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Tuning of Auto-disturbance-rejection Controller for a Class of Nonlinear Plants[1)]

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Abstract Design and adjusting rule of auto-disturbance-rejection controller are proposed for a class of first order nonlinear plants. Tracking differentiator and nonlinear combination are simplified. According to the analysis of observing error of a secould order extended state observer, an empirical tuning rule is proposed based on theoretic deduction and simulations. Simulations on a multivariable plant with adjustable zeros demonstrate validity of the tuning rule.

Key words Nonlinear plants, auto-disturbance-rejection controller, tuning rule, multivariable plant with adjustable zeros

1 Introduction

Auto-disturbance-rejection controller (ADRC) as a novel nonlinear controller is proposed by Han[1]. Recently ADRC has been applied to the thermal process control, electric power system control, flight and motion control, *etc*. The findings have demonstrated that ADRC has quick response precision, satisfactory control performance, strong robustness and disturbance rejection. However, the tuning method of controller is under research.

2 Problem statement and control structure simplification

This paper deals with a class of nonlinear plants as follows.

$$\dot{y} = f(y, v(t)) + b(t)u(t) \tag{1}$$

where $f(\cdot)$ is a continuous and differential nonlinear function, $v(t)$ is the unknown external disturbance with limited range, $b(t)$ is an uncertain function, $u(t)$ is the control input and y is the control output. Define $y_1 = y^{(n-1)}$, $y_2 = f(y, v(t)) + (b(t) - b_0)u(t)$, $w(t) = -\dot{y}_2$, where $b_0 \neq 0$ is a medium in the range of $b(t)$, y_2 is an extended state of plant (1). Therefore, the equation describing the dynamics of (1) can be rewritten as follows:

$$\begin{cases} \dot{y}_1 = y_2 + b_0 u(t) \\ \dot{y}_2 = -w(t) \end{cases} \tag{2}$$

Fig. 1 shows the structure of the simplified ADRC.

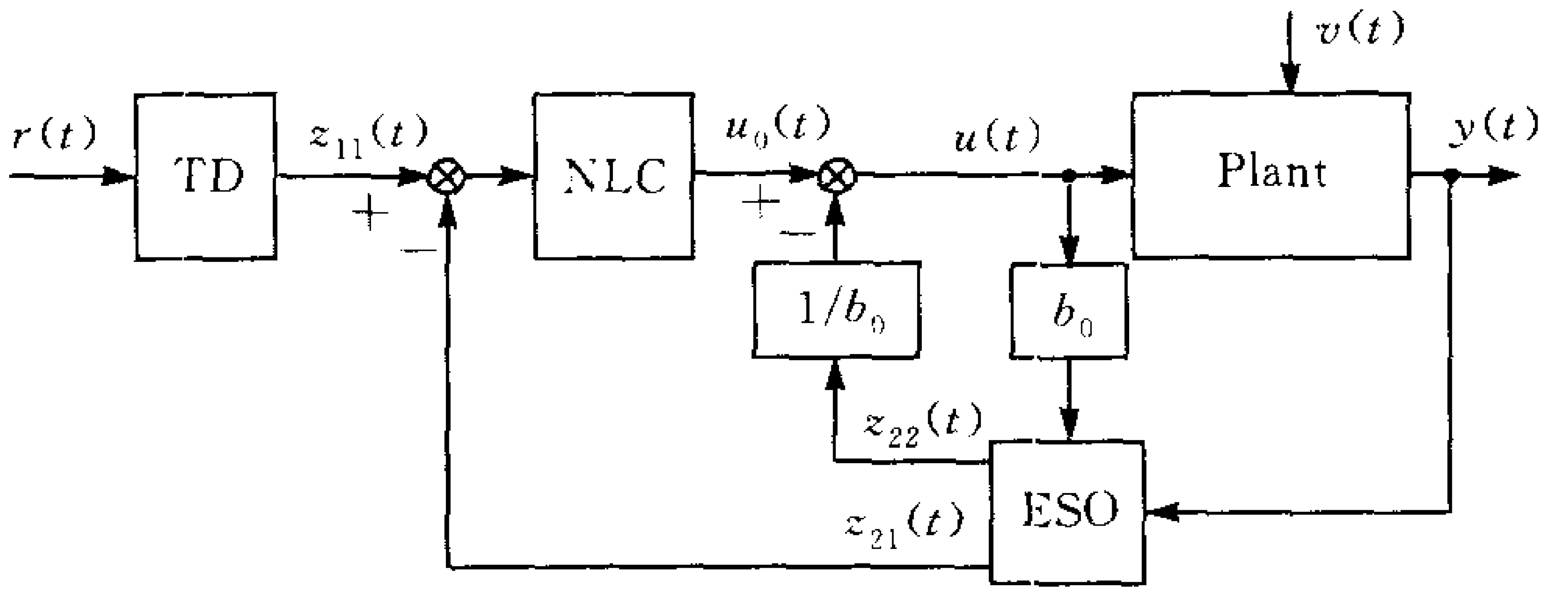

Fig. 1 Structure of first order ADRC

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The algorithm of second order ESO can be presented by the following equation[2].

