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一类非线性时滞输出反馈系统的自适应控制

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摘要：针对一类参数化非线性时滞输出反馈系统，提出了一种无记忆自适应跟踪控制器的设计方案.采用时滞滤波器估计系统状态，用Domination处理非线性时滞项，应用Backstepping技术设计控制器和参数自适应律.放宽了对时滞项的要求.通过构建一个Lyapunov-Krasoviskii泛函，证明了闭环系统的稳定性，实现了对目标轨线的渐近跟踪，保证了所有信号一致有界.实例仿真说明了该方案的可行性.

关键词：非线性时滞系统；输出反馈；自适应控制；backstepping
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Adaptive control for a class of nonlinear time-delay output-feedback systems

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Abstract: A design approach of memoryless adaptive tracking controller is proposed for a class of parametric nonlinear time-delay output-feedback systems. Time-delay filters are introduced to estimate the states of the system. Domination method is employed to deal with the nonlinear time-delay terms. Backstepping technique is used to design controller and parameters adaptive laws. The requirement on the time-delay terms is relaxed. The stability of the closed-loop system is proved by constructing a Lyapunov-Krasoviskii functional. The asymptotical tracking of given trajectories is achieved and the boundedness of all signals is also guaranteed. The feasibility of the approach is illustrated by a simulation example.

Key words: nonlinear time-delay systems; output feedback; adaptive control; backstepping

1 引言(Introduction)

时滞(或时间延迟)存在于各类工程系统之中，它的存在会对系统的性能产生重要影响，甚至破坏系统的稳定性[1]，因此，时滞系统的控制问题一直是一个比较活跃的研究领域，并取得了一些重要的成果[1~4].文献[2]研究了一类带有不确定界的非线性时滞系统的自适应控制问题，但要求系统时滞项满足Lipschitz条件并且拟有界.文献[3]解决了一类不确定非线性时滞系统的输出反馈镇定问题，接着将这一结果推广到随机非线性时滞系统[4]，但未考虑非线性时滞系统的自适应跟踪问题.

作者针对一类参数化非线性时滞输出反馈系统，采用时滞滤波器，结合Backstepping的设计方法，提出了一种无记忆自适应控制器的设计方案.采用Domination方法处理非线性时滞项.它只要求时滞项光滑，不仅可以解决调节问题，而且可以解决自适应跟踪问题.实例仿真说明了该方案的可行性.

2 问题描述(Problem description)

考虑以下非线性时滞输出反馈系统

$$\begin{cases} \dot{x} = Ax + \phi(y) + \Phi(y)a + \begin{bmatrix} 0 \\ b \end{bmatrix}\sigma(y)u + \\ \qquad H(y(t-\tau)) + G(y(t-\tau))\theta_2, \\ y = e_1^{\mathrm{T}}x \end{cases} \tag{1}$$

其中 $u \in \mathbb{R}, y \in \mathbb{R}, x = [x_1, \cdots, x_n]^{\mathrm{T}} \in \mathbb{R}^n$ 分别表示系统的输入、输出和状态；

$$A = \begin{bmatrix} 0 & & \\ \vdots & I_{n-1} & \\ 0 & \cdots & 0 \end{bmatrix},$$

$$\Phi(\cdot) = \begin{bmatrix} \phi_{1,1}(\cdot) & \cdots & \phi_{q,1}(\cdot) \\ \vdots & & \vdots \\ \phi_{1,n}(\cdot) & \cdots & \phi_{q,n}(\cdot) \end{bmatrix},$$

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$$G(\cdot) = \begin{bmatrix} 0 & \cdots & 0 \\ g_{1,2}(\cdot) & \cdots & g_{p,2}(\cdot) \\ \vdots & & \vdots \\ g_{1,n}(\cdot) & \cdots & g_{p,n}(\cdot) \end{bmatrix},$$

$\phi(\cdot) = [\phi_{0,1}(\cdot), \cdots, \phi_{0,n}(\cdot)]^{\mathrm{T}}, H(\cdot) = [h_1(\cdot), \cdots, h_n(\cdot)]^{\mathrm{T}}; \phi_{j,i}(\cdot)(0 \leqslant j \leqslant q, 1 \leqslant i \leqslant n)$, $g_{j,i}(\cdot)(1 \leqslant j \leqslant p, 2 \leqslant i \leqslant n), h_i(\cdot)(1 \leqslant i \leqslant n)$ 及 $\sigma(\cdot) \neq 0$ 是已知光滑函数;$a \in \Re^q, \theta_2 \in \Re^p, b = [b_m, \cdots, b_0]^{\mathrm{T}} \in \Re^{m+1}$ 是未知的常值参数向量;$e_1 = [1,0,\cdots,0]^{\mathrm{T}} \in \Re^n$,时滞 τ 已知,仅输出 y 可测.

