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Fault detection of a sandwich system with dead-zone based on robust observer

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ABSTRACT

Non-smooth sandwich systems with dead-zone widely exist in the real engineering applications. For accurately detecting its faults, a novel robust observer has been proposed in this paper. With the consideration of the model uncertainties, disturbances, and switching error which specially belongs to the system, the so-called general disturbance is defined. After that, the conventional dynamic robust observer design method can be applied to the system. Then, for saving the computing time and effectively reducing the effect of the disturbances to the residual, the main frequencies of the disturbances have been identified by the spectrum analysis of the residual created by the conventional observer and the zeros assignment methodology has been applied to get one feedback matrix of the robust observer. Finally, the rest of the feedback matrices of the robust observer can be obtained by solving an optimal problem with $H_{\infty,F}/H_{-,F}$ as the minimizing object. For verifying the effectiveness of this novel robust observer, the comparison between the proposed robust non-smooth scheme and the conventional method has been made. The final results show that the proposed robust fault detection approach can detect the actuator and sensor faults of the system more accurately and timely with a lower missing and false alarm rates comparing with the conventional one.

1. Introduction

A dead zone is a non-smooth and nonlinear character which widely exists in all kinds of motors, mechanical transition systems, hydraulic systems, and mechatronic systems [1]. Dead zone usually does not exist independently. On the contrary, it usually connects with other parts. For instance, in a DC motor servo system, the linear parts of the power amplifier and the DC motor can be regarded as the front linear subsystem while the load of the motor can be regarded as the back linear subsystem. The dead zone of the DC motor embedded between the two dynamic linear parts and this structure can be regarded as sandwich systems with dead zone. In the industry field, many systems can be described as sandwich systems with dead zone such as a hydraulic actuator of aircraft lift [2], position stage driven by a DC motor, and a hydraulic actuator controlled by a pilot valve etc. [3].

In engineering practice, the dead zone does not exist independently and it usually connects with other conventional parts. If the dead zone nonlinearity is sandwiched into two linear dynamic subsystems, this system can be defined as the sandwich system with dead zone. In real application, the model uncertainties and disturbances always exist and how to design a robust fault prediction observer to restrain the effect of the model uncertainties and disturbances are of crucial importance [4,5]. A Luenberger-type switching observer is designed for a class of hybrid linear systems [6,7], while an observer is proposed for a class of piecewise affine systems, respectively in [8,9].

In [10], a novel fault detection and identification (FDI) scheme is presented for a class of nonlinear systems with model uncertainty. The heart of this approach is an on-line approximator, referred to as fault tracking approximator (FTA). In [11], a new sensor fault detection, isolation, and identification (FDII) strategy is proposed using the multiple-model (MM) approach. The scheme is based on multiple hybrid Kalman filters (MHKFs), which represents an integration of a nonlinear mathematical model of the system with a number of piecewise linear (PWL) models. The work in [12] investigates a fault detection and accommodation (FDA) problem of saturated actuators for trajectory tracking of underactuated surface vessels (USVs) in the presence of nonlinear uncertainties.

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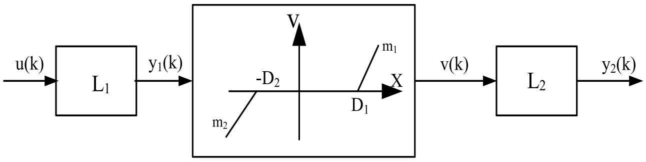

Fig. 1. The structure of the sandwich systems with dead zone.

In [13], a new strategy for integration of fault estimation within fault-tolerant control is proposed. A new delay-derivative-dependent sliding mode observer (SMO) design is given in [14] for a class of linear uncertain time-varying delay systems is presented. In [15], the problem of fault detection for discrete-time Lipschitz nonlinear systems with additive white Gaussian noise channels subject to signal-to-noise ratio constraints is investigated. An unknown input observer-based robust fault estimation for systems corrupted by partially decoupled disturbances is proposed, and the effectiveness of this method is verified by simulations [16]. In [17], both the steering angle and sideslip angle of a vehicle can be estimated by using an unknown input observer as well. In the unknown input observer, all the model uncertainties, disturbances, and even faults can be regarded as the unknown input in this observer. From the above literature review, it is clear that many works focusing on observer designs for specific nonlinear systems have been done in recent years by using a multiple-model approach, a hybrid Kalman filter, a sliding mode observer, and an unknown observer.