$$\begin{cases}\dot{z}_1 = z_2 - \beta_1(z_1 - y) + b_0 u(t) \\ \dot{z}_2 = -\beta_2 fal(z_1 - y, \alpha, \delta)\end{cases} \tag{3}$$

where $\beta_1 \in R$ and $\beta_2 \in R$ are adjustable parameters and $fal(\cdot)$ is a nonlinear function, i. e.,

$$fal(z, a, \delta) = \begin{cases}|z|^{a}\mathrm{sign}(z), & |z| > \delta \\ z\delta^{a-1}, & |z| \leqslant \delta\end{cases} \tag{4}$$

where $\delta \in (0,1)$ is the linear interval, $\alpha \in (0,1)$ is the nonlinear exponent. Define $e_1 = z_1 - y_1(t)$ and $e_2 = z_2 - y_2(t)$. Then by subtracting (2) from (3), the following equation is deduced.

$$\begin{cases}\dot{e}_1 = e_2 - \beta_1 e_1 \\ \dot{e}_2 = w(t) - \beta_2 fal(e_1, \alpha, \delta)\end{cases} \tag{5}$$

The nonlinear error feedback dynamics are simplified by pole distribution. Nonlinear combination (NLC) can be designed as follows:

$$u_0(t) = \gamma(z_{11} - z_{21}) \tag{6}$$

where $-\gamma b_0 (\gamma b_0 > 0)$ is the distributed poles.

For the first order ADRC, the tracking differentiator (TD) works as arranging transient process and flexing input reference $r(t)$. Therefore, a first order inertial structure is in place of nonlinear transient process.

With this simplification, the number of parameters in NLC and TD is reduced to one, so the process of tuning ADRC is further simplified.

3 Tuning rule of parameters

Under the assumption $|w(t)| \leqslant W$, if the parameters of (5) are satisfied with[2]

$$\beta_1^2 > c_2 \frac{(1+k)^2}{k}\beta_2\delta^{\alpha-1}, \quad c_2 > 1, k > 1 \tag{7}$$

the trajectories of (5) can be limited in the domain:

$$\begin{cases}e_1^* = \max(|e_1|) = \left(\dfrac{kc_2W}{\beta_2(c_2-1)}\right)^{\frac{1}{\alpha}}, & \text{when } \dfrac{kc_2W}{\beta_2(c_2-1)} > \delta^{\alpha} \\ e_2^* = \max(|e_2|) = \beta_1 e_1^* - \dfrac{(k-1)c_2W}{\beta_1(c_2-1)}\end{cases} \tag{8}$$

From (8), $\partial e_2^* / \partial\beta_1 > 0$, the coefficient β_1 should become the minimum which satisfies (7), thus

$$\beta_1 = \sqrt{c_2 \frac{(1+k)^2}{k}\beta_2\delta^{\alpha-1}} \tag{9}$$

Notice that $\partial e_1^* / \partial\beta_2 < 0$. Substituting (9) into (8) we obtain

$$\frac{\partial e_2{}^*}{\partial\beta_2} = \frac{1}{2\sqrt{c_2(1+k)^2\delta^{\alpha-1}/k}}\left[\frac{c_2(k-1)W}{(c_2-1)\beta_2} - \left(\frac{2}{\alpha}-1\right)c_2\frac{(1+k)^2}{k}\delta^{\alpha-1}\left(\frac{c_2kW}{(c_2-1)\beta_2}\right)^{1/\alpha}\right] <$$

$$\frac{1}{2\sqrt{c_2(1+k)^2\delta^{\alpha-1}k}}\left[(k-1) - \left(\frac{2}{\alpha}-1\right)c_2(1+k)^2\delta^{\alpha}\right] \tag{10}$$

In case of the right-hand side of (10) less than zero, $\partial e_1^* / \partial\beta_2 < 0$.

Base on the statement above, the method of tuning ESO can be depicted by the following flow chart:

In Fig. 2 ξ_1 and ξ_2 are the precision of the observer. From Fig. 2, β_1 and β_2 can directly be obtained by calculation, while other parameters are determined through experience.

Remarks.

