Passivation Control of Nonlinear Systems with Disturbances *

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Abstract: This paper proposes and investigates the passivation control problem for a class of nonlinear systems with disturbance, that is, to construct a feedback control law such that the corresponding closed-loop system is internally stable and passive. A necessary and sufficient condition of paassivation is given with feedthrough term. In addition, two special cases of the passivition problem are discussed using Lyapunov recursive design techniques. Then, more general case is solved via control Lyapunov function.

Key words: passivation; dissipative systems; control Lyapunov function

带有干扰的非线性系统的无源化控制

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摘要: 本文提出并考察一类带有干扰的非线性系统的无源化控制问题,即构造反馈控制器使得相应的闭环系统无源且保持内部稳定.本文给出了在此馈通项下系统无源的一个充分必要条件.另外,针对两类特殊情形下的无源控制,应用Lyapunov递归方法得到了解决该问题的一个条件;特别利用控制Lyapunov函数,对较一般情形的非线性系统构造出一类有效的无源化控制器.

关键词: 无源化; 耗散系统; 控制Lyapunov函数

1 Introduction

Dissipative system theory has played an important role in the study of nonlinear uncertain systems. In [1] and [3], Isidori A. constructed H_∞ controller via differential game approach to make the corresponding closed-loop system dissipative and internal stable. From the viewpoint of engineering, if we select $\|z\|^2 - \gamma\|w\|^2$ as a supply rate (here $\|\cdot\|^2$ is L_2 norm), where w and z represent the disturbance and penalty signal respectively, then the energy of system's engineering signal will be measured by L_2 norm. Therefore, when systems are dissipative for the supply rate, the disturbance will be attenuated in the sense of the L_2 gain less than or equal to a prescribed number.

On the other hand, if we take the inner product of system's input and output as supply rate, the goal of control should be to render the corresponding closed-loop system passive, which is a special case of dissipative system. As well known, the passivity of an input-output system originated by the dissipation of energy across resistors in an electrical circuit has been widely used in optimal control and stability analysis of systems[2~5]. Indeed, a lot of control problems for general nonlinear systems can be reduced to find a controller which renders the closed loop system passive. Many papers have addressed this passivation problem[4,8,10,11].

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As is shown in [4] and [12], passivity of a nonlinear system is equivalent to the system with appropriate transformation of external signals to be dissipative with γ-supply rate, i.e. having finite L_2 gain. This means that robust stabilization based on small gain theorem and H_∞ disturbance attenuation problem can be solved by finding such a controller that renders the nominal system passive. More generally, the design problem in this case should be formulated as follows: For a given system with both control input and disturbance input, find a feedback controller such that the resulting closed-loop system is passive and internally stable. In this paper, we provide some results for this problem. First, we will give a necessary and sufficient condition for a given nonlinear system with feedthrough term being passive. Then, using this condition, we will discuss two special cases in which KYP property or a kind of matching condition is satisfied respectively. Finally, a solution for a more general case is given via control Lyapunov function.

2 Passivity condition and problem description

Consider the following system:

$$\begin{cases} \dot{x} = f(x) + g_1(x)w, \\ y = h(x), \end{cases} \tag{2.1}$$

with $x \in \mathbb{R}^n, w \in \mathbb{R}^m, y \in \mathbb{R}^m$, where f, g_1, h are all smooth and $f(0) = 0, h(0) = 0$.

Definition 1[4] System (1) is said to be passive, if there exists a C^0 nonnegative function $V : \mathbb{R}^n \to \mathbb{R}$ which satisfies $V(0) = 0$ such that

$$V(x(t)) - V(x^0) \leqslant \int_0^t y^{\mathrm{T}}(s)w(s)\mathrm{d}s, \tag{2.2}$$

for all $w \in \mathbb{R}^n, x^0 \in \mathbb{R}^n$, where $x = \phi(t;x^0,w)$ is the solution of $\dot{x} = f(x) + g_2(x)w$ starting from $x(0) = x^0$. $V(x)$ is called a storage function of system (2.1).