Note that the work on a state-estimation of the sandwich system with dead zone, backlash, and hysteresis, has been conducted respectively [18–20]. Recently, an observer to realize the more accurate fault detection of a mechanical system with inherent backlash without considering the model uncertainties and disturbances is designed in [21].

However, the sandwich system with dead zone not only has the non-smooth and nonlinear part which connects with the front and back linear parts but also has the immeasurable interval variables i.e. , the input $y_1(k)$ and output $v(k)$ of the dead zone. In other words, only the input variable $u(k)$ and the output variable $y_2(k)$ are measurable (See in Fig. 1). In addition, in the robust fault detection observer design process, the model uncertainties and disturbances have to be considered. Therefore, this kind of system is much more complicated than the traditional ones and accurate fault prediction can be very challenging. Till now, from the authors' best knowledge, the problem of observers design to deal with robust fault prediction for the sandwich system with dead zone yet has not been fully investigated, which motivates our current work.

2. Model of the sandwich system with dead zone

A typical sandwich system with dead zone and the corresponding architecture of this system is shown in Fig. 1, where, $u(k)$ and $y_2(k)$ are the measurable input and output of the system, respectively. $y_1(k)$ and $v(k)$ are the interval variables which cannot be measured directly. $\mathrm{L}_1(\cdot)$ is the front linear subsystem and $\mathrm{L}_2(\cdot)$ is the back linear subsystem.

The front linear subsystem $\mathrm{L}_1(\cdot)$ can be described as

$$\begin{cases}\mathbf{x}_1(k+1) = \mathbf{A}_1\mathbf{x}_1(k) + \mathbf{B}_1u(k)\\ y_1(k) = \mathbf{C}_1\mathbf{x}_1(k)\end{cases} \tag{1}$$

and the back linear subsystem $\mathrm{L}_2(\cdot)$ can be described as

$$\begin{cases}\mathbf{x}_2(k+1) = \mathbf{A}_2\mathbf{x}_2(k) + \mathbf{B}_2v(k)\\ y_2(k) = \mathbf{C}_2\mathbf{x}_2(k)\end{cases} \tag{2}$$

where $\mathbf{x}_i \in \mathbf{R}^{n_i\times 1}$, $\mathbf{A}_i \in \mathbf{R}^{n_i\times n_i}$, $\mathbf{B}_i \in \mathbf{R}^{n_i\times 1}$, $y_i \in R^{1\times 1}$, $\mathbf{C}_i \in \mathbf{R}^{1\times n_i}$, $u \in R^{1\times 1}$, $v \in R^{1\times 1}$, and $i = 1, 2$.

Here, x_{1i} and x_{2i} represent the ith state variable of L_1 and L_2, respectively. $\mathbf{A}_i \in \mathbf{R}^{n_i\times n_i}$ is the state transition matrix, $\mathbf{B}_i \in \mathbf{R}^{n_i\times 1}$ is the input matrix, $y_2 \in R^{1\times 1}$ is the output variable of the whole system, n_i represents the dimension of the ith linear subsystem, $u \in R^{1\times 1}$ is the input variable, $y_1 \in R^{1\times 1}$ is the input variable of the dead zone and $v \in R^{1\times 1}$ is the output variable of the dead zone. Without loss of generality, in the state-space function, for L_1 and L_2, we set $x_{1n_1}(k) = y_1(k)$ and $x_{2n_2}(k) = y_2(k)$, respectively.

Based on Refs. [2,3] as well as the property of the dead zone in middle part of Fig. 1, the model of the dead zone can be obtained as follows.

Define $m(k)$ and $v_1(k)$, respectively, as the imposed variables, i.e.,

$$m(k) = m_1 + (m_2 - m_1)h(k), \tag{3}$$

$$v_1(k) = m(k)(y_1(k) - D_1h_1(k) + D_2h_2(k)), \tag{4}$$

where, $h(k) = \begin{cases}1, & y_1(k) < 0\\ 0, & \text{else}\end{cases}$, $h_1(k) = \begin{cases}1, & y_1(k) > D_1\\ 0, & \text{else}\end{cases}$,and $h_2(k) = \begin{cases}1, & y_1(k) < -D_2\\ 0, & \text{else}\end{cases}$ are the switch functions which are used to judge and switch the operation zones, i.e., the linear zone and the dead zone. Based on the properties of dead zone, it yields

$$\tilde{v}(k) = v_1(k) - h_3(k)v_1(k) = (1 - h_3(k))v_1(k) \tag{5}$$

where, $h_3(k) = \begin{cases}1, & h_1(k) + h_2(k) = 0\\ 0, & h_1(k) + h_2(k) = 1\end{cases}$ is the switch function utilized to separate the linear zones from the dead zone.

