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Incipient fault diagnosis on active disturbance rejection control

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Dear editor,

The incipient fault diagnosis method has received great attention in recent decades owing to the increasing demand for reliability and safety in industrial processes [1, 2]. A controller of active disturbance rejection control (ADRC) can effectively separate the incipient fault from the disturbance. Therefore, studying the incipient fault estimation has become a necessarily imminent research topic in this new frontier.

In the past two decades, the fruitful theoretic results of ADRC [3], which make up for the deficiencies of the traditional proportion integration differentiation (PID), have been proposed by Han et al. [4]. Accordingly, various results have been produced based on ADRC [5]. For example, the extended state observer (ESO) in ADRC has been applied to solve system uncertainty [6]. Furthermore, some improvements have been made to the ADRC controller [7]. However, a few research results have been presented on combining ADRC with incipient fault diagnosis; thus, it appears to be a relatively new innovation to the analysis of the incipient fault system with the ADRC strategy.

Motivated by the discussion above, this study proposes the application of ADRC to the diagnosis of the incipient fault system with disturbance. The main contributions of the proposed method include the following: (1) the analysis formula of the incipient fault is discussed; (2) the incipient fault is effectively separated from the disturbance as a new state variable using the ADRC method; and (3) two simulation results of incipient fault estimations are presented to show the effectiveness of the presented method.

Model description. The incipient fault system is described in the following form:

$$\begin{aligned} &\dot{x}(t) = Ax(t) + Bu(t) + Ff(t) + Wd(t), \\ &y(t) = Cx(t), \end{aligned} \tag{1}$$

where $x(t) \in \mathbb{R}^n$ is the system state vector; $u(t) \in \mathbb{R}^n$ is the system input vector; $y(t) \in \mathbb{R}^n$ is the system output vector; and $d(t) \in \mathbb{R}^n$ is the system disturbance. $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times m}$, $C \in \mathbb{R}^{p\times n}$, $F \in \mathbb{R}^n$, and $W \in \mathbb{R}^n$ represent the system state matrix, system input matrix, system output matrix, actuator fault vector, and disturbance vector, respectively. $f(t) \in \mathbb{R}^n$ is the incipient fault value.

Tracking differentiator (*TD*). A TD is used to track the input signal $v(t)$ through the tracking signal $v_1(t)$ and the approximate differentiated signal $v_2(t)$ to $v_1(t)$, $v_3(t)$ to $v_2(t), \ldots, v_n(t)$ to $v_{n-1}(t)$, and written in the following form:

$$\begin{cases} e(t) = v_1(t) - v(t), \\ \dot{v}_1(t) = v_2(t), \\ \dot{v}_2(t) = v_3(t), \\ \vdots \\ \dot{v}_{n-1}(t) = v_n(t), \\ \dot{v}_n = R^n \Big[g_1 + g_2 \dfrac{\text{flan}(k_1(t), v_2(t), r, h)}{R} \\ \qquad + g_3 \dfrac{\text{flan}(k_2(t), v_3(t), r, h)}{R^2} \\ \qquad + \cdots + g_n \dfrac{\text{flan}(k_{n-1}(t), v_n(t), r, h)}{R^{n-1}} \Big]. \end{cases} \tag{2}$$

The TD convergence is described in the following form [8].

Lemma 1. If there is an existing positive definite matrix

$$G = \begin{bmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ g_1 & g_2 & g_3 & \cdots & g_n \end{bmatrix},$$

the input signal $v : [0, \infty) \to \mathbb{R}$ fits $\sup_{t\in[0,T]} |v_i(t)| = W < \infty, i = 1, \ldots, n$. M is an arbitrary normal number. Hence, for any $0 < b < T$, $v_1(t) < \cdots < v_n(t)$ uniformly converges to $\dot{v}_1(t) < \cdots < \dot{v}_n(t)$ in $[b, T]$ when $\mathbb{R} \to \infty$.

ESO. According to the previous analysis, regard the incipient fault $f(t)$ in (1) as a new state variable $x_n(t)$, that

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is, $x_n(t) = f(t)$. Furthermore, let $\sigma(t) = \dot{f}(t)$, and Eq. (1) is reconstructed in the following way:

$$\begin{cases} \dot{x}_1(t) = x_2(t), \\ \dot{x}_2(t) = x_3(t), \\ \vdots \\ \dot{x}_n(t) = x_{n+1}(t) + bu(t) + wd(t), \\ \dot{x}_{n+1}(t) = \sigma(t), \\ y_1(t) = x_1(t), \quad t \geqslant t^*. \end{cases} \tag{3}$$