Proposition 1[4,5] System (2.1) is passive with C^1 storage function if and only if there exists a C^1 nonnegative function $V : \mathbb{R}^n \to \mathbb{R}$ with $V(0) = 0$ such that

$$L_fV \leqslant 0, \quad L_{g_1}V = h^{\mathrm{T}}, \tag{2.3}$$

for each $x \in \mathbb{R}^n$.

We claim system (2.1), which is passive with C^1 storage function, has KYP property, if there exists such a $V(x)$ satisfying (2.3).

Consider the following nonlinear system:

$$\begin{cases} \dot{x} = f(x) + g_1(x)w + g_2(x)u, \\ y = h(x) + K(x)w, \end{cases} \tag{2.4}$$

with state $x \in \mathbb{R}^n$, control $u \in \mathbb{R}^P$, disturbance $w \in \mathbb{R}^m$ and measurement output $y \in \mathbb{R}^m$; $f(0) = 0, h(0) = 0$, f, g_1, g_2, and h are smooth vector fields having suitable dimensions, K is a positive-definite matrix for all $x \in \mathbb{R}^n$.

Definition 2 Passivation Control Problem (henceforth just "PCP"):

PCP is to construct controller u, which enables system (2.4) to be passive with a C^1 storage function and to conserve inner stability, that is, find $u = u_*(x)$, such that

1) The closed loop system

$$\begin{cases} \dot{x} = f(x) + g_2(x)u_* + g_1(x)w, \\ y = h(x) + K(x)w \end{cases} \tag{2.5}$$

is passive, i.e. there exists a C^1 nonnegative function $V(x)$, $V(0) = 0$, such that

$$V(x(t)) - V(x^0) \leqslant \int_0^t y^{\mathrm{T}}w\mathrm{d}s, \tag{2.6}$$

$\forall\, w \in \mathbb{R}^m, \forall\, x^0 \in \mathbb{R}^n$ and $x = \phi(t;x^0,w)$ is the solution of the first equation of (2.1).

2) When $w = 0$, the system $\dot{x} = f(x) + g_2(x)u_*$ is asymptotically stable at $x = 0$.

Here u_* is called a passivation controller.

In order to solve this problem, the next theorem plays a key role. It gives a necessary and sufficient condition for a nonlinear system with the following form to be passive:

$$\begin{cases} \dot{x} = f(x) + g_1(x)w, \\ y = h(x) + K(x)w. \end{cases} \tag{2.7}$$

Theorem 1 System (2.7) is passive with C^1 storage function if and only if there exists a C^1 nonnegative function $V(x)$ with $V(0) = 0$ such that

$$L_fV(x) + \frac{1}{4}(L_{g_1}V - h^{\mathrm{T}})K^{-1}(L_{g_1}V - h^{\mathrm{T}})^{\mathrm{T}} \leqslant 0, \tag{2.8}$$

holds for all $x \in \mathbb{R}^n$.

Proof From (2.6), we may obtain its infinitesimal form: $\frac{\mathrm{d}V}{\mathrm{d}t} \leqslant y^{\mathrm{T}}w$, that is

$$L_fV + L_{g_1}Vw \leqslant h^{\mathrm{T}}w + w^{\mathrm{T}}Kw, \tag{2.9}$$

or equivalently

$$L_fV + (L_{g_1}V - h^{\mathrm{T}})w - w^{\mathrm{T}}Kw \leqslant 0. \quad (2.10)$$

By completing the square, it is easy to show that (2.10) is equivalent to

$$L_fV + \frac{1}{4}(L_{g_1}V - h^{\mathrm{T}})K^{-1}(L_{g_1}V - h^{\mathrm{T}})^{\mathrm{T}} - [w^{\mathrm{T}} - \frac{1}{2}(L_{g_1}V - h^{\mathrm{T}})K^{-1}]K[w - \frac{1}{2}K^{-1}(L_{g_1}V - h^{\mathrm{T}})^{\mathrm{T}}] \leqslant 0. \quad (2.11)$$

"only if": Consider the case of $w = \frac{1}{2}K^{-1}(x)(L_{g_1}V - h^{\mathrm{T}})^{\mathrm{T}}$ in (2.11), then it implies (2.8).