本文的目标是设计一个无记忆自适应跟踪控制器,使得系统输出渐近跟踪给定的目标轨线 $y_{\mathrm{r}}(t)$.

假设 2.1[5]　b_m 符号已知,$B(s) = b_m s^m + \cdots + b_1 s + b_0$ 是 Hurwitz 多项式.

假设 2.2　参考信号满足 $y_{\mathrm{r}}^{(i)}(t), 0 \leqslant i \leqslant \rho = n - m$ 已知且有界,$y_{\mathrm{r}}^{(\rho)}$ 分段连续.

由微分中值定理,存在已知的光滑非负函数 $s_{h_i}(t) = s_{h_i}(y, y_{\mathrm{r}}), s_{g_{j,i}}(t) = s_{g_{j,i}}(y, y_{\mathrm{r}})$,满足

$$\begin{cases} |h_i(y) - h_i(y_{\mathrm{r}})| \leqslant |y - y_{\mathrm{r}}| s_{h_i}(t), \\ |g_{j,i}(y) - g_{j,i}(y_{\mathrm{r}})| \leqslant |y - y_{\mathrm{r}}| s_{g_{j,i}}(t). \end{cases} \tag{2}$$

3　自适应控制器设计(Adaptive controller design)

由于系统状态不可测,首先设计以下时滞滤波器:

$$\begin{cases} \dot{\xi} = A_0 \xi + k y + \phi(y) + H(y(t-\tau)), \\ \dot{\Psi}^{\mathrm{T}} = A_0 \Psi^{\mathrm{T}} + G(y(t-\tau)), \\ \dot{\Xi} = A_0 \Xi + \Phi(y), \\ \dot{\lambda} = A_0 \lambda + e_n \sigma(y) u, \\ v_j = A_0^j \lambda, 0 \leqslant j \leqslant m, \\ \Omega^{\mathrm{T}} = [v_m, \cdots, v_1, v_0, \Xi]. \end{cases} \tag{3}$$

其中 $e_n = [0, \cdots, 0, 1]^{\mathrm{T}} \in \Re^n$,选择 $k = [k_1, \cdots, k_n]^{\mathrm{T}}$ 使得矩阵 $A_0 = A - k e_1^{\mathrm{T}}$ 为稳定矩阵.因此,存在正定矩阵 P 满足

$$P A_0 + A_0^{\mathrm{T}} P = -I. \tag{4}$$

定义状态估计 $\hat{x} = \xi + \Omega^{\mathrm{T}} \theta_1 + \Psi^{\mathrm{T}} \theta_2$,其中 $\theta_1 = [b^{\mathrm{T}}, a^{\mathrm{T}}]^{\mathrm{T}}$,则误差 $\varepsilon = x - \hat{x}$ 满足

$$\dot{\varepsilon} = A_0 \varepsilon. \tag{5}$$

类似于无时滞的情况[5],采用滤波器(3),系统(1)可转化为以下形式:

$$\begin{cases} \dot{y} = b_m v_{m,2} + w_0 + \bar{w}^{\mathrm{T}} \theta_1 + \Psi_{(2)}^{\mathrm{T}} \theta_2 + \\ \qquad \varepsilon_2 + h_1(y(t-\tau)), \\ \dot{v}_{m,i} = v_{m,i+1} - k_i v_{m,1}, 2 \leqslant i \leqslant \rho - 1, \\ \dot{v}_{m,\rho} = \sigma(y) u + v_{m,\rho+1} - k_\rho v_{m,1}. \end{cases} \tag{6}$$

其中 $w_0 = \phi_{0,1} + \xi_2, \bar{w} = [0, v_{m-1,2}, \cdots, v_{0,2}, \Phi_{(1)} + \Xi_{(2)}]^{\mathrm{T}}$,$X_{(i)}$ 表示矩阵 X 的第 i 行.