Aiming at (3), the ESO can be constructed as below:

$$\begin{cases} e_1(t) = z_1(t) - y(t), \\ \dot{z}_1(t) = z_2(t) - \beta_{01} e_1(t), \\ \dot{z}_2(t) = z_3(t) - \beta_{02} \mathrm{fal}(e_1(t), \alpha_1, \gamma), \\ \vdots \\ \dot{z}_n(t) = z_{n+1}(t) - \beta_{0n} \mathrm{fal}(e_1(t), \alpha_{n-1}, \gamma) \\ \qquad + wd(t) + bu(t), \\ \dot{z}_{n+1}(t) = -\beta_{0n+1} \mathrm{fal}(e_1(t), \alpha_n, \gamma), \end{cases} \tag{4}$$

where $z_1(t), \ldots, z_{n+1}(t)$ are the estimations of the system state vector of $x_1(t), \ldots, x_{n+1}(t)$. Select proper parameters $\beta_{01}, \ldots, \beta_{0n+1}$, and the energy function $\mathrm{fal}(e_1(t), \alpha_i, \gamma)$ $(i = 1, \ldots, n)$ is described in the following form:

$$\mathrm{fal}(e_1(t), \alpha_i, \gamma) = \begin{cases} \dfrac{e_1(t)}{\gamma^{1-\alpha_i}}, & |e_1(t)| \leqslant \gamma, \\ |e_1(t)|^{\alpha_i} \mathrm{sign}(e_1(t)), & |e_1(t)| > \gamma, \end{cases} \tag{5}$$

where γ and α_i are the controller parameters. Moreover, $\alpha_i \leqslant 1$.

Based on the system (3) and (4), the error dynamic equation of the whole system can be described and reconstructed in the following form:

$$\begin{cases} \dot{e}_1(t) = \dot{e}_{01}(t) = e_{02}(t) - \beta_{01} e_1(t), \\ \dot{e}_{02}(t) = e_{03}(t) - \beta_{02} \mathrm{fal}(e_1(t), \alpha_1, \gamma), \\ \dot{e}_{03}(t) = e_{04}(t) - \beta_{03} \mathrm{fal}(e_1(t), \alpha_2, \gamma), \\ \vdots \\ \dot{e}_{0n}(t) = e_{0n+1}(t) - \beta_{0n} \mathrm{fal}(e_1(t), \alpha_{n-1}, \gamma), \\ \dot{e}_{0n+1}(t) = -\beta_{0n+1} \mathrm{fal}(e_1(t), \alpha_n, \gamma) - \sigma(t). \end{cases} \tag{6}$$

Subsequently, Eq. (6) can be reconstructed as below to ensure that the ADRC structure itself can maintain a certain stability when the system has no incipient fault:

$$\dot{e} = -A(e)e. \tag{7}$$

Lemma 2 ([9])**.** An existing matrix is defined in the following form:

$$D = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1,(n+1)} \\ -d_{12} & d_{22} & \cdots & d_{2,(n+1)} \\ \vdots & \vdots & \ddots & \vdots \\ -d_{1,(n+1)} & -d_{2,(n+1)} & \cdots & d_{(n+1),(n+1)} \end{bmatrix},$$

where the principal diagnal is positive. The zero solution of (7) is Lyapunov's stability if the $DA(e)$ is a positive definiteness matrix.

Nonlinear state error feedback law (*NLSEF*). Based on the ADRC designed by Han et al., the controller can be set in the following form:

$$\begin{cases} e_{11}(t) = v_1(t) - z_1(t), \\ e_{12}(t) = v_2(t) - z_2(t), \\ \vdots \\ u_0(t) = \beta_1 \mathrm{fal}(e_{11}(t), \alpha_1, \gamma) + \beta_2 \mathrm{fal}(e_{12}(t), \alpha_2, \gamma) \\ \qquad + \cdots + \beta_n \mathrm{fal}(e_{1n}(t), \alpha_n, \gamma), \\ u(t) = u_0(t) - \dfrac{z_{n+1}(t)}{b}. \end{cases} \tag{8}$$

Conclusion. In this study, we investigated the linear nominal system with a soft incipient fault or the linear system with an abrupt fault based on the ADRC approach. The formulae of the soft incipient and abrupt incipient faults were discussed using the incipient fault definition. The incipient fault was effectively separated from the disturbance as a new state variable by using the ADRC approach. We demonstrated the effectiveness of the proposed method by the numerical verification in Appendix C according to the designed observer.

On the basis of the performed analysis, a further study on the intermittent incipient fault diagnosis method and the parameter selection method is worthy of research and discussion.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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