Necessary and Sufficient Conditions of Generalized Exponential Stability for Retarded Dynamic Systems

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Abstract: In this paper, the necessary and sufficient conditions of generalized exponential stability for general type of retarded dynamic systems are established. The exponential decay estimates on the transient responses for the systems are presented. A generalized exponential stability result with respect to a time-varying decay degree for a special class of retarded dynamic systems is also presented based on the matrix measures as the application of the established conditions. It is revealed that the established estimates can be less conservative than those obtained only by using the sufficient stability conditions in the literature.

Key words: retarded dynamic systems; generalized exponential stability; necessary and sufficient conditions

滞后动态系统广义指数稳定的充要条件

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摘要: 本文针对一般的滞后动态系统建立了广义指数稳定性的充分和必要条件,并由所建立的充要条件得出了系统过渡过程的时变指数衰减估计.作为所建结果的应用,基于矩阵测度给出了一类滞后动态系统过渡过程的相应指数衰减估计.本文揭示了所建衰减估计可好于那些仅基于充分稳定性条件所得的估计.

关键词: 滞后动态系统; 广义指数稳定性; 充要条件

1 Introduction

As we know, the main time-domain methods for stability analysis of the retarded dynamic systems described by an n-dimensional retarded functional differential equation are Lyapunov methods[1] including the well-known Lyapunov functional methods and Lyapunov function methods with Razumikhin-type techniques. So far most of the existing results have not provided decay estimates on the transient responses for general retarded dynamic systems. Recently, by using differential inequalities techniques and the matrix measures, Mori et al.[2,3], Wang et al.[4], Hmamed[5], and Lehman and Shujaee[6] have established some exponential decay estimates on the transient responses for a special class of retarded dynamic systems which have a linear retard-free term. But their results are all obtained under the sufficient stability conditions. As a matter of fact, it is necessary to establish not only sufficient but also necessary conditions of exponential stability for retarded dynamic systems so that as less conservative decay estimates as possible can be obtained.

In this paper, the necessary and sufficient conditions of the exponential stability for general type of retarded dynamic systems are established. Based on the conditions, the exponential decay estimates on the transient responses for the systems are presented. An application of the established conditions for a class of retarded dynamic systems is also suggested

2 Preliminaries

Let $\mathbb{R}^n$ denote an n-dimensional linear vector space over the reals with any convenient norm $\|\cdot\|$ in it, let $\mathbb{R} = (-\infty, \infty)$, $\mathbb{R}_+ = [0, \infty)$, $J_0 = [0, \infty)$, and $J_\tau = [-\tau, \infty)$ for given $\tau \geqslant 0$. Let $C_n = C([-\tau, 0], \mathbb{R}^n)$ be the Banach space of continuous functions mapping the interval $[-\tau, 0]$ into $\mathbb{R}^n$ with the topology of uniform convergence. For given $\phi \in C_n$, we define $\|\phi\|_\tau = \sup_{-\tau \leqslant \theta \leqslant 0} \|\phi(\theta)\|$, $\phi(\theta) \in \mathbb{R}^n$. Let $x_t \in C_n$ be defined by $x_t(\theta) = x(t+\theta)$, $\theta \in [-\tau, 0]$.

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Let us consider a retarded dynamic system described by the following n-dimensional retarded functional differential equation[1]

$$\dot{x}(t) = f(t, x_t), \tag{1}$$

where "$\cdot$" denotes the right-hand derivative and $f: J_0 \times C_n \to \mathbb{R}^n$ is continuous and sufficiently smooth so that for any initial function $x_{t_0} = \phi$ at $t = t_0 \in J_0$, system (1) has a unique solution $x(t_0, \phi)(t)$ on $[t_0 - \tau, \infty)$. We assume that $f(t, 0) \equiv 0$ for all t so that $x^* = 0$ is an equilibrium of system (1). For simplicity, we also denote the value of the solution $x(t_0, \phi)(t)$ by $x(t)$ and $x_t(t_0, \phi)(\theta), \theta \in [-\tau, 0]$, by x_t for $t \geqslant t_0$ without confusion.