Based on (5), when $h_3(k) = 0$ the system operates on linear zone and $\tilde{v}(k) = v_1(k)$. When $h_3(k) = 1$ the system operates on the dead zone and $\tilde{v}(k) = v_1(k) - v_1(k) = 0$.

Substituting (4) into (5) results in

$$\begin{aligned}\tilde{v}(k) &= (1 - h_3(k))v_1(k)\\ &= (1 - h_3(k))m(k)(y_1(k) - D_1h_1(k) + D_2h_2(k))\\ &= (1 - h_3(k))m(k)y_1(k) - (1 - h_3(k))m(k)D_1h_1(k)\\ &\quad + (1 - h_3(k))m(k)D_2h_2(k).\end{aligned} \tag{6}$$

By substituting (6) into (3) and noticing $y_1(k) = x_{1n_1}(k)$, it results in

$$\begin{aligned}&\mathbf{x}_2(k+1) = A_{22}\mathbf{x}_2(k+1) + B_{22}v(k) = A_{22}\mathbf{x}_2(k+1)\\ &\quad + B_{22}[(1 - h_3(k))m(k)x_{1n_1}(k) - (1 - h_3(k))m(k)D_1h_1(k)\\ &\quad\quad + (1 - h_3(k))m(k)D_2h_2(k)].\end{aligned} \tag{7}$$

Based on (1), (2) and (7), it leads to

$$\begin{cases}\begin{bmatrix}\mathbf{x}_1(k+1)\\ \mathbf{x}_2(k+1)\end{bmatrix} = \begin{bmatrix}\mathbf{A}_1 & \mathbf{0}\\ \mathbf{A}_{21i} & \mathbf{A}_2\end{bmatrix}\begin{bmatrix}\mathbf{x}_1(k)\\ \mathbf{x}_2(k)\end{bmatrix}\\ \quad + \begin{bmatrix}\mathbf{B}_1\\ \mathbf{0}\end{bmatrix}u(k) + \begin{bmatrix}\mathbf{0}\\ \boldsymbol{\theta}_{22i}\end{bmatrix}\\ y(k) = \mathbf{C}\mathbf{x}(k)\end{cases} \tag{8}$$

where $\mathbf{A}_{21i} = \begin{bmatrix}\boldsymbol{\beta}_1 & \boldsymbol{\beta}_{2i}\end{bmatrix}$, $\boldsymbol{\beta}_1 = \mathbf{0} \in \mathbf{R}^{n_2\times(n_2-1)}$, $\boldsymbol{\beta}_{2i} = \begin{cases}\mathbf{B}_2m_1(k), & i = 1\\ \mathbf{0}, & i = 2\\ \mathbf{B}_2m_2(k), & i = 3\end{cases}$, $\boldsymbol{\beta}_{2i} \in \mathbf{R}^{n_2\times 1}$, $\boldsymbol{\theta}_{22i} = \begin{cases}-\mathbf{B}_2m_1(k)D_1, & i = 1\\ \mathbf{0}, & i = 2\\ \mathbf{B}_2m_2(k)D_2, & i = 3\end{cases}$, $\boldsymbol{\theta}_{22i} \in \mathbf{R}^{n_2\times 1}$, and $\mathbf{x}(k) = \begin{bmatrix}\mathbf{x}_1(k)\\ \mathbf{x}_2(k)\end{bmatrix} \in \mathbf{R}^{(n_1+n_2)\times 1}$.

The index of the operation zone is defined as $i = \begin{cases}1, & x_{1n_1} > D_1 \text{ (linear increasing zone)}\\ 2, & -D_2 \le x_{1n_1}(k) \le D_1 \text{ (dead zone)}\\ 3, & x_{1n_1}(k) < -D_2 \text{ (linear decreasing zone)}.\end{cases}$.

Because only the output $y_2(k)$ of the sandwich system with dead zone described in Section 2 of Fig. 1 can be measurable, then we can obtain that $\mathbf{C} = [0, 0, \ldots, 0, 1] \in \mathbf{R}^{1\times(n_1+n_2)}$. For the convenience