1) Coefficient c_2 can vary within $(1, \infty)$. On the condition of e_1^* being constant, by substituting β_2 from (8) into (9), it can be proved that β_1 becomes minimum if $c_2 = 2$ and e_2^* becomes minimum if $c_2 \in U$, where U is a neighborhood ($c_2 < 2$) of 2. The simulation

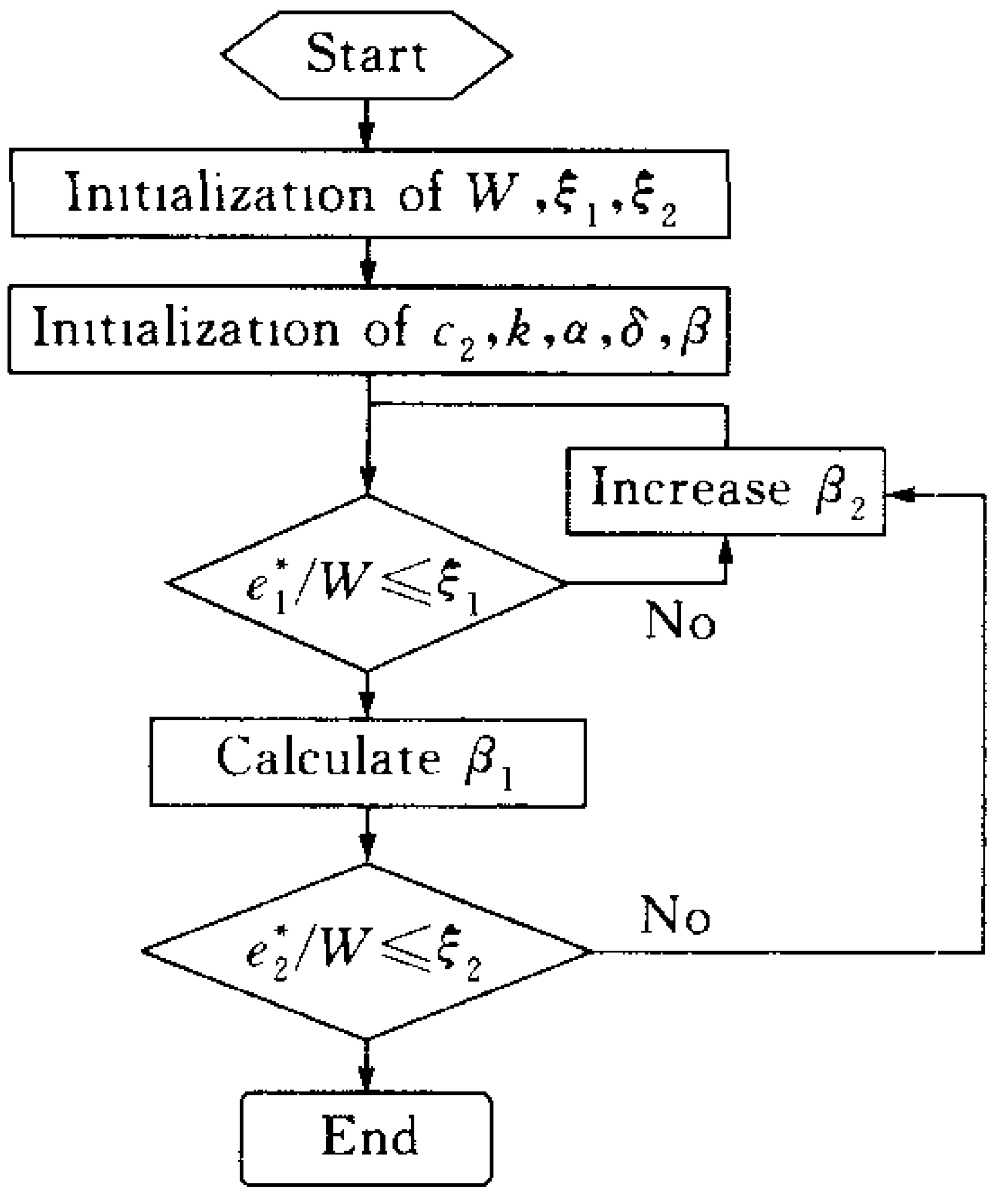

Fig. 2 Flow chart of tuning ESO

suggests that $c_2 \in [1.8, 2]$ be suitable.

2) Coefficient k can vary within $(1, \infty)$. When the right-hand side of (10)is less than 0, we can see

$$\delta^{\alpha}\left(\frac{2}{\alpha}-1\right)c_2 > \frac{k-1}{(1+k)^2} \tag{11}$$

From (11), the right-hand side of (11) is the maximum if $k=3$. Based on the simulation, $k \in [1.5, 3]$ is suitable.

3) Coefficients α and δ can vary within $(0, 1)$. Under weak α and δ, strong $\delta^{\alpha-1}$ leads to high frequencies noise and more difficult choice of other parameters. Based on simulations, it is suggested that $\delta^{\alpha-1}$ should be less than 100 and α and δ should be satisfied with (11). Therefore, $\alpha \in [0.2, 0.5]$ and $\delta \in [0.005, 0.05]$.