采用 Backstepping 技术设计控制律和参数自适应律.定义坐标变换

$$\begin{cases} z_1 = y - y_{\mathrm{r}}, \\ z_i = v_{m,i} - \hat{\beta} y_{\mathrm{r}}^{(i-1)} - \alpha_{i-1}, 2 \leqslant i \leqslant \rho. \end{cases} \tag{7}$$

其中 $\hat{\beta}$ 是 $\beta = 1/b_m$ 的估计值.为了描述方便,采用 $y_\tau, y_{\mathrm{r}\tau}$ 分别表示 $y(t-\tau), y_{\mathrm{r}}(t-\tau)$.

选择稳定化函数

$$\begin{cases} \alpha_1 = \hat{\beta} \bar{\alpha}_1, \\ \bar{\alpha}_1 = -c_1 z_1 - (d_1 + \frac{1}{2}) z_1 - W(t) z_1 - w_0 - \\ \qquad \bar{w}^{\mathrm{T}} \hat{\theta}_1 - \Psi_{(2)}^{\mathrm{T}} \hat{\theta}_2 - h_1(y_{\mathrm{r}\tau}), \\ \alpha_2 = -\hat{b}_m z_1 - \Lambda_2 z_2 - \Delta_2 - \frac{\partial \alpha_1}{\partial y} h_1(y_{\mathrm{r}\tau}) - \\ \qquad \frac{\partial \alpha_1}{\partial \xi} H(y_{\mathrm{r}\tau}) - \frac{\partial \alpha_1}{\partial \Psi^{\mathrm{T}}} G(y_{\mathrm{r}\tau}), \\ \alpha_i = -z_{i-1} - \Lambda_i z_i - \Delta_i - \sum_{j=2}^{i-1} \frac{\partial \alpha_{j-1}}{\partial \hat{\theta}_1} \Gamma_1 \frac{\partial \alpha_{i-1}}{\partial y} w z_j - \\ \qquad \sum_{j=2}^{i-1} \frac{\partial \alpha_{j-1}}{\partial \hat{\theta}_2} \Gamma_2 \frac{\partial \alpha_{i-1}}{\partial y} [\Psi_{(2)}^{\mathrm{T}}]^{\mathrm{T}} z_j - \frac{\partial \alpha_{i-1}}{\partial y} h_1(y_{\mathrm{r}\tau}) - \\ \qquad \frac{\partial \alpha_{i-1}}{\partial \xi} H(y_{\mathrm{r}\tau}) - \frac{\partial \alpha_{i-1}}{\partial \Psi^{\mathrm{T}}} G(y_{\mathrm{r}\tau}), \ 3 \leqslant i \leqslant \rho. \end{cases} \tag{8}$$

其中

$c_i, d_i > 0$,

$\alpha_\rho := \sigma(y) u + v_{m,\rho+1} - \hat{\beta} y_{\mathrm{r}}^{(\rho)}, \ z_{\rho+1} := 0.$

$$W(t) = W(y, y_{\mathrm{r}}) = \frac{\rho}{2} s_{h_1}^2(t) + \frac{\rho-1}{2} \sum_{j=1}^{n} s_{h_j}^2(t) + \frac{\rho-1}{2} \sum_{j=1}^{p} \sum_{k=2}^{n} s_{g_{j,k}}^2(t),$$

$$\Lambda_i = c_i + d_i \left(\frac{\partial \alpha_{i-1}}{\partial y}\right)^2 + \frac{1}{2} \left(\frac{\partial \alpha_{i-1}}{\partial y}\right)^2 + \frac{1}{2} \sum_{j=1}^{n} \left(\frac{\partial \alpha_{i-1}}{\partial \xi_j}\right)^2 + \frac{1}{2} \sum_{j=1}^{p} \sum_{k=2}^{n} \left(\frac{\partial \alpha_{i-1}}{\partial \Psi_{j,k}^{\mathrm{T}}}\right)^2, \ 2 \leqslant i \leqslant \rho,$$