Definition 1[7] A decay function is defined as $d(t): [t_0, \infty) \to (0, \infty), t_0 \in J_0$, with $\dot{d}(t) < 0$, where "$\cdot$" denotes the right-hand derivative. If the solution $x(t_0, \phi)(t)$ of system (1) through any given $(t_0, \phi) \in J_0 \times \mathbb{C}_n$ satisfies

$$\| x(t_0, \phi)(t) \| \leqslant d(t, \phi), \quad \forall t \geqslant t_0, \tag{2}$$

then the decay gain of the function $d(t, \phi)$ is defined as

$$\Gamma(t) = \frac{d(t, \phi)}{\| \phi \|_\tau} > 0, \quad t \geqslant t_0, \tag{3}$$

with the initial decay gain $\Gamma(t_0)$, and the decay degree of the function $d(t, \phi)$ is defined as

$$\gamma(t) = -\frac{\dot{d}(t, \phi)}{d(t, \phi)} > 0, \quad t \geqslant t_0. \tag{4}$$

Remark 1[7] The definition of the decay functions in Definition 1 depends on the initial instant $t_0 \in J_0$ and the different t_0 may imply the different decay function. Definitions (3) and (4) imply that $\Gamma(t)$ and $\gamma(t)$ depend only on $t \geqslant t_0$ for given $(t_0, \phi) \in J_0 \times C_n$. The physical meaning of $\Gamma(t)$ is obvious and as $d(t, \phi) = -(1/\gamma(t))\dot{d}(t, \phi)$, the physical meaning of $1/\gamma(t)$ at $t = s \geqslant t_0$ can be regarded as the time taken by $d(t, \phi)$ from $d(s, \phi)$ to 0 when keeping the velocity $-\dot{d}(s, \phi)$.

Definition 2[7] System (1) is said to be globally generalized exponentially stable with respect to an initial decay gain Γ and decay degree $\gamma(t)$ if the solution $x(t_0, \phi)(t)$ of system (1) through any $(t_0, \phi) \in J_0 \times C_n$ satisfies

$$\| x(t_0, \phi)(t) \| \leqslant \Gamma \| \phi \|_\tau \exp\{-\int_{t_0}^{t} \gamma(t) \mathrm{d}t\}, \quad \forall t \geqslant t_0, \tag{5}$$

where $\Gamma \geqslant 1$ is a constant and $\gamma: J_0 \to (0, \infty)$ is a continuous positive function.

Lemma 1[8] Let $f: (a, b) \to \mathbb{R}$. The computation law for D^+ is as follows:

$$D^+ (fg)(t) = D^+ f(t) g(t) + f(t) \frac{\mathrm{d}g(t)}{\mathrm{d}t}, \tag{6}$$

where $g(t)$ is differentiable, $g(t) \geqslant 0$ for all $t \in (a, b)$, and D^+ denotes the Dini derivative.

In the following sections, we let $\| \cdot \|_\sigma$ denote the corresponding norm[2~6] for $\sigma = 1$ or 2 or ∞ and $\mu_\sigma(\cdot)$ denote the matrix measure derived from the matrix norm for $\sigma = 1$ or 2 or ∞.

3 Necessary and sufficient conditions

This section presents the necessary and sufficient conditions of exponential stability for general retarded dynamic systems described by the retarded functional differential Equation (1).

Theorem 1 Assume that $\gamma_\sigma: J_\tau \to (0, \infty)$ is a continuous positive function. System (1) is globally generalized exponentially stable with respect to the initial decay gain $\Gamma = 1$ and the decay degree $\gamma_\sigma(t)$ if and only if along the solution $x(t_0, \phi)(t)$ of system (1) through $(t_0, \phi) \in J_0 \times C_n$,

$$D^+ \| x(t) \|_\sigma \leqslant -\gamma_\sigma(t) \| x(t) \|_\sigma \tag{7}$$

whenever

$$\begin{cases} \| x(t) \|_\sigma = \| \phi \|_{\sigma\tau} \exp\{-\int_{t_0}^{t} \gamma_\sigma(t) \mathrm{d}t\}, & t \geqslant t_0, \\ \| x_t \|_{\sigma\tau} \leqslant \| x(t) \|_\sigma \exp\{\int_{t-\tau}^{t} \gamma_\sigma(t) \mathrm{d}t\}, & t \geqslant t_0. \end{cases} \tag{8}$$

