t, x_t) = (\tau_2 - \tau) \int_{-\tau_2}^{-\tau} \int_{t+\theta}^{t} e^{\alpha(s-t)} \dot{x}^T(s) R_{3i} \dot{x}(s) ds d\theta.$$

When $\mu \le 1$, we obtain the following criterion for stability analysis of system (4).

Theorem 3.1: For given scalars $\tau_2 > \tau_1 > 0$, $\mu \le 1$, and $\alpha > 0$, if there exist matrices[1] $P_i > 0$, $Q_{ji} > 0$, $R_{li} > 0$, S_i, $i \in \{1, 2\}$, $j \in \{1, 2, 3, 4\}$, $l \in \{1, 2, 3\}$, of appropriate dimensions such that the following conditions hold:

$$\begin{bmatrix} R_{21} & S_1 \\ * & R_{21} \end{bmatrix} \ge 0,\ \begin{bmatrix} R_{32} & S_2 \\ * & R_{32} \end{bmatrix} \ge 0$$

$$\begin{bmatrix} \Phi & \Xi_1 \\ * & \Lambda_1 \end{bmatrix} < 0,\ \begin{bmatrix} \Psi & \Xi_2 \\ * & \Lambda_2 \end{bmatrix} < 0. \tag{6}$$

The terms in (6) are listed in Appendix A. Then, system (4) is exponentially stable with period

$$T \ge \frac{2 \ln \gamma}{\alpha} \tag{7}$$

where $\gamma \ge 1$ satisfying

$$P_{i_1} \le \gamma P_{i_2},\ Q_{ji_1} \le \gamma Q_{ji_2},\ R_{li_1} \le \gamma R_{li_2},\ i_1 \ne i_2 \in \{1, 2\}. \tag{8}$$

Proof: See Appendix B.

Theorem 3.1 gives the exponential stability of system (4), where $P_i, Q_{ji}, R_{li}, i \in \{1, 2\}, j \in \{1, 2, 3, 4\}, l \in \{1, 2, 3\}$, are corresponding to the matrices in the two Lyapunov functionals. In the numerical simulation, we will show that a finite γ always exists for (8). The condition (7) for period T guarantees that the Lyapunov functionals decrease sufficiently in a time interval such that the stability of the overall system can be achieved. Therefore, the stability criterion in Theorem 3.1 depends on system parameters and it can be used to predict the stability of the turning process under certain cutting parameters or select appropriate parameters.

For a real turning system, the parameter $\mu = 2\pi f \varepsilon \tau_0$ is usually less than 1. Therefore, in the numerical simulation, the results are obtained based on Theorem 3.1 with $\mu \le 1$. The following corollary with $\mu > 1$ is proposed using the similar argument just for the completeness of theoretical analysis.

Corollary 3.1: When $\mu > 1$, Theorem 3.1 still holds with Φ_{22} and Ψ_{22} listed in Appendix A replaced by $\hat{\Phi}_{22}$ and $\hat{\Psi}_{22}$ given

[1]For a matrix A, $A > 0$ ($A < 0$) means A is positive (negative) definite; $A \ge 0$ ($A \le 0$) means A is positive (negative) semidefinite.

TABLE I
PARAMETERS OF THE CUTTING SYSTEM (1)

m(kg)	c(N·s/m)	k(N/m)	k_c (N/m^2)	Ω_0(rpm)
50	2000	2.0×10^7	3.5×10^8	1410

by

$$\hat{\Phi}_{22} = -(1-\mu)e^{-\alpha\tau_1}Q_{41} - 2e^{-\alpha\tau}R_{21} - e^{-\alpha\tau}(S_1 + S_1^T)$$
$$\hat{\Psi}_{22} = -(1-\mu)e^{-\alpha\tau}Q_{42} - 2e^{-\alpha\tau_2}R_{32} - e^{-\alpha\tau_2}(S_2 + S_2^T).$$

IV. STABILIZATION CONTROLLER DESIGN

New stability criteria for the cutting process applying SSSV have been derived in the previous section. But with some constraints on the parameters, for example, ε is usually required to be small; the approach in the previous section cannot always guarantee the desired steady-state response for an open-loop system. For better response of the cutting process, we further consider the system with an additional control input

$$\dot{x}(t) = Ax(t) + A_d x(t-\tau(t)) + Bu(t),\ B = \begin{bmatrix} 0 \\ 1/m \end{bmatrix}. \quad (9)$$

We design a state feedback controller to stabilize the open system, and the controller has the form

$$u(t) = Kx(t),\ K \in \mathbb{R}^{1\times 2}. \quad (10)$$

Similar to the construction of Lyapunov functionals in Theorem 3.1, we can use the following criterion to design the feedback gain matrix K.