"if": If (2.8) holds, then (2.11) holds for all $w \in \mathbb{R}^m$, so system (2.7) is passive.

Remark 1 According to Theorem 2.4, system (2.5) is passive if and only if there exists $u = u_*(x)$, such that

$$L_fV + L_{g_2}Vu_* + \frac{1}{4}(L_{g_1}V - h^{\mathrm{T}})K^{-1}(L_{g_1}V - h^{\mathrm{T}})^{\mathrm{T}} \leqslant 0. \quad (2.12)$$

Remark 2 It should be noted that if system (2.1) satisfies KYP property, then the implication of (2.8) for (2.7) is passive, i.e. (2.5) with $u_* = 0$ is passive[6]. Hence, in this case, if we do not require the system to be inner stable, then PCP of (2.5) would be trivial.

3 Special cases of passive control

3.1 Case with KYP condition

Assume that the given system (2.4) satisfies the KYP conditions in the sense that $f(x)$, $g_1(x)$ and $h(x)$ in (2.4) satisfy (2.3) for a suitable C^1 function $V(x)$. This means that system (2.1) is passive with the storage function $V(x)$, and we can show that selection $u = 0$ makes system (2.4) passive.

Proposition 2 If system (2.1) is passive, then system (2.7) is passive.

Proof Since (2.1) is passive, then there exists a C^0 positive function $V(x)$, such that

$$V(x) - V(x^0) \leqslant \int_0^t h^{\mathrm{T}}(s)w(s)\mathrm{d}s, \quad (3.1)$$

$\forall w \in \mathbb{R}^m$.

Since $K(x)$ is positive-definite

$$V(x) - V(x^0) \leqslant \int_0^t (h^{\mathrm{T}}(s)w(s) + w^{\mathrm{T}}(s)K(x(s))w(s))\mathrm{d}s = \int_0^t y^{\mathrm{T}}(s)w(s)\mathrm{d}s, \quad (3.2)$$

$\forall w \in \mathbb{R}^n, \forall x^0 \in \mathbb{R}^n$.

Thus (2.7) is passive.

Note that passivity does not imply the stability of free system $\dot{x} = f(x)$. Hence, if $\dot{x} = f(x)$ is not asymptotically stable at $x = 0$, then we have to find feedback a $u = u_*(x)$ such that system $\dot{x} = f(x) + g(x)u_*$ is asymptotically stable at $x = 0$ and system (2.5) is passive.

Proposition 3 For system (2.4), if $\Omega \cap S = \{0\}$, then the PCP of system (2.4) can be solved by the control law $u = u_*(x) = -(L_{g_2}V)^{\mathrm{T}}$, where V (with $V(0) = 0$) is a nonnegative C^1 function satisfying

$$L_{g_1}V = h^{\mathrm{T}} \quad \text{and} \quad L_fV \leqslant 0, \quad \forall x \in \mathbb{R}^n,$$

$$\Omega = \{x \in \mathbb{R}^n \mid L_fV(x) = 0\},$$

$$S = \{x \in \mathbb{R}^n \mid L_\tau V(x) = 0, \forall \tau \in D\},$$

$$D = \mathrm{span}\{ad_f^k g_{2i} : 0 \leqslant k \leqslant n-1, 1 \leqslant i \leqslant p\},$$

$$g_2(x) = \{g_{21}(x), \cdots, g_{2p}\}.$$

Proof From (2.10), we have

$$\frac{\partial V}{\partial x}(f + g_1w + g_2u_*) \leqslant y^{\mathrm{T}}w,$$

$$\text{i.e.} \quad \frac{\mathrm{d}V}{\mathrm{d}t} \leqslant y^{\mathrm{T}}w.$$

System (2.5) is passive.

On the other hand, since $\dot{x} = f(x)$ is Lyapunov stable (from $L_fV \leqslant 0$) and $\Omega \cap S = \{0\}$, we conclude that $u = u_*(x) = -(L_{g_2}V)^{\mathrm{T}}$ globally stabilize $\dot{x} = f(x) + g_2(x)u$ ([8], Theorem 2.1), that is, system (2.5) is inner stable.