$$\Delta_i = -k_i v_{m,1} - \frac{\partial \alpha_{i-1}}{\partial \Psi^{\mathrm{T}}} A_0 \Psi^{\mathrm{T}} - \frac{\partial \alpha_{i-1}}{\partial y} (w_0 + w^{\mathrm{T}} \hat{\theta}_1 + \Psi_{(2)}^{\mathrm{T}} \hat{\theta}_2) - \frac{\partial \alpha_{i-1}}{\partial \xi} (A_0 \xi + k y + \phi(y)) - \frac{\partial \alpha_{i-1}}{\partial \Xi} (A_0 \Xi + \Phi(y)) - \sum_{j=1}^{m+i-1} \frac{\partial \alpha_{i-1}}{\partial \lambda_j} (-k_j \lambda_1 + \lambda_{j+1}) - \sum_{j=1}^{i-1} \frac{\partial \alpha_{i-1}}{\partial y_{\mathrm{r}}^{(i-1)}} y_{\mathrm{r}}^{(j)} -$$

$$\sum_{j=1}^{i-1}\frac{\partial\alpha_{i-1}}{\partial y_{r\tau}^{(i-1)}}y_{r\tau}^{(j)}-\left(\frac{\partial\alpha_{i-1}}{\partial\hat{\beta}}+y_r^{(i-1)}\right)\dot{\hat{\beta}}-$$

$$\frac{\partial\alpha_{i-1}}{\partial\hat{\theta}_1}\Gamma_1\tau_{\theta_1,i}-\frac{\partial\alpha_{i-1}}{\partial\hat{\theta}_2}\Gamma_2\tau_{\theta_2,i},2\leqslant i\leqslant\rho,$$

$$w=[v_{m,2},v_{m-1,2},\cdots,v_{0,2},\Phi_{(1)}+\Xi_{(2)}]^{\mathrm{T}}.$$

选择调节函数为

$$\begin{cases}\tau_{\theta_1,1}=(w-\hat{\beta}(\dot{y}_r+\bar{\alpha}_1)e_1)z_1,\\ \tau_{\theta_1,i}=\tau_{\theta_1,i-1}-\dfrac{\partial\alpha_{i-1}}{\partial y}wz_i,2\leqslant i\leqslant\rho,\\ \tau_{\theta_2,1}=[\Psi_{(2)}^{\mathrm{T}}]z_1,\\ \tau_{\theta_2,i}=\tau_{\theta_2,i-1}-\dfrac{\partial\alpha_{i-1}}{\partial y}[\Psi_{(2)}^{\mathrm{T}}]^{\mathrm{T}}z_i,2\leqslant i\leqslant\rho.\end{cases}\tag{9}$$

控制律为

$$u=\frac{1}{\sigma(y)}(\alpha_\rho-v_{m,\rho+1}+\hat{\beta}y_r^{(\rho)});\tag{10}$$

参数自适应律为

$$\begin{cases}\dot{\hat{\beta}}=-\gamma\mathrm{sgn}(b_m)(\dot{y}_r+\bar{\alpha}_1)z_1,\gamma>0,\\ \dot{\hat{\theta}}_1=\Gamma_1\tau_{\theta_1,\rho},\Gamma_1>0,\\ \dot{\hat{\theta}}_2=\Gamma_2\tau_{\theta_2,\rho},\Gamma_2>0.\end{cases}\tag{11}$$

定理 在假设2.1,2.2下,由系统(1),控制律(10)自适应律(11)和滤波器(3)组成的闭环系统,所有信号全局一致有界,并且 $\lim_{t\to\infty}[y(t)-y_r(t)]=0$.

