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Research Article

Sufficient Conditions on the Exponential Stability of Neutral Stochastic Differential Equations with Time-Varying Delays

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The exponential stability is investigated for neutral stochastic differential equations with time-varying delays. Based on the Lyapunov stability theory and linear matrix inequalities (LMIs) technique, some delay-dependent criteria are established to guarantee the exponential stability in almost sure sense. Finally a numerical example is provided to illustrate the feasibility of the result.

1. Introduction

Neutral differential equations are well-known models from many areas of science and engineering, wherein, quite often the future state of such systems depends not only on the present state but also involves derivatives with delays. Deterministic neutral differential equations were originally introduced by Hale and Meyer [1] and discussed in Hale and Lunel (see [2]) and Kolmanovskii et al. (for details, see also [3, 4]), among others. Motivated by chemical engineering systems as well as theory of aeroelasticity, stochastic neutral delay systems have been intensively studied over recent year [5–9]. Mao initiated the study of exponential stability of neutral stochastic differential delay equations in [5], while [9] incorporated Razumikhinis approach in neutral stochastic functional differential equations to investigate the stability problem. It is pointed out in Section 5 [10] that the conditions imposed in [5, 9] make the theory not applicable to the delay equation.

More recently, Luo et al. [6] proposed new criteria on exponential stability of neutral stochastic delay differential equations. In [11, 12], Milošević investigated the almost sure exponential stability of a class of highly nonlinear neutral stochastic differential equations with time-dependent delay, and some sufficient conditions were given for the considered systems. However, when the exponential stability of the neutral system with time-delay is considered, one always assumes that the derivative of the delay function is less than 1 (e.g., [6]). Meanwhile, the delay-independent conditions in [6, 10] are restricted when the delay is small. On the other hand, some results are proposed on stochastic Markovian jumping systems (e.g., [13–20]) and finite-time problems of stochastic systems (e.g., [18–22]), which can provide some useful methods and techniques for the neutral stochastic systems. This paper aims to develop the exponential stability in almost sure sense of the neutral stochastic differential equations with time-varying delays. Under the weaker assumptions that the derivative of time delay is less than some constant, sufficient conditions for the exponential stability are given in terms of linear matrix inequality (LMI) based on Lyapunov stability theory, which can be checked easily by MATLAB LMI Toolbox.

The paper is organized as follows. In the remainder of this section we recall some preliminaries, mainly from [5]. In Section 3 we state the main results on exponential stability.

Section 4 will provide numerical examples to illustrate the feasibility and effectiveness of the results, and the conclusion will be made in Section 5.

2. Preliminaries

Throughout this paper, unless otherwise specified, let $\{\Omega, \mathcal{F}, P\}$ be a complete probability space with a filtration $\{\mathcal{F}_t\}_{t\geq 0}$ satisfying the usual conditions (i.e., right continuous and F_0 containing all P-null sets). Let $w(t) = (w_1(t), w_2(t), \ldots, w_m(t))^n$ be m-dimensional Wiener process defined on the probability space. Let $|\cdot|$ denote the Euclidean norm in $\mathbb{R}^n$. A^T stands for the transpose of the vector or matrix A. If A is a matrix, its trace norm is denoted by $|A| = \sqrt{A^T A}$. $a \vee b$ denotes $\max\{a, b\}$. $\lambda_{\max}(\cdot), \lambda_{\min}(\cdot)$ are maximum eigenvalue and minimum eigenvalue, respectively.

Consider the following n-dimensional neutral stochastic differential delay equations with time-varying delays:

$$\begin{aligned} &\mathrm{d}\left[x(t) - G(x(t-\delta(t)))\right] \\ &\quad = f(x(t), x(t-\delta(t)), t)\,\mathrm{d}t \\ &\qquad + g(x(t), x(t-\delta(t)), t)\,\mathrm{d}w(t) \\ &x(t) = \xi(t) \in C^b_{\mathcal{F}_0}([-\tau, 0], \mathbb{R}^n), \quad t \in [-\tau, 0], \end{aligned} \tag{1}$$