3.2 Case with matching condition

Assume that the given system (2.4) satisfies the matching condition: $g_1(x) = g_2(x)m(x)$, where $m(x) \in \mathbb{R}^{m\times p}$ is a smooth matrix function with $n > m$.

As well known, if the system from control input u to output $\zeta = h(x)$ has relative degree $\{1, 1, \cdots, 1\}$, then under some geometric condition, there exist changes:

$$[z^{\mathrm{T}} \quad \zeta^{\mathrm{T}}]^{\mathrm{T}} = T(x) = [z_1^{\mathrm{T}}(x) \cdots z_{n-m}^{\mathrm{T}}(x) h^{\mathrm{T}}(x)]^{\mathrm{T}}$$

with feedback

$$u = \alpha(x)[v - \beta(x)],$$

which transform the system into the following form:

$$\begin{cases} \dot{z} = f_0(z) + f_1(z,\zeta)\zeta, \\ \dot{\zeta} = v + b(z,\zeta)w, \\ y = \zeta + M(z,\zeta)w, \end{cases} \tag{3.3}$$

where

$$M(z,\zeta) = K[T^{-1}(\begin{bmatrix} z \\ \zeta \end{bmatrix})],$$

$$\alpha(x) = (L_{g_2}h(x))^{-1}, \quad \beta(x) = L_f h(x),$$

$$b(z,\zeta) = L_{g_2}h(x)m(x)\mid_{x=T^{-1}(z,\zeta)},$$

$f_0(z)$ and $f_1(z,\zeta)$ are smooth functions[4,9].

Now, the problem is to find a feedback control $v = C(z,\zeta)$ such that the closed loop system of (3.3) is passive with inner stability.

Theorem 2 Suppose that

A1) There exists $W(z) > 0$ such that $L_{f_0}W < 0$ for each nonzero z.

A2) $\{f,h\}$ is zero-state detectable.

Then, PCP of (3.3) is solved by

$$v = C(z,\zeta) = -f_1^{\mathrm{T}}(z,\zeta)\frac{\partial^{\mathrm{T}}W}{\partial z} - \frac{1}{4}(b(z,\zeta) - I)M^{-1}(b^{\mathrm{T}} - I)\zeta - \zeta. \tag{3.4}$$

Proof Let $V(z,\zeta) = W(z) + \frac{1}{2}\zeta^{\mathrm{T}}\zeta$. Note that system (3.3) with control (3.4) can be rewritten as:

$$\begin{cases} \begin{bmatrix} \dot{z} \\ \dot{\zeta} \end{bmatrix} = F(z,\zeta) + G(z,\zeta)w, \\ y = h_1(\zeta) + M(z,\zeta)w, \end{cases} \tag{3.5}$$

where

$$F(z,\zeta) = \begin{bmatrix} f_0 + f_1\zeta \\ C(z,\zeta) \end{bmatrix}, \quad G(z,\zeta) = \begin{bmatrix} 0 \\ b \end{bmatrix}, \quad h_1(\zeta) = \zeta.$$

Since

$$L_F V + \frac{1}{4}(L_G V - h_1^{\mathrm{T}})M^{-1}(L_G V - h_1^{\mathrm{T}})^{\mathrm{T}} = L_{f_0}W + L_{f_1}W\cdot\zeta + \zeta^{\mathrm{T}}C(z,\zeta) + \frac{1}{4}(\zeta^{\mathrm{T}}b - \zeta^{\mathrm{T}})M^{-1}(\zeta^{\mathrm{T}}b - \zeta^{\mathrm{T}})^{\mathrm{T}} = L_{f_0}W + \zeta^{\mathrm{T}}L_{f_1}^{\mathrm{T}}W + \frac{1}{4}\zeta^{\mathrm{T}}(b - I)M^{-1}(b^{\mathrm{T}} - I)\zeta + \zeta^{\mathrm{T}}C(z,\zeta). \tag{3.6}$$

