第26卷 第6期
2000年11月

自 动 化 学 报
ACTA AUTOMATICA SINICA

Vol. 26, No. 6
Nov., 2000

短文

非线性广义时变系统的干扰解耦[1)]

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摘　要　讨论了在正则状态反馈作用下，一类非线性广义时变系统的干扰解耦问题. 首先，提出了一种新的解耦算法；然后，基于该算法，对系统的干扰解耦问题进行了研究，推导出该问题可解的充分必要条件，并且构造出反馈控制律；最后，举例说明了该方法的可行性.

关键词　非线性系统，广义系统，时变系统，干扰解耦.

DISTURBANCE DECOUPLING OF NONLINEAR GENERALIZED TIME-VARYING SYSTEMS

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Abstract　The disturbance decoupling problem for nonlinear generalized time-varying control systems is discussed. A new decoupling algorithm is proposed. By which a sufficient and necessary condition for the solvability of the disturbance decoupling problem is derived. The algorithm also provides a procedure for constructing a decoupling feedback control law. At last, an example is provided to illustrate the method presented in this paper.

Key words　Nonlinear system, generalized system, time-varying system, disturbance decoupling

1　引言

考虑如下非线性广义时变系统

1) 国家自然科学基金(69974007)、留学回国人员科研基金和中国博士后基金、国家教委跨世纪优秀人才计划基金资助课题.
收稿日期　1997-05-08　　收修改稿日期　1999-07-22

$$\begin{cases}\dot{\boldsymbol{x}} = F_1(x,t) + P_1(\boldsymbol{x},t)\boldsymbol{z} + G_1(\boldsymbol{x},t)\boldsymbol{u} + W_1(\boldsymbol{x},t)\boldsymbol{d}, \\ 0 = F_2(\boldsymbol{x},t) + P_2(\boldsymbol{x},t)\boldsymbol{z} + G_2(\boldsymbol{x},t)\boldsymbol{u} + W_2(\boldsymbol{x},t)\boldsymbol{d}, \\ \boldsymbol{y} = H(\boldsymbol{x},t). \end{cases} \tag{1}$$

上式中 $\boldsymbol{x}\in R^n$ 是状态向量;$\boldsymbol{z}\in R^s$ 是代数向量;$\boldsymbol{u}\in R^m$ 是输入向量;$\boldsymbol{d}\in R^l$ 是干扰向量;$\boldsymbol{y}\in R^p$ 是输出向量;$P_i(\boldsymbol{x},t)$,$G_i(\boldsymbol{x},t)$,$W_i(\boldsymbol{x},t)(i=1,2)$是具有适当维数的解析矩阵;$F_1(\boldsymbol{x},t)$,$F_2(\boldsymbol{x},t)$,$H(\boldsymbol{x},t)$是维数分别为 n,s 和 p 的向量函数.

近年来,广义系统方面的研究取得了一定的进展[1~4].对于非线性广义系统,注意力主要集中于可解性、能控性、线性化、干扰解耦、反馈稳定化和 Kronecker 标准型等等.

干扰解耦在系统控制问题中占有重要地位.关于线性与非线性系统的干扰解耦问题可见 Wonham[5],Isidori[6],Nijmeijer 和 A. J. van der Schaft[7]的文章.对于非线性广义系统,相同问题的研究可见文[8,9].但是,关于非线性广义时变系统的结果还很少见.本文正是针对这样一类系统,提出一种新的解耦算法,利用该算法对干扰解耦问题进行研究.

下面给出本文将要用到的一些符号及关系式

$$\boldsymbol{\phi}(x,t) = \begin{bmatrix}\boldsymbol{\phi}_1(\boldsymbol{x},t)\\ \vdots \\ \boldsymbol{\phi}_l(\boldsymbol{x},t)\end{bmatrix},\quad \mathrm{d}\boldsymbol{\phi} = \begin{bmatrix}\mathrm{d}\boldsymbol{\phi}_1\\ \vdots \\ \mathrm{d}\boldsymbol{\phi}_l\end{bmatrix},\quad \mathrm{d}\boldsymbol{\phi}_i = (\frac{\partial\boldsymbol{\phi}_i}{\partial\boldsymbol{x}_1}\cdots\frac{\partial\boldsymbol{\phi}_i}{\partial\boldsymbol{x}_n}),$$

$$L_F\boldsymbol{\phi} = \mathrm{d}\boldsymbol{\phi}\cdot F,\quad L_F\boldsymbol{\phi}_i = \mathrm{d}\boldsymbol{\phi}_i\cdot F.$$