Proof Let $\tau > 0$ without loss of generality. For any $(t_0, \phi) \in J_0 \times C_n$, along the solution $x(t_0, \phi)(t)$ of system (1), we have

$$\| x(t_0 + \theta) \|_\sigma \leqslant \| \phi \|_{\sigma\tau} \leqslant \| \phi \|_{\sigma\tau} \exp\{-\int_{t_0}^{t_0+\theta} \gamma_\sigma(t) \mathrm{d}t\}, \quad \forall \theta \in [-\tau, 0], \tag{9}$$

where $\gamma_\sigma(t) = \gamma_\sigma(0)$ for all $t \in [-\tau, 0]$. Suppose there exists some $s \geqslant t_0$ such that

$$\| x(s + \theta) \|_\sigma \leqslant \| \phi \|_{\sigma\tau} \exp\{-\int_{t_0}^{s+\theta} \gamma_\sigma(t) \mathrm{d}t\} \leqslant$$

$$\| \phi \|_{\sigma\tau} \exp\{-\int_{t_0}^{s-\tau} \gamma_\sigma(t)\mathrm{d}t\},$$

$$\forall \theta \in [-\tau, 0], \tag{10}$$

as well as

$$\| x(s) \|_\sigma = \| \phi \|_{\sigma\tau} \exp\{-\int_{t_0}^{s} \gamma_\sigma(t)\mathrm{d}t\} \tag{11}$$

and

$$\| x(t) \|_\sigma > \| \phi \|_{\sigma\tau} \exp\{-\int_{t_0}^{t} \gamma_\sigma(t)\mathrm{d}t\} \tag{12}$$

on $t \in (s, s+r)$ for some $r > 0$. (10) and (11) imply

$$\| x_s \|_{\sigma\tau} \leqslant \| x(s) \|_\sigma \exp\{\int_{s-\tau}^{s} \gamma_\sigma(t)\mathrm{d}t\}. \tag{13}$$

Let

$$W(t,x) = \| x \|_\sigma \exp\{\int_{t_0}^{t} \gamma_\sigma(t)\mathrm{d}t\},$$

$$t \geqslant t_0, \quad t_0 \in J_0, \quad x \in \mathbb{R}^n. \tag{14}$$

Along the solution $x(t_0,\phi)(t)$ of system (1) and by Lemma 1, (7),(8),(11) and (13), we obtain

$$D^+ W(t,x(t)) = [D^+ \| x(t) \|_\sigma + \gamma_\sigma(t) \| x(t) \|_\sigma] \exp\{\int_{t_0}^{t} \gamma_\sigma(t)\mathrm{d}t\} \tag{15}$$

at any $t \geqslant t_0$ and

$$D^+ \| x(s) \|_\sigma \leqslant - \gamma_\sigma(s) \| x(s) \|_\sigma = - \gamma_\sigma(s) \| \phi \|_{\sigma\tau} \exp\{-\int_{t_0}^{s} \gamma_\sigma(t)\mathrm{d}t\}, \tag{16}$$

at $t = s \geqslant t_0$. Then, we have

$$D^+ W(s,x(s)) \leqslant 0. \tag{17}$$

(17) implies that for a sufficient small $h > 0$ and $s + h \in (s, s+r)$, we have

$$W(s+h, x(s+h)) \leqslant W(s, x(s)). \tag{18}$$

By (11),(14) and (18), we obtain

$$\| x(s+h) \|_\sigma \leqslant \| x(s) \|_\sigma \exp\{-\int_{s}^{s+h} \gamma_\sigma(t)\mathrm{d}t\} = \| \phi \|_{\sigma\tau} \exp\{-\int_{t_0}^{s+h} \gamma_\sigma(t)\mathrm{d}t\}. \tag{19}$$