Theorem 4.1: For given scalars $\tau_2 > \tau_1 > 0$, $\mu \le 1$, and $\alpha > 0$, if there exist matrices $\tilde{P} > 0$, $\tilde{Q}_{ji} > 0$, $\tilde{S}_i$, $\tilde{K}$, and positive scalars ϵ_{li}, $i \in \{1,2\}$, $j \in \{1,2,3,4\}$, $l \in \{1,2,3\}$, of appropriate dimensions such that the following conditions hold:

$$\begin{bmatrix} \epsilon_{21}\tilde{P} & \tilde{S}_1 \\ * & \epsilon_{21}\tilde{P} \end{bmatrix} \ge 0,\ \begin{bmatrix} \epsilon_{32}\tilde{P} & \tilde{S}_2 \\ * & \epsilon_{32}\tilde{P} \end{bmatrix} \ge 0$$
$$\begin{bmatrix} \tilde{\Phi} & \tilde{\Xi} \\ * & \tilde{\Lambda}_1 \end{bmatrix} < 0,\ \begin{bmatrix} \tilde{\Psi} & \tilde{\Xi} \\ * & \tilde{\Lambda}_2 \end{bmatrix} < 0. \quad (11)$$

The terms in (11) are listed in Appendix C. Then, system (9) can be stabilized by $u(t) = \tilde{K}\tilde{P}^{-1}x(t)$, if the period satisfies

$$T \ge 2\frac{\ln\gamma}{\alpha} \quad (12)$$

where $\gamma \ge 1$ satisfying

$$\tilde{Q}_{ji_1} \le \gamma\tilde{Q}_{ji_2},\ \epsilon_{li_1} \le \gamma\epsilon_{li_2},\ i_1 \ne i_2 \in \{1,2\}. \quad (13)$$

Proof: See Appendix D.

V. NUMERICAL SIMULATION

In this section, a practical case study of an SDOF cutting system using SSSV is considered with the realistic parameters [21] listed in Table I. If the spindle speed is constant and equals Ω_0, Fig. 1 shows the system response when the width of cut is 6.5 mm. It is easy to see that the turning process is unstable and the time response is divergent. By SSSV with $f = 1$ Hz and $\varepsilon = 0.1$, the relative displacement $y(t)$ is depicted in Fig. 2. The system response can be modulated not to be divergent by SSSV but the displacement is not asymptotically stable.

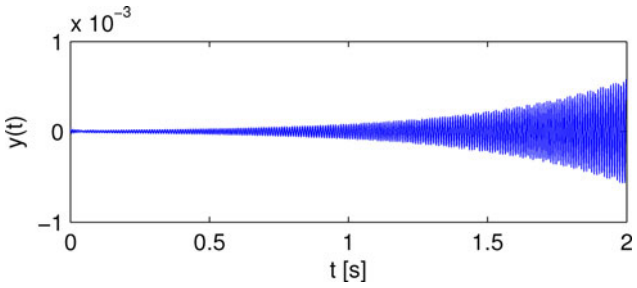


Fig. 1. Displacement of the tool under a constant spindle speed.

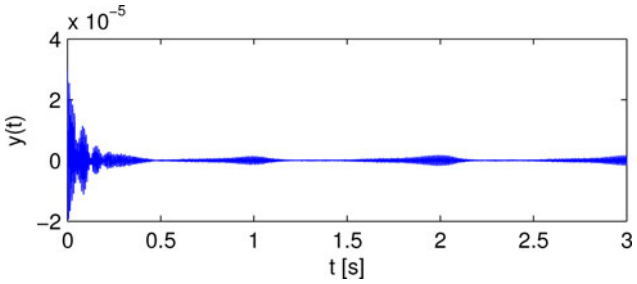


Fig. 2. Displacement of the tool by SSSV.