2 定义及算法

定义1.(干扰解耦问题).给定一非线性广义时变系统(1)及初始点 x_0,存在定义在 U 及$[0,T]$上的正则状态反馈

$$\boldsymbol{u} = A(\boldsymbol{x},t) + B(\boldsymbol{x},t)\,\boldsymbol{v} + \Gamma(\boldsymbol{x},t)\boldsymbol{z}, \tag{2}$$

其中 U 是 x_0的一个邻域,$B(\boldsymbol{x},t)$在 U 及$[0,T]$上是非奇异的,使所得的闭环系统

$$\begin{cases}\dot{\boldsymbol{x}} = [F_1(\boldsymbol{x},t) + G_1(\boldsymbol{x},t)A(\boldsymbol{x},t)] + [P_1(\boldsymbol{x},t) + G_1(\boldsymbol{x},t)\Gamma(\boldsymbol{x},t)]\boldsymbol{z} + \\ \qquad G_1(\boldsymbol{x},t)B(\boldsymbol{x},t)\,\boldsymbol{v} + W_1(\boldsymbol{x},t)\boldsymbol{d}, \\ 0 = [F_2(\boldsymbol{x},t) + G_2(\boldsymbol{x},t)A(\boldsymbol{x},t)] + [P_2(\boldsymbol{x},t) + G_2(\boldsymbol{x},t)\Gamma(\boldsymbol{x},t)]\boldsymbol{z} + \\ \qquad G_2(\boldsymbol{x},t)B(\boldsymbol{x},t)\,\boldsymbol{v} + W_2(\boldsymbol{x},t)\boldsymbol{d}, \\ \boldsymbol{y} = H(\boldsymbol{x},t)\end{cases} \tag{3}$$

具有如下性质:

(a)对任意分段连续输入$\boldsymbol{v}(t)$和干扰 $\boldsymbol{d}(t)$ 存在唯一分段可微解 $\boldsymbol{x}(t)$,$\boldsymbol{x}(0)=x_0$及分段连续解 $\boldsymbol{z}(\boldsymbol{x},t)$;

(b)输出 $\boldsymbol{y}(t)$ 不受干扰 $\boldsymbol{d}(t)$ 的影响.

假设1. 对于所有 $t\in[0,T]$,矩阵$[P_2(\boldsymbol{x},t)\quad G_2(\boldsymbol{x},t)]$在 x_0点有行满秩.

下面给出求解干扰解耦问题的算法:

第一步.假设 $H(\boldsymbol{x},t)$在 U 及$[0,T]$上有常秩 ρ_0,且 $H(\boldsymbol{x},t)$的前 ρ_0行是独立的(如果

需要可进行行重排). 令 ϕ_1是由 $H(\boldsymbol{x},t)$ 的前 ρ_0行组成的向量,计算

$$\dot{\phi}_1 = L_{F_1}\phi_1(\boldsymbol{x},t) + \frac{\partial \phi_1(\boldsymbol{x},t)}{\partial t} + L_{P_1}\phi_1(\boldsymbol{x},t)\boldsymbol{z} + L_{G_1}\phi_1(\boldsymbol{x},t)\boldsymbol{u} + L_{W_1}\phi_1(\boldsymbol{x},t)\boldsymbol{d}. \quad (4)$$

假设 $\begin{bmatrix} P_2(\boldsymbol{x},t) & G_2(\boldsymbol{x},t) & W_2(\boldsymbol{x},t) \\ L_{P_1}\phi_1(\boldsymbol{x},t) & L_{G_1}\phi_1(\boldsymbol{x},t) & L_{W_1}\phi_1(\boldsymbol{x},t) \end{bmatrix}$ 在 U 及$[0,T]$上有常秩 σ_1,则 ϕ_1 可分解为 $\begin{bmatrix} \hat{\phi}_1 \\ \tilde{\phi}_1 \end{bmatrix}$,使 $\begin{bmatrix} P_2 & G_2 & W_2 \\ L_{P_1}\hat{\phi}_1 & L_{G_1}\hat{\phi}_1 & L_{W_1}\hat{\phi}_1 \end{bmatrix}$ 有行满秩 σ_1,此时存在 $T_1(\boldsymbol{x},t)$和 $\Lambda_1^1(\boldsymbol{x},t)$,使得