Let $C(z,\zeta)$ be given by (3.4), we have $L_{f_0}W - \zeta^{\mathrm{T}}\zeta \leqslant -h^{\mathrm{T}}(x)h(x) \leqslant 0$. Hence, passivity is followed by Theorem 1 with (3.6)), and inner stability is followed by

$$L_F V = L_{f_0}W + \zeta^{\mathrm{T}}L_{f_1}^{\mathrm{T}}W + \zeta^{\mathrm{T}}C(z,\zeta) \leqslant -\zeta^{\mathrm{T}}\zeta = -h^{\mathrm{T}}(x)h(x) \leqslant 0,$$

which is from (3.6), and $\{f,h\}$ being detectable.

4 Passivation controller design via control Lyapunov function

The last section shows that the PCP of (2.4) is to find $u = u_*$ such that (2.6) holds, and with inner stability. Now we combine constructing u_* with seeking a positive function $V(x)$, this needs the following preliminary concepts.

Consider control system of the type:

$$\dot{x} = f(x) + \sum_{i=1}^{m} g_i(x)u_i, \tag{4.1}$$

with states $x \in \mathbb{R}^n$ and controls $u \in \mathbb{R}^m$, where f and the g_i's are smooth vector fields and $f(0) = 0$.

Definition 3 The function $V(x)$ is called control Lyapunov function (henceforth just "clf") for system (4.1), if there exists a neighborhood N of $0 \in \mathbb{R}^n$ and a real function $V: N \to \mathbb{R}$, which is at least C^1 on N, is positive definite, and such that for any $x \in N - \{0\}$, the following condition holds:

$$\inf_{u\in\mathbb{R}^m}\{L_f V(x) + \sum_{i=1}^{m} u_i L_{g_i}V(x)\} < 0, \tag{4.2}$$

for each $x \neq 0$.

Denote:

$$a(x) = L_f V(x), \; b_i(x) = L_{g_i}V(x), \; i = 1,\cdots,m.$$

Proposition 4 The condition that V is a clf equivalent to the statement that

$$L_{g_i}V(x) = 0; \quad i = 1,\cdots,m \rightarrow L_f V(x) < 0, \tag{4.3}$$

for all $x \in N - \{0\}$.

Since clf is as a general rule easier to obtain than the feedback stabilization, we can construct u_* to solve PCP from clf V. As we know, there is not a genaral method to solve the partial differential inequality such as (2.8) and Hamilton-Jacobi-Issacs inequality (H_∞ method). Now we use clf, from the viewpoint of numerical computation, this is more feasible than ever.

Theorem 3[7] If there is a smooth clf V for system (4.1), then there is feedback stabilizer $u = k(x)$

which is smooth on $N-\{0\}$ and

$$k(0)=0,\quad k(x)=(k_1(x),\cdots,k_m(x)),$$
$$k_i(x)=-b_i(x)\varphi(a(x),\beta(x)),$$
$$a(x)=L_fV(x),\quad b_i(x)=L_{g_i}V,\quad i=1,\cdots,m,$$
$$\beta(x)=\sum_{i=1}^{m}b_i^2(x),$$
$$\varphi(a,b)=\begin{cases}0, & a<0,\quad b=0,\\ \dfrac{a+\sqrt{a^2+bq(b)}}{b}, & b>0 \quad \text{or} \quad b<0,\ a<0,\end{cases} \tag{4.4}$$

where $q:\mathbb{R}\to\mathbb{R}$ such that $q(0)=0$ and $bq(b)>0$ whenever $b\neq 0$.

For system (2.4), denote:

$$\hat{a}(x)=L_fV(x)+\frac{1}{4}(L_{g_1}V-h^{\mathrm{T}})\cdot K^{-1}(L_{g_1}V-h^{\mathrm{T}})^{\mathrm{T}},$$
$$\hat{b}(x)=(\hat{b}_1(x),\cdots,\hat{b}_p(x))=L_{g_2}V=(L_{g_{21}}V,\cdots,L_{g_{2p}}V),$$
$$g_2(x)=(g_{21}(x),\cdots,g_{2p}(x)),$$

so we have:

Theorem 4 If there exist a neighborhood N of $0\in\mathbb{R}^n$ and a C^1 nonnegative function $V:N\to\mathbb{R}$ with $V(0)=0$, such that $\hat{a}(x)<0$ for each $x\in N-\{0\}$ and $\hat{b}(x)=0$, then the PCP of system (2.4) is solved by the feedback stabilizer $u=\alpha(x)$, which is smooth on $N-\{0\}$,

$$\alpha(0)=0,\quad \alpha(x)=(\alpha_1(x),\cdots,\alpha_p(x)),$$
$$\alpha_i(x)=-\hat{b}_i(x)\varphi(\hat{a}(x),\hat{\beta}(x)),$$
$$\hat{b}_i(x)=L_{g_{2i}}V(x),\quad i=1,\cdots,p,$$
$$\hat{\beta}(x)=\sum_{i=1}^{p}\hat{b}_i^2(x).$$

Proof According to the given conditions and Theorem 4, there exist $u=\alpha(x)$ and a positive C^1 function $V(x)$, such that

$$L_fV+L_{g_2}V\alpha+\frac{1}{4}(L_{g_1}V-h^{\mathrm{T}})K^{-1}(L_{g_1}V-h^{\mathrm{T}})^{\mathrm{T}}=$$
$$\hat{a}(x)+(\alpha_1(x),\cdots,\alpha_p(x))\hat{b}^{\mathrm{T}}(x)=$$
$$\hat{a}(x)+\sum_{i=1}^{p}L_{g_{2i}}V\cdot(-\hat{b}_i(x)\varphi(\hat{a}(x),\hat{\beta}(x)))=$$
$$\begin{cases}\hat{a}(x), & L_{g_{2i}}V(x)=0,\quad i=1,\cdots,p,\\ -\sqrt{\hat{a}^2(x)+\hat{\beta}(x)q(\hat{\beta}(x))}, & \text{otherwise}\end{cases}$$
$$<0. \tag{4.5}$$

From the above illustration of the inequality, it can be seen that $u=\alpha(x)$ enables system (2.4) passive. On the other hand, we have obviously: $L_fV+L_{g_2}V\alpha<0$ for each $x\in N-\{0\}$, so system $\dot{x}=f(x)+g_2(x)\alpha(x)$ is asymptotically stable at $x=0$.

Hence the PCP of system (2.4) is solvable.

Remark 3 In Theorem 3 and 4, the stabilizer $u=\alpha(x)$ is C^1 on $N-\{0\}$. But, if the clf satisfies small control property[7], it can be proven that u is continuous at $x=0$.

5 Conclusion

In this work, we first presents the passivation control problem (PCP), and investigates the conditions under which PCP is solved for nonlinear systems with disturbance. As in the case of systems having relative degree $\{1,1,\cdots,1\}$ and matching condition, the nonlinear systems can be rendered passive and inner stable via state feedback control law. Moreover, a sufficient condition for solving PCP is obtained by means of control Lyapunov function. This condition (4.3) can be used to make computation programming seek the nonnegative solution V of the partial differential inequality (2.12), it is a feasible approach for this problem and, in some sense, is helpful to the solution of HJI inequality in nonlinear H_∞ theory. We hope that our problem is meaningful and our methods copying with the problem are effective.

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References

1 Isidori A. Dissipative inequalities in nonlinear H_∞ control. Proc 31st Conf. Decis. Contr., Tucson, AZ, 1992, 3265 – 3270

2 Hill D and Moylan H. The stability of nonlinear dissipative systems. IEEE Trans. Automat. Contr., 1976, 21(6): 708 – 711

3 Isidori A and Astolfi A. Disturbance attenuation and H_∞ control via measurement feedback in nonlinear systems. IEEE Trans. Automat. Contr., 1992, 37(11): 1283 – 1293

4 Bynes C, Isidori A and Willems J. Passivity feedback equivalence and the global stabilization of minimum phase nonlinear systems. IEEE Trans. Automat. Contr., 1991, 36(11): 1228 – 1240

5 Qin Huashu and Hong Yiguang. Passivity, optimality and stability.

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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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