(19) contradicts (12). In this way, we show that along the solution $x(t_0,\phi)(t)$ of system (1) through any $(t_0,\phi) \in J_0 \times C_n$, if conditions (7) and (8) are satisfied, we have

$$\| x(t+\theta) \|_\sigma \leqslant \| \phi \|_{\sigma\tau} \exp\{-\int_{t_0}^{t+\theta} \gamma_\sigma(t)\mathrm{d}t\},$$

$$\forall \theta \in [-\tau, 0] \tag{20}$$

for all $t \geqslant t_0$, where $\gamma_\sigma(t) = \gamma_\sigma(0)$ for all $t \in [-\tau, 0]$. (20) is equivalent to

$$\| x(t_0,\phi)(t) \|_\sigma \leqslant \| \phi \|_{\sigma\tau} \exp\{-\int_{t_0}^{t} \gamma_\sigma(t)\mathrm{d}t\},$$

$$\forall t \geqslant t_0 \tag{21}$$

for all $(t_0,\phi) \in J_0 \times C_n$. By Definition 2, system (1) is globally generalized exponentially stable with respect to the initial decay gain $\Gamma = 1$ and the decay degree $\gamma_\sigma(t)$. The proof of the sufficiency is thus completed.

Now, let us prove the necessity by contradiction. Assume that system (1) is globally generalized exponentially stable with respect to thd initial decay gain $\Gamma = 1$ and the decay degree $\gamma_\sigma(t)$, i.e. (20) or (21) holds but

$$D^+ \| x(s) \|_\sigma > - \gamma_\sigma(s) \| x(s) \|_\sigma \tag{22}$$

when

$$\| x(s) \|_\sigma = \| \phi \|_{\sigma\tau} \exp\{-\int_{t_0}^{s} \gamma_\sigma(t)\mathrm{d}t\}, \ s \geqslant t_0. \tag{23}$$

(20) and (23) imply

$$\| x_s \|_{\sigma\tau} \leqslant \| x(s) \|_\sigma \exp\{\int_{s-\tau}^{s} \gamma_\sigma(t)\mathrm{d}t\}. \tag{24}$$

According to the above assumption and (21) and (23), along the solution $x(t_0,\phi)(t)$ of system (1), we obtain at $t = s$

$$D^+ \| x(s) \|_\sigma =$$

$$\limsup_{h\to 0+} \frac{1}{h}[\| x(s+h) \|_\sigma - \| x(s) \|_\sigma] \leqslant$$

$$\lim_{h\to 0+} \frac{1}{h}[\| \phi \|_{\sigma\tau} \exp\{-\int_{t_0}^{s+h} \gamma_\sigma(t)\mathrm{d}t\} - \| \phi \|_{\sigma\tau} \exp\{-\int_{t_0}^{s} \gamma_\sigma(t)\mathrm{d}t\}] =$$

$$\| \phi \|_{\sigma\tau} \exp\{-\int_{t_0}^{s} \gamma_\sigma(t)\mathrm{d}t\} \cdot \lim_{h\to 0+} \frac{1}{h}[\exp\{-\int_{s}^{s+h} \gamma_\sigma(t)\mathrm{d}t\} - 1] =$$

$$\| x(s) \|_\sigma \lim_{h\to 0+} [-\gamma_\sigma(s+h) \cdot \exp\{-\int_{s}^{s+h} \gamma_\sigma(t)\mathrm{d}t\}] =$$

$$- \gamma_\sigma(s) \| x(s) \|_\sigma =$$
$$- \gamma_\sigma(s) \| \phi \|_{\sigma\tau} \exp\{ - \int_{t_0}^{s} \gamma_\sigma(t) dt \}. \quad (25)$$

(25) contradicts (22). The proof of the necessity is thus completed. Q.E.D.

Remark 2 An advantage of Theorem 1 is that it provides the following estimate on the transient response of system (1):

$$\| x(t_0, \phi)(t) \|_\sigma \leqslant \| \phi \|_{\sigma\tau} \exp\{ - \int_{t_0}^{t} \gamma_\sigma(t) dt \}, \quad \forall t \geqslant t_0. \quad (26)$$

Besides, it is easy to show that Theorem 1 still holds if we use γ_σ instead of $\gamma_\sigma(t)$ in (7) and (8), where $\gamma_\sigma > 0$ is a constant. Then, another estimate on the transient response for system (1) is given by

$$\| x(t_0, \phi)(t) \|_\sigma \leqslant \| \phi \|_{\sigma\tau} \exp\{ - \gamma_\sigma (t - t_0) \}, \quad \forall t \geqslant t_0. \quad (27)$$

Remark 3 Theorem 1 enables us to employ a special Lyapunov function $\| x \|_\sigma$ instead of Lyapunov functional to study the exponential stability for general retarded dynamic systems. For more general case of Lyapunov functions, some results have been established in [7].