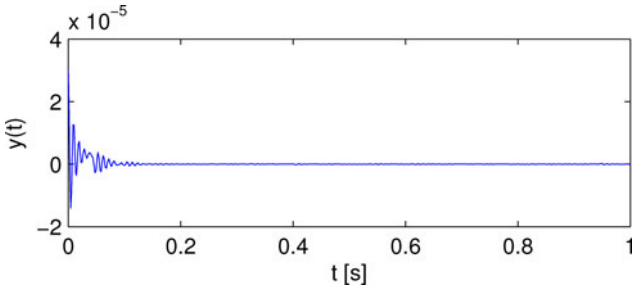


Fig. 3. Displacement of the tool by state feedback control.

The state feedback controller designed by Theorem 4.1 are used to stabilize the turning process and improve the steady-state response. From Theorem 4.1, when $\alpha = 1$, $\gamma = 1.2$, and $T \ge 2\ln\gamma/\alpha \approx 0.36$, system (9) is exponentially stable with controller (10). It is easy to calculate the period $T = 1/f = 1$ s and it is obvious that $T \ge 0.36$ which means that the cutting system can be stabilized using Theorem 4.1. The relative displacement $y(t)$ by state feedback is depicted in Fig. 3. In particular, the relative displacement of the tool satisfactorily converges to zero in a short time.

VI. CONCLUSION

In this paper, stability analysis and stabilization for an SDOF cutting system were conducted. Based on L–K theorem, new stability criteria for the open-loop cutting system with SSSV were derived. We selected different Lyapunov functionals when the periodic time delay belongs to different subintervals so that

the information of time delay can be made use of sufficiently. Based on the stability analysis, the state feedback controller was designed to improve the steady-state response of the cutting process.

APPENDIX A

TERMS IN LMIS (6)

The matrices Λ_i, Ξ_i, Φ, and Ψ are given as follows in order:

$$\mathrm{diag}\{-R_{1i}, -R_{2i}, -R_{3i}\}$$

$$\begin{bmatrix} \tau_1 A^T R_{1i} & \tau_{10} A^T R_{2i} & \tau_{02} A^T R_{3i} \\ \tau_1 A_d^T R_{1i} & \tau_{10} A_d^T R_{2i} & \tau_{02} A_d^T R_{3i} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix} \Phi_{11} & P_1 A_d & e^{-\alpha\tau_1} R_{11} & 0 & 0 \\ * & \Phi_{22} & \Phi_{23} & \Phi_{24} & 0 \\ * & * & \Phi_{33} & -e^{-\alpha\tau} S_1 & 0 \\ * & * & * & \Phi_{44} & e^{-\alpha\tau_2} R_{31} \\ * & * & * & * & \Phi_{55} \end{bmatrix}$$

$$\begin{bmatrix} \Psi_{11} & P_2 A_d & e^{-\alpha\tau_1} R_{12} & 0 & 0 \\ * & \Psi_{22} & 0 & \Psi_{24} & \Psi_{25} \\ * & * & \Psi_{33} & e^{-\alpha\tau} R_{22} & 0 \\ * & * & * & \Psi_{44} & -e^{-\alpha\tau_2} S_2 \\ * & * & * & * & \Psi_{55} \end{bmatrix}$$

where

$$\tau_{10} = \tau - \tau_1 \quad \tau_{02} = \tau_2 - \tau$$

$$\begin{aligned}
\Phi_{11} &= P_1 A + A^T P_1 + \alpha P_1 + Q_{11} - e^{-\alpha\tau_1} R_{11} \\
\Phi_{22} &= e^{-\alpha\tau}[-(1-\mu)Q_{41} - 2R_{21} - S_1 - S_1^T] \\
\Phi_{23} &= e^{-\alpha\tau}(R_{21} + S_1^T) \qquad \Phi_{24} = e^{-\alpha\tau}(R_{21} + S_1) \\
\Phi_{33} &= e^{-\alpha\tau_1}(-Q_{11} + Q_{21} + Q_{41} - R_{11}) - e^{-\alpha\tau} R_{21} \\
\Phi_{44} &= e^{-\alpha\tau}(-Q_{21} + Q_{31} - R_{21}) - e^{-\alpha\tau_2} R_{31} \\
\Phi_{55} &= e^{-\alpha\tau_2}(-Q_{31} - R_{31})
\end{aligned}$$

and

$$\begin{aligned}
\Psi_{11} &= P_2 A + A^T P_2 + \alpha P_2 + Q_{12} - e^{-\alpha\tau_1} R_{12} \\
\Psi_{22} &= e^{-\alpha\tau_2}[-(1-\mu)Q_{42} - 2R_{32} - S_2 - S_2^T] \\
\Psi_{24} &= e^{-\alpha\tau_2}(R_{32} + S_2^T) \qquad \Psi_{25} = e^{-\alpha\tau_2}(R_{32} + S_2) \\
\Psi_{33} &= e^{-\alpha\tau_1}(-Q_{12} + Q_{22} + Q_{42} - R_{12}) - e^{-\alpha\tau} R_{22} \\
\Psi_{44} &= e^{-\alpha\tau}(-Q_{22} + Q_{32} - R_{22}) - e^{-\alpha\tau_2} R_{32} \\
\Psi_{55} &= e^{-\alpha\tau_2}(-Q_{32} - R_{32}).
\end{aligned}$$