where $f : \mathbb{R}^n \times \mathbb{R}^n \times \mathbb{R}_+ \to \mathbb{R}^n$, $g : \mathbb{R}^n \times \mathbb{R}^n \times \mathbb{R}_+ \to \mathbb{R}^{n\times m}$, and $G \in C(\mathbb{R}^n, \mathbb{R}^n)$. The functions $\delta(t) : \mathbb{R}_+ \to [0, \tau]$ are continuously differentiable such that $0 \leq \delta(t) \leq \delta, \dot{\delta}(t) \leq \bar{\delta}$. Let $C([-\tau, 0], \mathbb{R}^n)$ denote the family of continuous functions ϕ from $[-\tau, 0]$ to $\mathbb{R}^n$ with the norm $\|\phi\| = \sup_{-\tau\leq\theta\leq 0}|\phi(\theta)|$. Let $C^b_{\mathcal{F}_0}([-\tau, 0], \mathbb{R}^n)$ be the family of all $\mathcal{F}_0$-measurable $C([-\tau, 0], \mathbb{R}^n)$-valued random variables $\xi = \{\xi(\theta) : \tau \leq \theta \leq 0\}$ such that $\sup_{-\tau\leq\theta\leq 0} E|\xi(\theta)|^2 < \infty$. To guarantee the existence and uniqueness of the solution, we first list the following hypotheses.

(H_1) Both the functionals f and g satisfy the uniform Lipschitz conditions. That is, there is a diagonal positive matrix $L = \operatorname{diag}\{L_1, L_2, \ldots, L_n\}$ such that

$$\begin{aligned} &\left|f(x, y, t) - f(\bar{x}, \bar{y}, t)\right| \vee \left|g(x, y, t) - g(\bar{x}, \bar{y}, t)\right| \\ &\qquad \leq \left|L(x - \bar{x})\right| + \left|L(y - \bar{y})\right| \end{aligned} \tag{2}$$

for all $t \geq 0$ and those $x, y, \bar{x}, \bar{y} \in \mathbb{R}^n$.

(H_2) There is a constant $k \in (0, 1)$ such that for all $\phi_1, \phi_2 \in C^b_{\mathcal{F}_0}([-\tau, 0], \mathbb{R}^n)$

$$\left|G(\phi_1) - G(\phi_2)\right|^2 \leq k \sup_{-\tau\leq\theta\leq 0}\left|\phi_1(\theta) - \phi_2(\theta)\right|^2. \tag{3}$$

It is well known (see, e.g., [3]) that under hypotheses H_1, H_2 (1) has a unique continuous solution on $t \geq -\tau$.

To obtain sufficient conditions on almost sure exponential stability, the following lemmas and definition are given.

Lemma 1 (see [23]). *For any positive definite constant matrix $M \in \mathbb{R}^{n\times n}$, scalar $r > 0$, and vector function $f(\cdot) : [0, r] \to \mathbb{R}^n$ such that the integrations in the following are well defined, then the following inequality holds:*

$$\left(\int_0^r f(s)ds\right)^T M \left(\int_0^r f(s)\,ds\right) \leq r\int_0^r f^T(s)\,Mf(s)\,ds. \tag{4}$$

The following semimartingale convergence theorem will play an important role in the later parts.

Lemma 2 (see [24]). *Let $A(t)$ and $U(t)$ be two continuous adapted increasing processed on $t \geq 0$ with $A(0) = U(0) = 0$ a.s. Let $M(t)$ be a real-valued continuous local martingale with $M(0) = 0$ a.s. Let ς be a nonnegative $\mathcal{F}_0$-measurable random variable. Define*

$$X(t) = \varsigma + A(t) - U(t) + M(t) \quad \text{for } t \geq 0. \tag{5}$$

If $X(t)$ is nonnegative, then

$$\begin{aligned} \left\{\lim_{t\to\infty} A(t) < \infty\right\} &\subset \left\{\lim_{t\to\infty} X(t) < \infty\right\} \\ &\quad \cap \left\{\lim_{t\to\infty} U(t) < \infty\right\} \quad \text{a.s.}, \end{aligned} \tag{6}$$

where $B \subset D$ a.s. means $P(B \cap D) = 0$. In particular, if $\lim_{t\to\infty} A(t) < \infty$ a.s., then for almost all $w \in \Omega$,

$$\lim_{t\to\infty} X(t) < \infty, \qquad \lim_{t\to\infty} U(t) < \infty; \tag{7}$$

that is, both $X(t)$ and $U(t)$ converge to finite random variables.