$$[L_{P_1}\tilde{\phi}_1 \quad L_{G_1}\tilde{\phi}_1 \quad L_{W_1}\tilde{\phi}_1] = \Lambda_1^1[L_{P_1}\hat{\phi}_1 \quad L_{G_1}\hat{\phi}_1 \quad L_{W_1}\hat{\phi}_1] + T_1[P_2 \quad G_2 \quad W_2]. \quad (5)$$

令 $M_1 = L_{F_1}\tilde{\phi}_1 + \frac{\partial \tilde{\phi}_1}{\partial t} - \Lambda_1^1(L_{F_1}\hat{\phi}_1 + \frac{\partial \hat{\phi}_1}{\partial t}) - T_1F_2$,容易看出

$$\dot{\hat{\phi}}_1 = A_1(\boldsymbol{x},t) + B_1(\boldsymbol{x},t)\boldsymbol{z} + C_1(\boldsymbol{x},t)\boldsymbol{u} + E_1(\boldsymbol{x},t)\boldsymbol{d}, \dot{\tilde{\phi}}_1 = M_1(\boldsymbol{x},t) + \Lambda_1^1(\boldsymbol{x},t)\dot{\hat{\phi}}_1, (6)$$

其中 $A_1(\boldsymbol{x},t) = L_{F_1}\hat{\phi}_1 + \frac{\partial \hat{\phi}_1}{\partial t}$, $B_1(\boldsymbol{x},t) = L_{P_1}\hat{\phi}_1$, $C_1(\boldsymbol{x},t) = L_{G_1}\hat{\phi}_1$, $E_1(\boldsymbol{x},t) = L_{W_1}\hat{\phi}_1$.

令 $\varphi_1(\boldsymbol{x},t)$是由 $M_1(\boldsymbol{x},t)$和 $\Lambda_1^1(\boldsymbol{x},t)$的所有元素组成,如果

$$\operatorname{rank}\begin{bmatrix} \mathrm{d}\phi_1 \\ \mathrm{d}\psi_1 \end{bmatrix} = \operatorname{rank}[\mathrm{d}\phi_1] \quad (7)$$

成立,则算法结束;否则,继续下一步.

第 k 步. 假设由第一步到第 $k-1$步定义了一系列向量函数 $\phi_1(\boldsymbol{x},t),\cdots,\phi_{k-1}(\boldsymbol{x},t)$, $\varphi_1(\boldsymbol{x},t),\cdots,\varphi_{k-1}(\boldsymbol{x},t)$. 假设 $\begin{bmatrix} \mathrm{d}\phi_1 \\ \vdots \\ \mathrm{d}\phi_{k-1} \\ \mathrm{d}\psi_{k-1} \end{bmatrix}$ 在 U 及$[0,T]$上有行满秩 ρ_{k-1},且 $\begin{bmatrix} \mathrm{d}\phi_1 \\ \vdots \\ \mathrm{d}\phi_{k-1} \\ \mathrm{d}\psi_{k-1} \end{bmatrix}$ 的前 ρ_{k-1}行是独立的(如果需要可进行行重排). 令 $\phi_k(\boldsymbol{x},t)$由 $\varphi_{k-1}(\boldsymbol{x},t)$的前 $\rho_{k-1}-\rho_{k-2}$行组成,计算

$$\dot{\phi}_k = L_{F_1}\phi_k + \frac{\partial \phi_k}{\partial t} + L_{P_1}\phi_k\boldsymbol{z} + L_{G_1}\phi_k\boldsymbol{u} + L_{W_1}\phi_k\boldsymbol{d}. \quad (8)$$