APPENDIX B

PROOF OF THEOREM 3.1

The time derivatives of $V_i(t, x_t)$ along the state trajectory of the system (4) combined with Jensen inequality [22] are calculated as follows:

$$\begin{aligned}
\dot{V}_{1i} &= x^T(t)(P_i A + A^T P_i)x(t) + 2x^T(t) P_i A_d x(t-\tau(t)) \\
\dot{V}_{2i} &= -\alpha V_{2i} + x^T(t) Q_{1i} x(t) - e^{-\alpha\tau_1} x^T(t-\tau_1) Q_{1i} x(t-\tau_1) \\
\dot{V}_{3i} &= -\alpha V_{3i} + e^{-\alpha\tau_1} x^T(t-\tau_1) Q_{2i} x(t-\tau_1) \\
&\quad - e^{-\alpha\tau} x^T(t-\tau) Q_{2i} x(t-\tau) \\
\dot{V}_{4i} &= -\alpha V_{4i} + e^{-\alpha\tau} x^T(t-\tau) Q_{3i} x(t-\tau) \\
&\quad - e^{-\alpha\tau_2} x^T(t-\tau_2) Q_{3i} x(t-\tau_2) \\
\dot{V}_{5i} &\le -\alpha V_{5i} + e^{-\alpha\tau_1} x^T(t-\tau_1) Q_{4i} x(t-\tau_1) \\
&\quad - (1-\mu) e^{-\alpha\tau(t)} x^T(t-\tau(t)) Q_{4i} x(t-\tau(t)) \\
\dot{V}_{6i} &\le -\alpha V_{6i} + \tau_1^2 \dot{x}^T(t) R_{1i} \dot{x}(t) \\
&\quad - e^{-\alpha\tau_1}[x^T(t) - x^T(t-\tau_1)] R_{1i} [x(t) - x(t-\tau_1)] \\
\dot{V}_{7i} &\le -\alpha V_{7i} + \tau_{10}^2 \dot{x}^T(t) R_{2i} \dot{x}(t) \\
&\quad - \tau_{10} \int_{t-\tau}^{t-\tau_1} e^{-\alpha\tau} \dot{x}^T(s) R_{2i} \dot{x}(s) ds \\
\dot{V}_{8i} &\le -\alpha V_{8i} + \tau_{02}^2 \dot{x}^T(t) R_{3i} \dot{x}(t) \\
&\quad - \tau_{02} \int_{t-\tau_2}^{t-\tau} e^{-\alpha\tau_2} \dot{x}^T(s) R_{3i} \dot{x}(s) ds.
\end{aligned}$$

Case 1: When $t \in \Delta_1$

$$\begin{aligned}
&- \tau_{10} \int_{t-\tau}^{t-\tau_1} e^{-\alpha\tau} \dot{x}^T(s) R_{21} \dot{x}(s) ds \\
&= -\tau_{10} \int_{t-\tau(t)}^{t-\tau_1} e^{-\alpha\tau} \dot{x}^T(s) R_{21} \dot{x}(s) ds \\
&\quad - \tau_{10} \int_{t-\tau}^{t-\tau(t)} e^{-\alpha\tau} \dot{x}^T(s) R_{21} \dot{x}(s) ds.
\end{aligned}$$