Definition 3 (see [25]). The equilibrium of solution $\{x(t), t \geq 0\}$ of (1) is said to be almost sure exponentially stable if there exists a constant $\varepsilon > 0$ such that

$$\limsup_{t\to\infty} \frac{1}{t}\log|x(t)| \leq -\varepsilon \quad \text{a.s.} \tag{8}$$

for any bounded initial condition ξ.

3. Main Results

Theorem 4. *Let hypotheses H_1, H_2 hold. System* (1) *is almost sure exponentially stable, if there exists positive definite matrix such that the following LMI holds*

$$\Omega = \begin{pmatrix} \Xi_{11} & N_2^T - N_1^T & N_3^T + U^T & N_4^T & -N_1^T + N_5^T & 0 \\ * & \Xi_{22} & -N_3^T & -N_4^T & -N_2^T - N_5^T & 0 \\ * & * & \Xi_{33} & 0 & -N_3^T & U \\ * & * & * & \Xi_{44} & -N_4^T & 0 \\ * & * & * & * & -\frac{1}{\delta}R - 2N_5^T & 0 \\ * & * & * & * & * & -\varepsilon I \end{pmatrix} < 0, \tag{9}$$

where

$$\begin{aligned} \Xi_{11} &= \beta P + e^{\beta\delta} Q + P + 2N_1^T, \\ \Xi_{22} &= \left(-\left(1-\overline{\delta}\right) e^{\beta\delta} \vee -\left(1-\overline{\delta}\right)\right) Q - 2N_2, \\ \Xi_{33} &= -2U + e^{\beta\delta} S + 2\lambda_{\max}(P) L^T L \\ &\quad + \frac{2}{\beta}\lambda_{\max}(R)\left(e^{\beta\delta} - 1\right) L_1, \\ \Xi_{44} &= -\left(1-\overline{\delta}\right) S + 2\lambda_{\max}(P) L^T L \\ &\quad + \frac{2}{\beta}\lambda_{\max}(R)\left(e^{\beta\delta} - 1\right) L_1 + \varepsilon k I. \end{aligned} \tag{10}$$

Proof. To confirm that the stochastic neutral differential equation (1) is mean-square exponentially stable with decay rate β, we define a Lyapunov-Krasovskii functional $V(x(t), t)$ as follows:

$$\begin{aligned} V(x(t), t) &= e^{\beta t} \rho^T(t) P \rho(t) \\ &\quad + \int_{t-\delta(t)}^{t} e^{\beta(s+\delta)} \rho^T(s) Q \rho(s)\, \mathrm{d}s \\ &\quad + \int_{-\delta}^{0} \int_{t+\theta}^{t} e^{\beta(s-\theta)} f^T(x(s), y(s), s) \\ &\qquad \times R f(x(s), y(s), s)\, \mathrm{d}s\, \mathrm{d}\theta \\ &\quad + \int_{t-\delta(t)}^{t} e^{\beta(s+\delta)} x^T(s) S x(s)\, \mathrm{d}s. \end{aligned} \tag{11}$$

For simplicity, let $y(t) = x(t - \delta(t))$, $\rho(t) = x(t) - G(y(t))$. By generalizing Ito's formula, we have that

$$EV(\rho(t), t) = EV(\rho(0), 0) + \int_0^t \mathscr{L}V(x(s), y(s), s)\, \mathrm{d}s. \tag{12}$$