假设 $\begin{bmatrix} P_2 & G_2 & W_2 \\ L_{P_1}\hat{\phi}_1 & L_{G_1}\hat{\phi}_1 & L_{W_1}\hat{\phi}_1 \\ \vdots & \vdots & \vdots \\ L_{P_1}\hat{\phi}_{k-1} & L_{G_1}\hat{\phi}_{k-1} & L_{W_1}\hat{\phi}_{k-1} \\ L_{P_1}\phi_k & L_{G_1}\phi_k & L_{W_1}\phi_k \end{bmatrix}$ 在 U 及$[0,T]$上有常秩 σ_k,则 ϕ_k 可分解为 $\begin{bmatrix} \hat{\phi}_k \\ \tilde{\phi}_k \end{bmatrix}$,使得 $\begin{bmatrix} P_2 & G_2 & W_2 \\ L_{P_1}\hat{\phi}_1 & L_{G_1}\hat{\phi}_1 & L_{W_1}\hat{\phi}_1 \\ \vdots & \vdots & \vdots \\ L_{P_1}\hat{\phi}_{k-1} & L_{G_1}\hat{\phi}_{k-1} & L_{W_1}\hat{\phi}_{k-1} \\ L_{P_1}\hat{\phi}_k & L_{G_1}\hat{\phi}_k & L_{W_1}\hat{\phi}_k \end{bmatrix}$ 有行满秩 σ_k,此时存在 $T_k(\boldsymbol{x},t)$及 $\Lambda_k^1(\boldsymbol{x},t),\cdots,\Lambda_k^k(\boldsymbol{x},t)$,使

$$[L_{P_1}\tilde{\phi}_k \quad L_{G_1}\tilde{\phi}_k \quad L_{W_1}\tilde{\phi}_k] = \sum_{i=1}^{k}\Lambda_k^i[L_{P_1}\hat{\phi}_i \quad L_{G_1}\hat{\phi}_i \quad L_{W_1}\hat{\phi}_i] + T_k[P_2 \quad G_2 \quad W_2]. \quad (9)$$

令 $M_k(\boldsymbol{x},t)=L_{F_1}\hat{\phi}_k+\frac{\partial\tilde{\phi}_k}{\partial t}-\sum_{i=1}^{k}\Lambda_k^i(L_{F_1}\hat{\phi}_i+\frac{\partial\tilde{\phi}_i}{\partial t})-T_kF_2$,容易看出

$$\dot{\hat{\phi}}_k=A_k(\boldsymbol{x},t)+B_k(\boldsymbol{x},t)\boldsymbol{z}+C_k(\boldsymbol{x},t)\boldsymbol{u}+E_k(\boldsymbol{x},t)\boldsymbol{d},\dot{\tilde{\phi}}_k=M_k(\boldsymbol{x},t)+\sum_{i=1}^{k}\Lambda_k^i(\boldsymbol{x},t)\dot{\hat{\phi}}_i, \tag{10}$$

其中 $A_k(\boldsymbol{x},t)=L_{F_1}\hat{\phi}_k+\frac{\partial\hat{\phi}_k}{\partial t},\quad B_k(\boldsymbol{x},t)=L_{P_1}\hat{\phi}_k,\quad C_k(\boldsymbol{x},t)=L_{G_1}\phi_k,\quad E_k(\boldsymbol{x},t)=L_{W_1}\hat{\phi}_k.$

令 $\varphi_k(\boldsymbol{x},t)$是由所有 $M_k(\boldsymbol{x},t)$和 $\Lambda_k^1(\boldsymbol{x},t),\cdots,\Lambda_k^k(\boldsymbol{x},t)$的所有元素组成,如果

$$\mathrm{rank}[\mathrm{d}\phi_1\cdots\mathrm{d}\phi_k\mathrm{d}\psi_k]^{\mathrm{T}}=\mathrm{rank}[\mathrm{d}\phi_1\cdots\mathrm{d}\phi_k]^{\mathrm{T}} \tag{11}$$

成立,则算法结束;否则,继续下一步.