Remark 4 It should be pointed out that all of the results established in this section hold for case $\tau = 0$.

4 An application

Let us consider the following system

$$\begin{cases} \dot{x}(t) = A(t)x(t) + F(t, x_t), & t \geqslant 0, \\ x_0 = \phi, & \phi \in C_n, \end{cases} \quad (28)$$

where $x(t) \in \mathbb{R}^n, A(t) \in \mathbb{R}^{n \times n}$ is continuous on $[0, \infty), F: [0, \infty) \times C_n \to \mathbb{R}^n$ is continuous and has a bound

$$\| F(t, x_t) \|_\sigma \leqslant \beta \| x_t \|_{\sigma\tau}, \quad \beta > 0, \quad (29)$$

for all $(t, x_t) \in [0, \infty) \times C_n$.

Theorem 2 Assume that $\mu_\sigma(A(t)) < 0$ is non-increasing on $t \geqslant 0$. System (28) is globally generalized exponentially stable with respect to the initial decay gain $\Gamma = 1$ and the time-varying decay degree $\gamma_\sigma(t)$ if and only if the following equation

$$\gamma_\sigma(t) = - \mu_\sigma(A(t)) - \beta e^{\gamma_\sigma(t)\tau}, \quad t \geqslant 0 \quad (30)$$

has the unique non-decreasing positive solution $\gamma_\sigma(t) > 0$. An estimate on the transient response is given by

$$\| x(t) \|_\sigma \leqslant \| \phi \|_{\sigma\tau} \exp\{ - \int_0^t \gamma_\sigma(t) dt \}, \quad t \geqslant 0. \quad (31)$$

Proof As $\gamma_\sigma(t)$ is non-decreasing on $t \geqslant 0$[6], we have $\exp\{ \int_{t-\tau}^{t} \gamma_\sigma(t) dt \} \leqslant \exp\{ \gamma_\sigma(t) \tau \}$ which holds at any $t \geqslant 0$, where $\gamma_\sigma(t) = \gamma_\sigma(0)$ for all $t \in [-\tau, 0]$. Along the solution $x(t_0, \phi)(t)$ of system (28) and by conditions (7) and (8) of Theorem 1, we obtain

$$D^+ \| x(t) \|_\sigma =$$
$$\limsup_{h \to 0+} \frac{1}{h} [\| x(t+h) \|_\sigma - \| x(t) \|_\sigma] =$$
$$\limsup_{h \to 0+} \frac{1}{h} [\| x(t) + hA(t)x(t) +$$
$$hF(t, x_t) + o(h) \|_\sigma - \| x(t) \|_\sigma] \leqslant$$
$$\lim_{h \to 0+} \frac{1}{h} [(\| I + hA(t) \|_\sigma - 1) \| x(t) \|_\sigma] +$$
$$\beta \| x_t \|_{\sigma\tau} = \mu_\sigma(A(t)) \| x(t) \|_\sigma + \beta \| x_t \|_{\sigma\tau} \leqslant$$
$$[\mu_\sigma(A(t)) + \beta \exp\{ \int_{t-\tau}^{t} \gamma_\sigma(t) dt \}] \| x(t) \|_\sigma \leqslant$$
$$[\mu_\sigma(A(t)) + \beta \exp\{ \gamma_\sigma(t) \tau \}] \| x(t) \|_\sigma =$$
$$- \gamma_\sigma(t) \| x(t) \|_\sigma =$$
$$- \gamma_\sigma(t) \| \phi \|_{\sigma\tau} \exp\{ - \int_0^t \gamma_\sigma(t) dt \}. \quad (32)$$

Due to the uniqueness of the solution $\gamma_\sigma(t)$ (see [6]) of Equation (30) and Theorem 1, the proof of Theorem 2 is completed. Q.E.D.