Then, the derivative of $V(\rho(t), t)$ along the solution of (1) gives

$$\begin{aligned} &LV(x(t), y(t), t) \\ &\quad = \beta e^{\beta t} \rho^T(t) P \rho(t) + 2e^{\beta t} \rho(t)^T P f(x(t), y(t), t) \\ &\qquad + e^{\beta t} g^T(x(t), y(t), t) P g(x(t), y(t), t) \\ &\qquad + e^{\beta(t+\delta)} \rho(t) Q \rho(t) \\ &\qquad - e^{\beta(t-\delta(t))+\delta} \rho^T(t - \delta(t)) Q \rho(t - \delta(t)) \left(1 - \dot{\delta}(t)\right) \\ &\qquad + \frac{1}{\beta} e^{\beta t} \left(e^{\beta\delta} - 1\right) f^T(x(t), y(t), t) R f(x(t), y(t), t) \\ &\qquad - e^{\beta t} \int_{t-\delta}^{t} f^T(x(s), y(s), s) R f(x(s), y(s), s)\, \mathrm{d}s \\ &\qquad + e^{\beta(t+\delta)} x(t) S x(t) - e^{\beta(t-\delta(t))+\delta} \\ &\qquad \times x^T(t - \delta(t)) S x(t - \delta(t)) \left(1 - \dot{\delta}(t)\right). \end{aligned} \tag{13}$$

Note that, from system (1) and Newton-Leibniz formula, we have

$$\begin{aligned} M = \Bigg(&\rho(t) - \rho(t - \delta(t)) - \int_{t-\delta(t)}^{t} f(x(s), y(s), s)\, \mathrm{d}s \\ &- \int_{t-\delta(t)}^{t} g(x(s), y(s), s)\, \mathrm{d}w(s) \Bigg) = 0. \end{aligned} \tag{14}$$

By calculation, it is clear that

$$\begin{aligned} &f^T(x(t), y(t), t) R f(x(t), y(t), t) \\ &\quad \le \lambda_{\max}(R) f^T(x(t), y(t), t) f(x(t), y(t), t) \\ &\quad \le \lambda_{\max}(R) \left| f(x(t), y(t), t) \right|^2 \\ &\quad \le 2\lambda_{\max}(R) \left(x^T(t) L^T L x(t) + x^T(t - \delta(t)) L^T L y(t) \right), \end{aligned} \tag{15}$$

and then by which, we have

$$\begin{aligned}
&2\rho^T(t)Pf(x(t),y(t),t)\\
&\quad\le \rho^T(t)P^T\rho(t)\\
&\qquad+f^T(x(t),y(t),t)Pf(x(t),y(t),t)\\
&\quad\le \rho^T(t)P^T\rho(t)\\
&\qquad+2\lambda_{\max}(P)\left(x^T(t)L^TLx(t)+y^T(t)L^TLy(t)\right),\\
&-e^{\beta(t-\delta(t))+\delta}\rho^T(t)Q\rho(t)\left(1-\dot{\delta}(t)\right)\\
&\qquad\le-\left(1-\overline{\delta}\right)e^{\beta t}\rho^T(t)Q\rho(t).\\
&-e^{\beta(t-\delta(t))+\delta}x^T(t)Sx(t)\left(1-\dot{\delta}(t)\right)\\
&\qquad\le-\left(1-\overline{\delta}\right)e^{\beta t}x^T(t)Sx(t).
\end{aligned}\tag{16}$$

Moreover, by Lemma 2, one can get

$$\begin{aligned}
&-\int_{t-\delta}^{t}f^T(x(s),y(s),s)Rf(x(s),y(s),s)\,\mathrm{d}s\\
&\quad\le-\int_{t-\delta(t)}^{t}f^T(x(s),y(s),s)Rf(x(s),y(s),s)\,\mathrm{d}s\\
&\quad\le-\frac{1}{\delta}\left(\int_{t-\delta(t)}^{t}f(x(s),y(s),s)\mathrm{d}s\right)^T\\
&\qquad\times R\left(\int_{t-\delta(t)}^{t}f(x(s),y(s),s)\,\mathrm{d}s\right).
\end{aligned}\tag{17}$$