证 由以上设计过程,误差系统可最终表示为

$$\dot{z}=A_z(z,t)z+W_\varepsilon(z,t)\varepsilon_2+W_{\theta_1}(z,t)^{\mathrm{T}}\tilde{\theta}_1+W_{\theta_2}(z,t)^{\mathrm{T}}\tilde{\theta}_2-b_m(\dot{y}_r+\bar{\alpha}_1)e_1\tilde{\beta}+W_d(t-\tau).\tag{12}$$

其中 $A_z(z,t)$ 为斜反对称矩阵,对角线元素为

$$a_{11}=-c_1-d_1-\frac{1}{2}-W(t),$$

$$a_{ii}=-\Lambda_i,\ 2\leqslant i\leqslant\rho,$$

$$z=[z_1,\cdots,z_\rho]^{\mathrm{T}},$$

$$W_\varepsilon(z,t)=\left[1,-\frac{\partial\alpha_1}{\partial y},\cdots,-\frac{\partial\alpha_{\rho-1}}{\partial y}\right]^{\mathrm{T}},$$

$$W_{\theta_1}(z,t)^{\mathrm{T}}=W_\varepsilon(z,t)w^{\mathrm{T}}-\hat{\beta}(\dot{y}_r+\bar{\alpha}_1)e_1e_1^{\mathrm{T}},$$

$$W_{\theta_2}(z,t)^{\mathrm{T}}=W_\varepsilon(z,t)\Psi_{(2)}^{\mathrm{T}},$$

$$W_d(t-\tau)=\begin{bmatrix}h_1(y_\tau)-h_1(y_{r\tau})\\ -\dfrac{\partial\alpha_1}{\partial y}[h_1(y_\tau)-h_1(y_{r\tau})]-\dfrac{\partial\alpha_1}{\partial\xi}[H(y_\tau)-H(y_{r\tau})]-\dfrac{\partial\alpha_1}{\partial\Psi^{\mathrm{T}}}[G(y_\tau)-G(y_{r\tau})]\\ \vdots\\ -\dfrac{\partial\alpha_{\rho-1}}{\partial y}[h_1(y_\tau)-h_1(y_{r\tau})]-\dfrac{\partial\alpha_{\rho-1}}{\partial\xi}[H(y_\tau)-H(y_{r\tau})]-\dfrac{\partial\alpha_{\rho-1}}{\partial\Psi^{\mathrm{T}}}[G(y_\tau)-G(y_{r\tau})]\end{bmatrix}.\tag{13}$$

选择 Laypunov-Krasoviskii 泛函

$$V=\frac{1}{2}z^{\mathrm{T}}z+\frac{1}{2}\tilde{\theta}_1^{\mathrm{T}}\Gamma_1^{-1}\tilde{\theta}_1+\frac{1}{2}\tilde{\theta}_2^{\mathrm{T}}\Gamma_2^{-1}\tilde{\theta}_2+\frac{|b_m|}{2\gamma}\tilde{\beta}^2+\sum_{i=1}^{\rho}\frac{1}{4d_i}\varepsilon^{\mathrm{T}}P\varepsilon+\int_{t-\tau}^{t}S(\delta)\mathrm{d}\delta\tag{14}$$

其中 $S(\delta)$ 为待定的非负函数.

沿式(5),(11),(12),对式(14)求导得

$$\dot{V}=\frac{1}{2}z^{\mathrm{T}}(A_z+A_z^{\mathrm{T}})z-\sum_{i=1}^{\rho}z_i\frac{\partial\alpha_{i-1}}{\partial y}\varepsilon_2-\sum_{i=1}^{\rho}\frac{1}{4d_i}|\varepsilon|^2-\sum_{i=2}^{\rho}z_i\frac{\partial\alpha_{i-1}}{\partial\xi}[H(y_\tau)-H(y_{r\tau})]-\sum_{i=2}^{\rho}z_i\frac{\partial\alpha_{i-1}}{\partial\Psi^{\mathrm{T}}}[G(y_\tau)-G(y_{r\tau})]+(z_1(t)-\sum_{i=2}^{\rho}z_i\frac{\partial\alpha_{i-1}}{\partial y})[h_1(y_\tau)-h_1(y_{r\tau})]+S(t)-S(t-\tau)\leqslant$$