Remark 5 For the system in Theorem 2, Lehman and Shujaee[6] has obtained the estimate (31) based on the sufficient stability condition

$$- \mu_\sigma(A(t)) > \beta \quad (33)$$

but we prove Theorem 2 based on the necessary and sufficient conditions established in Theorem 1. If only using the sufficient stability condition (33), we can always find a constant $\gamma_\sigma > 0$ such that

$$- \sup_{t \geqslant 0} \mu_\sigma(A(t)) = \beta e^{\gamma_\sigma \tau} + \gamma_\sigma. \quad (34)$$

On the basis of the proof of the sufficiency in Theorem 1, we obtain another estimate on the transient response for system (28) as follows:

$$\| x(t) \|_\sigma \leqslant \| \phi \|_{\sigma\tau} \exp\{ - \gamma_\sigma t \}, \quad t \geqslant 0. \quad (35)$$

As $\gamma_\sigma \leqslant \gamma_\sigma(t)$ for all $t \geqslant 0$, the estimate (31) is better than estimate (35). This shows clearly that there is no guarantee of obtaining less conservative results only based on the sufficient stability conditions.

5 Conclusion

The necessary and sufficient conditions of generalized exponential stability for general type of retarded dynamic systems are established. Based on the established necessary and sufficient conditions, an exponential decay estimate on the transient response for general retarded dynamic system is presented. All of the results are derived from a special Lyapunov function. An application by using the established conditions for a sapecial class of retarded dynamic systems is also studied. It is revealed that the established estimates can be less conservative than those obtained by only using the sufficient stability conditions in the literature.

References

1 Hale J K and Lunel S M V. Introduction to Functional Differential Equations. New York: Springer-Verlag, 1993

2 Mori T, Fukuma N and Kuwahara M. Simple stability criteria for single and composite linear systems with time delays. Int. J. Contr., 1981, 34(6): 1175 – 1184

3 Mori T, Fukuma N and Kuwahara M. On an estimate of the decay rate for stable linear delay systems. Int. J. Contr., 1982, 36(1): 95 – 97

4 Wang S S, Chen B S and Lin T P. Robust stability of uncertain time-delay systems. Int. J. Contr., 1987, 46(3): 963 – 976

5 Hmamed A. Further results on the delay-independent asymptotic stability of linear systems. Int. J. Systems Sci., 1991, 22(3): 1127 – 1132

6 Lehman B and Shujaee K. Delay independent stability conditions and decay estimates for time-varying functional differential equations. IEEE Trans. Automat. Contr., 1994, 39(8): 1673 – 1676

7 Xu B. N & S conditions for exponential stability of retarded dynamic systems and some applications. Proceedings of 1998 American Control Conference, Philadelphia, 1998, 3: 1953 – 1957

8 McShane E J. Integration. Princeton: Princeton University Press, 1947

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Control Theory and Application, 1995, 12(6): 808 – 813

6 Mei Shengwei, Lu Qiang, Sun Yuangzhang and Li Xiong. Robust Control of Nonlinear Systems Based on Passivity, Proceedings of Cninese Control Conference, Lushan, 1997, 381 – 385

7 Sontag E. A 'universial' construction of Artstein's theorem on nonlinear stabilization. System & Control Letters, 1989, 13(1): 117 – 123

8 Wei Lin. Feedback stabilization of general nonlinear control systems: A passive system approach. Systems & Control Letters, 1995, 25(1): 41 – 52

9 Shen T and Tamura K. Robust H_∞ control of uncertain nolinear systems via state feedback. IEEE Transaction on Automatic Control, 1995, 39(4): 766 – 768

10 Willems J. Dissipative dynamical systems, – Part I: General Theory, Arch. Rational Mechanics and Analysis, 1972, 45: 321 – 351

11 Willems J. Dissipative dynamical systems, – Part II: Linear systems with quadratic supply rates, Arch. Rational Mechanics and Analysis, 1972, 45: 352 – 393

12 Van der Schaft A. L_2 gain and passivity techniques in nonlinear control. New York: Springer-Verlag, 1996

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