3 主要结果

由算法可知,$\phi_1,\cdots,\phi_k$ 是独立的.因此,如果 $\rho_{k^*-1}<n$,则总可以找到 $n-\rho_{k^*-1}$个光滑函数 $\delta_1(\boldsymbol{x},t),\cdots,\delta_{n-\rho_{k-1}^*}(\boldsymbol{x},t)$,使其与 $\phi_1,\cdots,\phi_k$ 一起构成一个新的坐标变换

$$\begin{cases}\hat{\xi}_k=\hat{\phi}_k(\boldsymbol{x},t), & k=1,\cdots,k^*,\\ \tilde{\xi}_k=\tilde{\phi}_k(\boldsymbol{x},t), & k=1,\cdots,k^*,\\ \eta_k=\delta_k(\boldsymbol{x},t), & k=1,\cdots,n-\rho_{k^*-1}.\end{cases} \tag{12}$$

在新的坐标下,系统(1)具有如下形式:

$$\begin{cases}\dot{\hat{\xi}}_1=A_1(\boldsymbol{\xi},\boldsymbol{\eta},t)+B_1(\boldsymbol{\xi},\boldsymbol{\eta},t)\boldsymbol{z}+C_1(\boldsymbol{\xi},\boldsymbol{\eta},t)\boldsymbol{u}+E_1(\boldsymbol{\xi},\boldsymbol{\eta},t)\boldsymbol{d},\\ \dot{\tilde{\xi}}_1=M_1(\hat{\xi}_1,\tilde{\xi}_1,\hat{\xi}_2,\tilde{\xi}_2,t)+\Lambda_1^1(\hat{\xi}_1,\tilde{\xi}_1,\hat{\xi}_2,\tilde{\xi}_2,t)\dot{\hat{\xi}}_1,\\ \cdots\\ \dot{\hat{\xi}}_{k^*}=A_{k^*}(\boldsymbol{\xi},\boldsymbol{\eta},t)+B_{k^*}(\boldsymbol{\xi},\boldsymbol{\eta},t)\boldsymbol{z}+C_{k^*}(\boldsymbol{\xi},\boldsymbol{\eta},t)\boldsymbol{u}+E_{k^*}(\boldsymbol{\xi},\boldsymbol{\eta},t)\boldsymbol{d},\\ \dot{\tilde{\xi}}_{k^*}=M_{k^*}(\hat{\xi}_1,\tilde{\xi}_1,\cdots,\hat{\xi}_{k^*},\tilde{\xi}_{k^*},t)+\sum_{i=1}^{k^*}\Lambda_{k^*}^i(\hat{\xi}_1,\tilde{\xi}_1,\cdots,\hat{\xi}_2,\tilde{\xi}_{k^*},t)\dot{\hat{\xi}}_i,\\ \dot{\eta}=\hat{F}_1(\boldsymbol{\xi},\boldsymbol{\eta},t)+\hat{P}_1(\boldsymbol{\xi},\boldsymbol{\eta},t)\boldsymbol{z}+\hat{G}_1(\boldsymbol{\xi},\boldsymbol{\eta},t)\boldsymbol{u}+\hat{W}_1(\boldsymbol{\xi},\boldsymbol{\eta},t)\boldsymbol{d},\\ 0=F_2(\boldsymbol{\xi},\boldsymbol{\eta},t)+P_2(\boldsymbol{\xi},\boldsymbol{\eta},t)\boldsymbol{z}+G_2(\boldsymbol{\xi},\boldsymbol{\eta},t)\boldsymbol{u}+W_2(\boldsymbol{\xi},\boldsymbol{\eta},t)\boldsymbol{d},\\ \boldsymbol{y}^1=\hat{\xi}_1,\boldsymbol{y}^2=\tilde{\xi}_1,\boldsymbol{y}^3=\hat{\boldsymbol{H}}(\hat{\xi}_1,\tilde{\xi}_1),\end{cases} \tag{13}$$

其中 $\boldsymbol{\eta}=\mathrm{col}(\eta_1,\cdots,\eta_{n-\rho_{k^*-1}}),\boldsymbol{\xi}=\mathrm{col}(\hat{\xi}_1,\tilde{\xi}_1,\cdots\hat{\xi}_{k^*},\tilde{\xi}_{k^*})$.