From [23], we have

$$\begin{aligned}
&- \tau_{10} \int_{t-\tau}^{t-\tau_1} e^{-\alpha\tau} \dot{x}^T(s) R_{21} \dot{x}(s) ds \\
&\le -e^{-\alpha\tau} \begin{bmatrix} X_{11}(t) \\ X_{21}(t) \end{bmatrix}^T \begin{bmatrix} R_{21} & -S_1 \\ * & R_{21} \end{bmatrix} \begin{bmatrix} X_{11}(t) \\ X_{21}(t) \end{bmatrix}
\end{aligned}$$

where $X_{11}(t) = x(t-\tau_1) - x(t-\tau(t))$, $X_{21}(t) = x(t-\tau(t)) - x(t-\tau)$, and $\begin{bmatrix} R_{21} & S_1 \\ * & R_{21} \end{bmatrix} \ge 0$. Also,

$$\begin{aligned}
\dot{V}_{51} &\le -\alpha V_{51} + e^{-\alpha\tau_1} x^T(t-\tau_1) Q_{41} x(t-\tau_1) \\
&\quad - (1-\mu) e^{-\alpha\tau} x^T(t-\tau(t)) Q_{41} x(t-\tau(t)) \\
\dot{V}_{81} &\le -\alpha V_{81} + \tau_{02}^2 \dot{x}^T(t) R_{31} \dot{x}(t) - e^{-\alpha\tau_2} X_{31}^T R_{31} X_{31}
\end{aligned}$$

where $X_{31} = x(t-\tau) - x(t-\tau_2)$.

Since

$$\dot{V}_1 = \sum_{n=1}^{8} \dot{V}_{n1} - \alpha V_{11} + \alpha V_{11}$$

combining the above derivatives gives

$$\dot{V}_1 + \alpha V_1 \le \eta^T(t)\Theta_1\eta(t)$$

where $\eta(t) = \text{col}\{x(t), x(t-\tau(t)), x(t-\tau_1), x(t-\tau), x(t-\tau_2)\}$. Therefore, $\dot{V}_1 \le -\alpha V_1$, if $\Theta_1 < 0$.

Case 2: When $t \in \Delta_2$, similarly, we have

$$\begin{aligned} &-(\tau_2-\tau)\int_{t-\tau_2}^{t-\tau} e^{-\alpha\tau_2}\dot{x}^T(s)R_{32}\dot{x}(s)ds \\ &\le -e^{-\alpha\tau_2}\begin{bmatrix} X_{12}(t) \\ X_{22}(t)\end{bmatrix}^T\begin{bmatrix} R_{32} & -S_2 \\ * & R_{32}\end{bmatrix}\begin{bmatrix} X_{12}(t) \\ X_{22}(t)\end{bmatrix} \end{aligned}$$

where $X_{12}(t) = x(t-\tau) - x(t-\tau(t))$, $X_{22}(t) = x(t-\tau(t)) - x(t-\tau_2)$, and $\begin{bmatrix} R_{32} & S_2 \\ * & R_{32}\end{bmatrix} \ge 0$. Also,

$$\begin{aligned} \dot{V}_{52} &\le -\alpha V_{52} + e^{-\alpha\tau_1}x^T(t-\tau_1)Q_{42}x(t-\tau_1) \\ &\quad -(1-\mu)e^{-\alpha\tau_2}x^T(t-\tau(t))Q_{42}x(t-\tau(t)) \\ \dot{V}_{72} &\le -\alpha V_{72} + \tau_{10}^2\dot{x}^T(t)R_{22}\dot{x}(t) - e^{-\alpha\tau}X_{32}^T R_{22}X_{32} \end{aligned}$$

where $X_{32} = x(t-\tau_1) - x(t-\tau)$. Similarly,

$$\dot{V}_2 + \alpha V_2 \le \eta^T(t)\Theta_2\eta(t).$$

So, we have $\dot{V}_2 \le -\alpha V_2$, if $\Theta_2 < 0$.

Let $t_0 = 0$ be the initial time and $t_1, t_2, \ldots t_s, t_{s+1}, \ldots$ be the switching time, it is easy to see that $t_1 = T/2,\ t_2 = T, \ldots, t_s = sT/2, t_{s+1} = (s+1)T/2, \ldots$. We assume that the switching signal $\sigma(t)$ is continuous from the right everywhere: $\sigma(t) = \lim_{\theta\to t^+}\sigma(\theta)$ for each $t \ge 0$, which has the following form:

$$\sigma(t) = \begin{cases} 1, & t \in \Delta_1 \\ 2, & t \in \Delta_2. \end{cases}$$

For convenience, we denote $\sigma(t) = i,\ i \in \{1, 2\}$. From Shur Completement [24], it is obvious that the conditions in (6) are equivalent to $\Theta_1 < 0$ and $\Theta_2 < 0$. Then, we have

$$V(t) = V_{\sigma(t)}(t) \le e^{-\alpha(t-t_s)}V_{\sigma(t_s)}(t_s) \quad t \in [t_s, t_{s+1}). \quad (14)$$