Letting $L_1=L^TL$ and substituting (14)–(17) into (13) yield

$$\begin{aligned}
&LV(x(t),y(t),t)\\
&\quad\le e^{\beta t}\Big\{\beta\rho^T(t)P\rho(t)+\rho^T(t)P^T\rho(t)\\
&\qquad+2\lambda_{\max}(P)x^T(t)L_1x(t)\\
&\qquad+2\lambda_{\max}(P)y^T(t)L_1y(t)\\
&\qquad+\left(-\left(1-\overline{\delta}\right)e^{\beta\delta}\vee-\left(1-\overline{\delta}\right)\right)\rho^T(t)Q\rho(t)\\
&\qquad+e^{\beta\delta}\rho^T(t)Q_1\rho(t)+2\lambda_{\max}\frac{1}{\beta}\left(e^{\beta\delta}-1\right)\\
&\qquad\times\left(x^T(t)L_1x(t)+y^T(t)L_1y(t)\right)\\
&\qquad-\frac{1}{\delta}\left(\int_{t-\delta(t)}^{t}f(x(s),y(s),s)\mathrm{d}s\right)^T\\
&\qquad\times R\left(\int_{t-\delta(t)}^{t}f(x(s),y(s),s)\,\mathrm{d}s\right)\Big\}.
\end{aligned}\tag{18}$$

Furthermore, from (14), it follows that

$$\begin{aligned}
A&=2\eta^T\left(N_1^T,N_2^T,N_3^T,N_4^T,N_5^T\right)^TM=0,\\
B&=2x^T(t)U\left[\rho(t)-x(t)+G\left(y(t)\right)\right]=0,
\end{aligned}\tag{19}$$

where $\eta=(\rho^T,\rho^T(t-\delta(t)),x^T(t),y^T(t),(\int_{t-\delta(t)}^{t}f(x,y,s)\,\mathrm{d}s)^T)^T$, and N_i $(1\le i\le 5)$, U are matrices with compatible dimensions.

It can be shown that

$$\begin{aligned}
&\int_0^t\mathscr{L}V(x(s),y(s),s)\,\mathrm{d}s\\
&\qquad+e^{\beta t}(A+B)+e^{\beta t}M^TP_1\left(M(t)+\int_{t-\delta(t)}^{t}g(x,y,s)\,\mathrm{d}s\right)\\
&\quad\le e^{\beta t}\Big\{\beta\rho^T(t)P\rho(t)+\rho^T(t)P^T\rho(t)\\
&\qquad+x^T(t)L_1x(t)+e^{\beta\delta}\rho^T(t)Q\rho(t)\\
&\qquad+y^T(t)L_1y(t)+2\lambda_{\max}(P)x^T(t)L_1x(t)\\
&\qquad+2\lambda_{\max}y^T(t)L_1y(t)\\
&\qquad-\left(1-\overline{\delta}\right)\rho^T(t)Q\rho(t)+e^{\beta\delta}x^T(t)Sx(t)\\
&\qquad-\left(1-\overline{\delta}\right)x^T(t)Sx(t)+2\lambda_{\max}\frac{1}{\beta}\left(e^{\beta\delta}-1\right)\\
&\qquad\times\left(x^T(t)L_1x(t)+y^T(t)L_1y(t)\right)\\
&\qquad-\frac{1}{\delta}\left(\int_{t-\delta(t)}^{t}f(x(s),y(s),s)\mathrm{d}s\right)^T\\
&\qquad\times R\left(\int_{t-\delta(t)}^{t}f(x(s),y(s),s)\,\mathrm{d}s\right)\Big\}\\
&\quad\le e^{\beta t}\left\{\eta^T\widetilde{\Omega}\eta+\varepsilon^{-1}x^T(t)UU^Tx(t)\right\},
\end{aligned}\tag{20}$$

where Ω is defined as

$$\widetilde{\Omega}=\begin{pmatrix}
\Xi_{11} & N_2^T-N_1^T & N_3^T+U^T & N_4^T & -N_1^T+N_5^T\\
* & \Xi_{22} & -N_3^T & -N_4^T & -N_2^T-N_5^T\\
* & * & \Xi_{33} & 0 & -N_3^T\\
* & * & * & \Xi_{44} & -N_4^T\\
* & * & * & * & -\frac{1}{\delta}R-2N_5^T
\end{pmatrix}.\tag{21}$$