According to the designing process above, the second order ESO could be applied to the plant that is satisfied with $|w(t)| \leqslant W$ and (2) under low precision of observer.

Considering the anticipated control purpose and the properties of the plant, coefficient γ of NLC can be designed by pole distribution. The time constant of first order inertial structure of TD varies from 1/10 to 1/5 of the inverse of the anticipated poles γb_0.

4 Simulations

In this work we have conducted simulation of the plants[3] with adjustable zeros, TITO, nonlinear and strong coupling. In [3], the plant divided into two loops was controlled by PI controllers. However, our plant is done by two ADRC's with parameters based on the tuning rule above. Fig. 3 shows the two control results under designed working conditions. Good dynamic properties are guaranteed using ADRC even if the plant has uncertain inner or external perturbation.

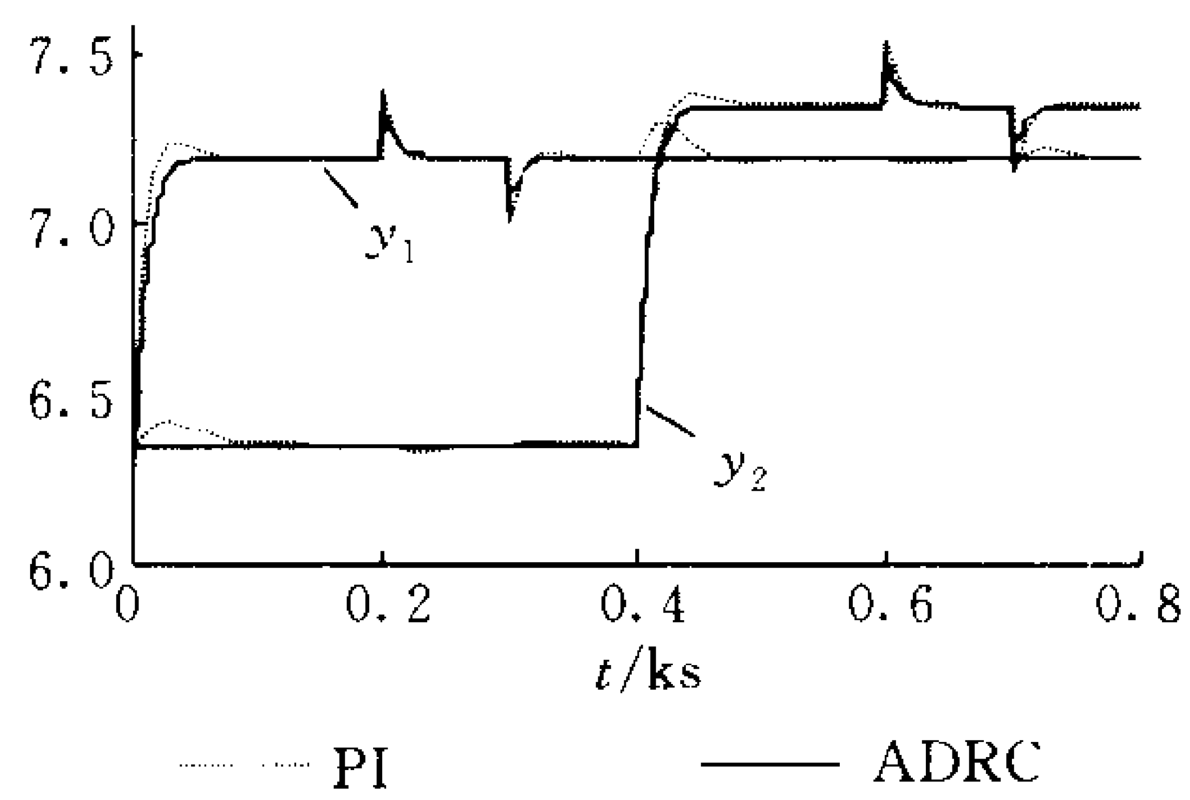

Fig. 3 Response of the control system

5 Conclusions

This paper has completed with simplifying the first order ADRC and proposed the designing and adjusting rule of parameters. The simulation has demonstrated the validity of the rule.

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一类非线性对象的自抗扰控制器参数整定

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摘 要 研究一类一阶非线性对象的自抗扰控制器的设计与参数整定规则. 首先简化跟踪微分器和非线性组合的设计,然后根据二阶扩张状态观测器的观测误差分析,通过理论推导和仿真实验得出控制器的参数整定规则,并以一个具有可调零点的多变量对象为仿真实例,证实了整定规则的有效性.

关键词 非线性对象,自抗扰控制器,整定规则,具有可调零点的多变量对象

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