To simplify denotation, let $V_{\sigma(t)}(t) \triangleq V_{\sigma(t)}(t, x_t)$ and similarly, $V(t) \triangleq V(t, x_t)$. From (8), it yields

$$V(t) = V_{\sigma(t_s)}(t_s) \le \gamma V_{\sigma(t_s^-)}(t_s^-) \quad s = 1, 2, \cdots. \quad (15)$$

Let $n = N_\sigma(t, t_0) \le N_0 + (t-t_0)/\tau_a$, where $N_\sigma(t, t_0)$ denotes the number of discontinuities of a switching signal $\sigma(t)$ on an interval (t_0, t) and $N_0 \ge 0$ is some constant integer. For the switching case in this paper, we have $\tau_a = T/2$ and $N_0 \ge 1$. From (14) and (15), we have

$$\begin{aligned} V(t) &\le e^{-\alpha(t-t_n)}V_{\sigma(t_n)}(t_n) \\ V_{\sigma(t_n)}(t_n) &\le \gamma V_{\sigma(t_n^-)}(t_n^-) = \gamma V_{\sigma(t_{n-1})}(t_n). \end{aligned}$$

By the use of (14) and (15) repeatedly as the above process, we have the following calculation:

$$\begin{aligned} V(t) &\le e^{-\alpha(t-t_n)}V_{\sigma(t_n)}(t_n) \le \gamma e^{-\alpha(t-t_n)}V_{\sigma(t_{n-1})}(t_n) \\ &\le \gamma e^{-\alpha(t-t_n)}e^{-\alpha(t_n-t_{n-1})}V_{\sigma(t_{n-1})}(t_{n-1}) \\ &\le \gamma^2 e^{-\alpha(t-t_{n-1})}V_{\sigma(t_{n-1}^-)}(t_{n-1}^-) \\ &\le \gamma^2 e^{-\alpha(t-t_{n-2})}V_{\sigma(t_{n-2})}(t_{n-2})\ldots \\ &\le \gamma^{N_\sigma(t,t_0)}e^{-\alpha(t-t_0)}V_{\sigma(t_0)}(t_0) \\ &\le e^{N_0\ln\gamma}e^{(-\alpha+\ln\gamma/\tau_a)(t-t_0)}V_{\sigma(t_0)}(t_0). \end{aligned}$$

By $a\|x(t)\| \le V(t) \le b\|x_t\|_c$, where $\|\cdot\|$ denotes the two norms $\|\cdot\|_2$ and $\|x_t\|_c \triangleq \max_{-\tau\le\theta\le 0}\|x_t\|$, we have $\|x(t)\| \le \frac{1}{a}V(t) \le \lambda e^{(-\alpha+\ln\gamma/\tau_a)(t-t_0)}$ with $\lambda = \frac{b}{a}e^{N_0\ln\gamma}\|x_{t_0}\|_c$. When $\tau_a \ge \ln\gamma/\alpha$ or $T \ge 2\ln\gamma/\alpha$, $x(t)$ converges to zero exponentially as $t \to \infty$, which completes the proof.

APPENDIX C
TERMS IN LMIS (11)

The matrices $\tilde{\Lambda}_i$, $\tilde{\Xi}$, $\tilde{\Phi}$, and $\tilde{\Psi}$ are give as follows in order:

$$\text{diag}\{-\epsilon_{1i}^{-1}\tilde{P}, -\epsilon_{2i}^{-1}\tilde{P}, -\epsilon_{3i}^{-1}\tilde{P}\}$$

$$\begin{bmatrix} \tilde{\Xi}_{11} & \tilde{\Xi}_{12} & \tilde{\Xi}_{13} \\ \tau_1\tilde{P}A_d^T & \tau_{10}\tilde{P}A_d^T & \tau_{02}\tilde{P}A_d^T \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix} \tilde{\Phi}_{11} & A_d\tilde{P} & \epsilon_{11}e^{-\alpha\tau_1}\tilde{P} & 0 & 0 \\ * & \tilde{\Phi}_{22} & \tilde{\Phi}_{23} & \tilde{\Phi}_{24} & 0 \\ * & * & \tilde{\Phi}_{33} & -e^{-\alpha\tau}\tilde{S}_1 & 0 \\ * & * & * & \tilde{\Phi}_{44} & \epsilon_{31}e^{-\alpha\tau_2}\tilde{P} \\ * & * & * & * & \tilde{\Phi}_{55} \end{bmatrix}$$