By Schur complement, we know that $\eta^T\widetilde{\Omega}\eta + \varepsilon^{-1}x^T(t)UU^Tx(t) < 0$. On the other hand, it follows that

$$V(\rho(t),t) = V(\rho(0),0) + \int_0^t \mathscr{L}V(x(s),y(s),s)\,\mathrm{d}s + \int_0^t 2e^{\beta s}x^s(t)\,g(x(s),y(s),s)\,\mathrm{d}\omega(s). \tag{22}$$

Note that ξ is bounded and V, G are continuous; then $V(\rho(0))$ must be nonnegative bounded. Moreover, $\mathscr{L}V(x,y,t) \le 0$ can be obtained directly:

$$V(\rho(t),t) \le V(\rho(0),0) + \int_0^t 2e^{\beta t}x^T(s)\,g(x(s),y(s),s)\,\mathrm{d}\omega(s). \tag{23}$$

By applying Lemma 2 to (23), one sees that

$$\lim_{t\to\infty}\sup V(\rho(t),t) < \infty; \tag{24}$$

hence there exists a positive random variable ζ satisfying

$$\sup_{0\le t<\infty} e^{\beta t}\left|x(t) - G(y(t))\right|^2 \le \zeta. \tag{25}$$

Since, for any $\varepsilon_3 \in (0,1)$

$$\left|x(t) - G(y(t))\right|^2 \ge \left(1-\varepsilon_3^{-1}\right)|x(t)|^2 - (\varepsilon_3 - 1)\left|G(y(t))\right|^2, \tag{26}$$

we must have

$$\sup_{0\le t\le T} e^{\beta t}|x(t)|^2 \le \zeta + \frac{k^2}{\varepsilon_3}\sup_{0\le t\le T} e^{\beta t}\left|y(t)\right|^2 \le \zeta + k^2e^{\beta\tau}\|\xi\|^2 + \frac{k^2}{\varepsilon_3}e^{\beta\tau}\sup_{0\le t\le T} e^{\beta t}|x(t)|^2. \tag{27}$$

From the above inequality (26), it yields the desired result

$$\limsup_{t\to\infty}\frac{1}{t}\log|x(t)| \le -\frac{\beta}{2}. \tag{28}$$

That completes the proof. □

4. Example

In this section, a numerical example will be given to illustrate that the proposed method is effective.

Example 1. Consider the following system:

$$\begin{aligned} d\left[x_1(t) - 0.1x_2(t-\delta(t))\right] &= -x_1(t)\,x_2(t-\delta(t))\,\mathrm{d}t + x_1(t)\sin^2(t-\delta(t))\,\mathrm{d}\omega(t), \\ d\left[x_2(t) - 0.1x_1(t-\delta(t))\right] &= -x_2(t)\,x_1(t-\delta(t))\,\mathrm{d}t + x_2(t)\cos^2(t-\delta(t))\,\mathrm{d}\omega(t), \end{aligned} \tag{29}$$

where the delay function is defined as $\delta(t) = (1/4)\sin(t), t > 0$. It is obvious that (29) satisfies the assumptions H_1 and H_2, and here $L = I$, $k = 0.1$. Moreover, since $\dot{\delta} = (1/4)\cos(t)$, then $\overline{\delta} = 1/4$.

According to Theorem 4 and employing MATLAB LMI Toolbox, it is relatively easy to deduce that the neutral stochastic differential equation (29) is almost sure exponentially stable.

Remark 5. Comparing with some existing sufficient criteria for neural stochastic differential equations (e.g., [6, 11, 12]), the obtained result is given in terms of linear matrix inequality (LMI), which can be easily checked by MATLAB LMI Toolbox.

5. Conclusion

The exponential stability is investigated for a class of neutral stochastic differential equations with time-varying delays. In order to overcome the difficulties, we introduce suitable Lyapunov functionals and employ linear matrix inequalities (LMIs) technique, and then a delay-dependent criteria are given to check the almost sure exponential stability of the concerned equations.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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