$$\frac{1}{2}z^{\mathrm{T}}(A_z+A_z^{\mathrm{T}})z-\sum_{i=1}^{\rho}z_i\frac{\partial\alpha_{i-1}}{\partial y}\varepsilon_2-\sum_{i=1}^{\rho}\frac{1}{4d_i}|\varepsilon|^2+\frac{1}{2}\sum_{i=2}^{\rho}z_i^2[\sum_{j=1}^{n}\left(\frac{\partial\alpha_{i-1}}{\partial\xi_j}\right)^2+\sum_{j=1}^{\rho}\sum_{k=2}^{n}\left(\frac{\partial\alpha_{i-1}}{\partial\Psi_{j,k}^{\mathrm{T}}}\right)^2+\left(\frac{\partial\alpha_{i-1}}{\partial y}\right)^2]+\frac{1}{2}z_1^2(t)+z_1^2(t-\tau)[\frac{\rho}{2}s_{h_1}^2(t-\tau)+\frac{\rho-1}{2}\sum_{j=1}^{n}s_{h_j}^2(t-\tau)+\frac{\rho-1}{2}\sum_{j=1}^{\rho}\sum_{k=2}^{n}s_{g_{j,k}}^2(t-\tau)]+S(t)-S(t-\tau).\tag{15}$$

其中定义 $\dfrac{\partial\alpha_0}{\partial y}:=-1$, 选择非负函数 $S(\delta)=z_1^2(\delta)W(\delta)$, 则有

$$\dot{V}\leqslant-\sum_{i=1}^{\rho}c_iz_i^2-\sum_{i=1}^{\rho}d_i\left(z_i\frac{\partial\alpha_{i-1}}{\partial y}+\frac{1}{2d_i}\varepsilon_2\right)^2-\sum_{i=1}^{\rho}\frac{1}{4d_i}(\varepsilon_1^2+\varepsilon_3^2+\cdots+\varepsilon_n^2)\leqslant$$

$$-\sum_{i=1}^{\rho} c_i z_i^2. \tag{16}$$

由时滞系统稳定性定理[6]，$\lim\limits_{t\to\infty} z(t)=0$，其余部分的证明类似于无时滞的情况[5].

4 仿真(Simulation)

考虑以下非线性时滞系统：

$$\begin{cases} \dot{x}_1 = x_2 + \theta_1 y^2 + \sin(y(t-\tau)), \\ \dot{x}_2 = u + \theta_2 \cos(y(t-\tau)), \\ y = x_1. \end{cases}$$

在仿真中，参考信号选为 $y_r(t) = \sin t \sin 2t$，初始条件为：$x_1(t) = 0.1, t\in[-\tau,0]$；$x_2(0)=1, y_r(t) = 0, t\in[-\tau,0]$；$\tau = 2$，其余全取为 $0, t\in[0,20]$；$c_1 = c_2 = d_1 = d_2 = 0.1$；$\gamma_1 = 0.65, \gamma_2 = 0.5$；$k_1 = k_2 = 1$；$\theta_1 = 0.5, \theta_2 = -1$. 仿真结果如图1,2所示.

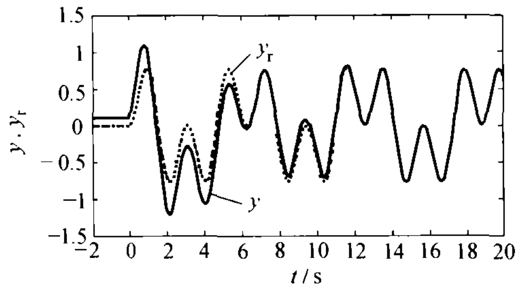

图 1　系统输出仿真结果

Fig. 1　Simulation result of system output

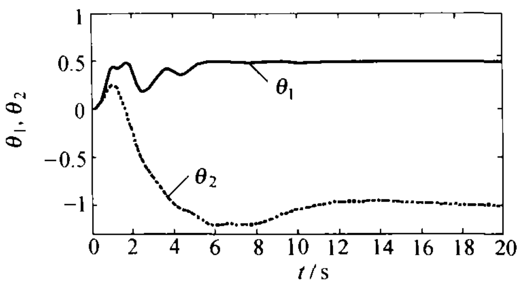

图 2　估计参数仿真结果

Fig. 2　Simulation result of estimated parameters

5 结语(Conclusion)

针对一类具有参数化输出反馈形式的非线性时滞系统，采用时滞滤波器估计系统状态，运用占优化方法处理非线性时滞项，结合 Backstepping 的设计技巧，提出了一种无记忆自适应输出跟踪控制方法.但仍然要求时滞矩阵 G 的第一行为零，如何取消这假设，仍然是一个有待于进一步研究的问题.

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