$$\begin{bmatrix} \tilde{\Psi}_{11} & A_d\tilde{P} & \epsilon_{12}e^{-\alpha\tau_1}\tilde{P} & 0 & 0 \\ * & \tilde{\Psi}_{22} & 0 & \tilde{\Psi}_{24} & \tilde{\Psi}_{25} \\ * & * & \tilde{\Psi}_{33} & \epsilon_{22}e^{-\alpha\tau}\tilde{P} & 0 \\ * & * & * & \tilde{\Psi}_{44} & -e^{-\alpha\tau_2}\tilde{S}_2 \\ * & * & * & * & \tilde{\Psi}_{55} \end{bmatrix}$$

where

$$\begin{aligned} \tilde{\Phi}_{11} &= A\tilde{P} + \tilde{P}A^T + B\tilde{K} + \tilde{K}^T B^T + (\alpha - \epsilon_{11}e^{-\alpha\tau_1})\tilde{P} + \tilde{Q}_{11} \\ \tilde{\Phi}_{22} &= e^{-\alpha\tau}[-(1-\mu)\tilde{Q}_{41} - 2\epsilon_{21}\tilde{P} - \tilde{S}_1 - \tilde{S}_1^T] \\ \tilde{\Phi}_{23} &= e^{-\alpha\tau}(\epsilon_{21}\tilde{P} + \tilde{S}_1^T) \qquad \tilde{\Phi}_{24} = e^{-\alpha\tau}(\epsilon_{21}\tilde{P} + \tilde{S}_1) \\ \tilde{\Phi}_{33} &= e^{-\alpha\tau_1}(-\tilde{Q}_{11} + \tilde{Q}_{21} + \tilde{Q}_{41}) - (\epsilon_{21}e^{-\alpha\tau} + \epsilon_{11}e^{-\alpha\tau_1})\tilde{P} \\ \tilde{\Phi}_{44} &= e^{-\alpha\tau}(-\tilde{Q}_{21} + \tilde{Q}_{31}) - (\epsilon_{21}e^{-\alpha\tau} + \epsilon_{31}e^{-\alpha\tau_2})\tilde{P} \\ \tilde{\Phi}_{55} &= e^{-\alpha\tau_2}(-\tilde{Q}_{31} - \epsilon_{31}\tilde{P}) \end{aligned}$$

and

$$\tilde{\Psi}_{11} = A\tilde{P} + \tilde{P}A^T + B\tilde{K} + \tilde{K}^T B^T + (\alpha - \epsilon_{12}e^{-\alpha\tau_1})\tilde{P} + \tilde{Q}_{12}$$
$$\tilde{\Psi}_{22} = e^{-\alpha\tau_2}[-(1-\mu)\tilde{Q}_{42} - 2\epsilon_{32}\tilde{P} - \tilde{S}_2 - \tilde{S}_2^T]$$
$$\tilde{\Psi}_{24} = e^{-\alpha\tau_2}(\epsilon_{32}\tilde{P} + \tilde{S}_2^T) \qquad \tilde{\Psi}_{25} = e^{-\alpha\tau_2}(\epsilon_{32}\tilde{P} + \tilde{S}_2)$$
$$\tilde{\Psi}_{33} = e^{-\alpha\tau_1}(-\tilde{Q}_{12} + \tilde{Q}_{22} + \tilde{Q}_{42}) - (\epsilon_{12}e^{-\alpha\tau_1} + \epsilon_{22}e^{-\alpha\tau})\tilde{P}$$
$$\tilde{\Psi}_{44} = e^{-\alpha\tau}(-\tilde{Q}_{22} + \tilde{Q}_{32}) - (\epsilon_{22}e^{-\alpha\tau} + \epsilon_{32}e^{-\alpha\tau_2})\tilde{P}$$
$$\tilde{\Psi}_{55} = e^{-\alpha\tau_2}(-\tilde{Q}_{32} - \epsilon_{32}\tilde{P}) \qquad \tilde{\Xi}_{11} = \tau_1(\tilde{P}A^T + \tilde{K}^T B^T)$$
$$\tilde{\Xi}_{12} = \tau_{10}(\tilde{P}A^T + \tilde{K}^T B^T) \qquad \tilde{\Xi}_{13} = \tau_{02}(\tilde{P}A^T + \tilde{K}^T B^T).$$