定理1. 假设 x_0是上述算法的一个正则点,系统(1)干扰解耦问题可解的充分必要条件是,存在反馈 $\boldsymbol{u}=A(\boldsymbol{x},t)+B(\boldsymbol{x},t)\boldsymbol{v}+\Gamma(\boldsymbol{x},t)\boldsymbol{z}$,其中 $\Gamma(\boldsymbol{x},t)$使得 $P_2(\boldsymbol{x},t)+G_2(\boldsymbol{x},t)\Gamma(\boldsymbol{x},t)$在 x_0点处非奇异,且

$$\begin{cases}\tilde{E}_1=E_1-(B_1+C_1\Gamma)(P_2+G_2\Gamma)^{-1}W_2=0,\\ \cdots\\ \tilde{E}_{k^*}=E_{k^*}-(B_{k^*}+C_{k^*}\Gamma)(P_2+G_2\Gamma)^{-1}W_2=0\end{cases} \tag{14}$$

在 x_0的邻域 U 及$[0,T]$上成立.

例.

$$
\begin{cases}
\dot{x}_1 = x_4 - x_3 - (x_3 + t)x_4 + 2(1 - x_3 - t)\boldsymbol{z} + (1 - x_3 - t)u_1 + \\
\qquad x_2(1 - x_3 - t)x_4\boldsymbol{d}, \\
\dot{x}_2 = x_3 + (x_3 + t)x_4 + 2(x_3 + t)\boldsymbol{z} + (x_3 + t)\boldsymbol{u}_1 + x_2(x_3 + t)x_4\boldsymbol{d}, \\
\dot{x}_3 = u_2, \\
\dot{x}_4 = (x_1 + 2x_2)x_3 + (x_3 + t)\boldsymbol{z} + (x_3 + x_4)\boldsymbol{u}_1 + x_2x_3x_4\boldsymbol{d}, \\
0 = (x_1 + x_2)(x_3 + t) + \boldsymbol{u}_1 + \boldsymbol{u}_2 - x_2x_4\boldsymbol{d}, \\
y_1 = x_1 + x_2, \quad y_2 = x_2.
\end{cases}
\tag{15}
$$

通过运行解耦算法,取 $\hat{\xi}_1=x_1+x_2$,$\tilde{\xi}_1=x_2$,$\hat{\xi}_2=x_3+t$,$\eta=x_4$,则原系统变为

$$
\begin{cases}
\dot{\hat{\xi}}_1 = x_4 + 2\boldsymbol{z} + \boldsymbol{u}_1 + x_2x_4\boldsymbol{d}, \quad \dot{\tilde{\xi}}_1 = \tilde{\xi}_2 + \hat{\xi}_2\dot{\hat{\xi}}_1, \dot{\hat{\xi}}_2 = 1 + \boldsymbol{u}_2, \\
\dot{\eta} = (\xi_1 + \tilde{\xi}_1)\tilde{\xi}_2 + \tilde{\xi}_2\boldsymbol{z} + (\tilde{\xi}_2 + \eta)\boldsymbol{u}_1 + (\hat{\xi}_1 - \tilde{\xi}_1)(\tilde{\xi}_2 + \eta)\boldsymbol{d}, \\
0 = \tilde{\xi}_1\hat{\xi}_2 + \boldsymbol{u}_1 + \boldsymbol{u}_2 - \tilde{\xi}_1\eta\boldsymbol{d}, \quad \boldsymbol{y}^1 = \xi_1, \quad \boldsymbol{y}^2 = \tilde{\xi}_1.
\end{cases}
\tag{16}
$$

取 $\Gamma(\boldsymbol{x},t)=\begin{pmatrix}-1\\0\end{pmatrix}$,满足使 $P_2+G_2\Gamma$ 非奇异的条件,$\tilde{E}_1=0$,$\tilde{E}_2=0$,所以该系统是可干扰解耦的.此时取如下反馈,即可达到干扰解耦的目的.

$$
\begin{cases}
\boldsymbol{u}_1 = -\frac{1}{2}x_4 - \frac{1}{2}(x_1 + x_2)(x_3 + t) + \frac{1}{2} + \frac{1}{2}\boldsymbol{v}_1 - \frac{1}{2}\boldsymbol{v}_2 - \boldsymbol{z}, \\
\boldsymbol{u}_2 = -1 + \boldsymbol{v}_2.
\end{cases}
\tag{17}
$$

4 结论

本文讨论了非线性广义时变系统的干扰解耦问题,给出了一种新的解耦算法并导出系统干扰解耦问题可解的充分必要条件,同时给出解耦反馈的构造方法,所给例子证明了本文方法的可行性.

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