APPENDIX D
PROOF OF THEOREM 4.1

Replace A by $A + BK$ and let $P_1 = P_2 = P$ in (6). Then, multiply the resulting matrices from left and right by

$$\text{diag}\{P^{-1}, P^{-1}, P^{-1}, P^{-1}, P^{-1}, R_{1i}^{-1}, R_{2i}^{-1}, R_{3i}^{-1}\},\ i = 1, 2$$

correspondingly, and let

$$\tilde{P} = P^{-1},\ \tilde{Q}_{ji} = \tilde{P}Q_{ji}\tilde{P}$$
$$\tilde{R}_{li} = \tilde{P}R_{li}\tilde{P},\ \tilde{S}_i = \tilde{P}S_i\tilde{P},\ \tilde{K} = K\tilde{P}.$$

Furthermore, let $\tilde{R}_{li} = \epsilon_{li}\tilde{P}$, where $\epsilon_{li} > 0$, $l \in \{1, 2, 3\}$, then $R_{li}^{-1} = \tilde{P}\tilde{R}_{li}^{-1}\tilde{P} = \epsilon_{li}^{-1}\tilde{P}$. Therefore, the solvability of (11) implies the existence of gain K to stabilize the system. Next, multiplying $\begin{bmatrix} R_{21} & S_1 \\ * & R_{21} \end{bmatrix}$ and $\begin{bmatrix} R_{32} & S_2 \\ * & R_{32} \end{bmatrix}$ from left and right by $\begin{bmatrix} \tilde{P} & 0 \\ 0 & \tilde{P} \end{bmatrix}$, respectively, we have $\begin{bmatrix} \epsilon_{21}\tilde{P} & \tilde{S}_1 \\ * & \epsilon_{21}\tilde{P} \end{bmatrix} \geq 0$ and $\begin{bmatrix} \epsilon_{32}\tilde{P} & \tilde{S}_2 \\ * & \epsilon_{32}\tilde{P} \end{bmatrix} \geq 0$. Also,

$$Q_{ji_1} \leq \gamma Q_{ji_2} \Leftrightarrow \tilde{Q}_{ji_1} \leq \gamma\tilde{Q}_{ji_2}.$$

In addition,

$$\epsilon_{li_1}P \leq \gamma\epsilon_{li_2}P \Leftrightarrow \epsilon_{li_1} \leq \gamma\epsilon_{li_2}.$$

Therefore, if conditions (12) and (13) are satisfied, the proof is completed.

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1. Stability analysis and stabilization of a class of cutting systems with chatter suppression

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Author affiliation: (1) Department of Automation, University of Science and Technology of China, Hefei, China; (2) School of Electrical Engineering and Computer Science, University of Newcastle, Callaghan; NSW, Australia; (3) College of Information Engineering, Zhejiang University of Technology, Hangzhou, China; (4) CTGT Center, Harbin Institute of Technology, Harbin, China; (5) School of Engineering, University of South Wales, Pontypridd, United Kingdom
Corresponding author: Meng, Hao-Fei
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Addresses: [Meng, Hao-Fei; Kang, Yu] Univ Sci & Technol China, Dept Automat, Hefei 230026, Peoples R China.
[Chen, Zhiyong] Univ Newcastle, Sch Elect Engn & Comp Sci, Callaghan, NSW 2308, Australia.
[Zhao, Yun-Bo] Zhejiang Univ Technol, Coll Informat Engn, Hangzhou 310023, Zhejiang, Peoples R China.
[Zhao, Yun-Bo; Liu, Guo-Ping] Harbin Inst Technol, CTGT Ctr, Harbin 150001, Peoples R China.
[Liu, Guo-Ping] Univ South Wales, Sch Engn, Pontypridd CF37 1DL, M Glam, Wales.

Reprint Address: Meng, HF (reprint author), Univ Newcastle, Sch Elect Engn & Comp Sci, Callaghan, NSW 2308, Australia.

E-mail Addresses: haofei.meng@uon.edu.au; kangduyu@ustc.edu.cn; zhiyong.chen@newcastle.edu.au; yunbo.zhao@imperial.ac.uk; guoping.liu@southwales.ac.uk

Author Identifiers:

Author	ResearcherID Number	ORCID Number
Zhao, Yun-Bo	F-1699-2010	
Liu, Guo-Ping	O-3511-2014	0000-0002-0699-2296

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