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Soft measurement of states of sandwich system with dead zone and its application

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ABSTRACT

In this paper, a novel non-smooth observer is proposed to handle the soft measurement of the states of the sandwich system with dead zone. The convergence theorem of the non-smooth observer and its proof are given, respectively. After that, the experimental results are presented. The comparison between the proposed non-smooth scheme and the conventional method is illustrated. Finally, the robust observer is proposed for the sandwich system with dead zone and the states' estimation results of the experimental equipment by the robust observer and the conventional non-robust observer have been compared in order to illustrate the necessity of proposing the robust 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]. A 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 DC motor can be regarded as the front linear subsystem while the load of the motor can be regarded as the rear linear subsystem. The dead zone of the DC motor is embedded between these above two dynamic linear parts and this structure can be described as sandwich systems with dead zone. In the industrial field, many systems can be described as sandwich systems with dead zone such as hydraulic actuator of aircraft lift [2], position stage driven by DC motor, and hydraulic actuator controlled by pilot valve [3].

It is well known that the accurate and quick state estimation of the above mentioned sandwich system with dead zone is of crucial importance not only for its optimal control design but also for its fault diagnosis in practical applications [4,5]. For these reasons, a more accurate estimation of the states is desirable. Therefore, constructing the specific observer for this specific system is always one of the most important research topics in the field of control engineering practice.

In Ref. [6], an adaptive robust observer is constructed for estimating the states of the nonlinear system with delay and uncertainty. In Ref. [7], by solving the matrix inequalities the switching observer is achieved and the observer is used to estimate the states of mechanical Wiener system with hysteresis. In Ref. [8], a high gain observer is constructed for estimating the states and dead zone parameters of the Hammerstein system with dead zone simultaneously. In Ref. [9], a two layer neural network is used to construct the observer for estimating

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the states of a complicated nonlinear system. Some researches have considered design the switching observers for the switching and non-smooth systems, however, they all limit to the linear systems or the piecewise affine linear systems [10–14].

Zupeng Zhou and Yonghong Tan have done some research works on non-robust state-estimations of sandwich systems with dead zone, backlash, and hysteresis, respectively [15–19]. However, Refs. [15–19] have proposed the non-smooth observer for the corresponding sandwich systems without experimental validation and without considering the disturbances and noises of the system. Therefore, the robust observer design method and the real applications of these observers have not explored yet in these papers. Recently, Yonghong Tan and Zupeng Zhou also designed an observer to realize the more accurate fault detection of mechanical systems with inherent backlash without considering the model uncertainties and disturbances [20]. Therefore, the proposed non-smooth observers in Refs. [15–20] have not been verified by the real experiment equipment and their real applications have not been illustrated in details yet. However, in this paper, the effectiveness of the non-smooth and robust observers have both been verified by experiments and their possible future applications have been fully explored. These are the major contributions of this paper.

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 and output of the dead zone. In other words, only the input variable $u(k)$ and the output variable $y(k)$ are measurable. Therefore, this system is much more complicated than traditional ones. Therefore, the accurate and quick state estimations of this system in real applications can be very challenging.

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 $y(k)$ are the measurable input and output of the system, respectively. $x(k)$ and $v(k)$ are the interval variables which cannot be measured directly. $L_1(\cdot)$ is the front linear subsystem and $L_2(\cdot)$ is the rear linear subsystem.

The front linear subsystem $L_1(\cdot)$ can be described as

$$\begin{cases} \mathbf{x}_1(k+1) = \mathbf{A}_{11}\mathbf{x}_1(k) + \mathbf{B}_{11}u(k) \\ \mathbf{y}_1(k) = \mathbf{C}_1\mathbf{x}_1(k) \end{cases} \tag{1}$$

and the rear linear subsystem $L_2(\cdot)$ can be described as

$$\begin{cases} \mathbf{x}_2(k+1) = \mathbf{A}_{22}\mathbf{x}_2(k) + \mathbf{B}_{22}v(k) \\ \mathbf{y}_2(k) = \mathbf{C}_2\mathbf{x}_2(k) \end{cases}. \tag{2}$$

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

Here, x_{1i} and x_{2i} represent the ith state variable of L_1 and L_2, respectively. $\mathbf{A}_{ii} \in R^{n_i\times n_i}$ is the state transition matrix, $\mathbf{B}_{ii} \in R^{n_i\times 1}$ is the input matrix, $y_i \in R^{1\times 1}$ is the output variable, n_i represents the dimension of the ith linear subsystem, $u \in R^{1\times 1}$ is the input variable, $x \in R^{1\times 1}$ is the input variable of the dead zone and $v \in R^{1\times 1}$ is the output variable of the dead zone. Without the loss of generality, set $x_{1n_1}(k) = x(k)$ and $x_{2n_2}(k) = y(k)$, respectively.

Based on Ref. [2,15] as well as the property of the dead zone in the middle 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.,

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

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

where $h(k) = \begin{cases} 1, & x(k) < 0 \\ 0, & \text{else} \end{cases}$, $h_1(k) = \begin{cases} 1, & x(k) > D_1 \\ 0, & \text{else} \end{cases}$, and $h_2(k) = \begin{cases} 1, & x(k) < -D_2 \\ 0, & \text{else} \end{cases}$ 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

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

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 Eq. (5), when $h_3(k) = 0$ the system operates on linear zone. When $h_3(k) = 1$ the system operates on the dead zone.

By substituting Eq. (5) into Eq. (2) and noticing $x(k) = x_{1n_1}(k)$, it results in

$$\begin{aligned} \mathbf{x}_2(k+1) &= \mathbf{A}_{22}\mathbf{x}_2(k) + \mathbf{B}_{22}v(k) \\ &= \mathbf{A}_{22}\mathbf{x}_2(k) + \mathbf{B}_{22}[(1 - h_3(k))m(k)x_{1n_1}(k) \\ &\quad - (1 - h_3(k))m(k)D_1h_1(k) \\ &\quad + (1 - h_3(k))m(k)D_2h_2(k)]. \end{aligned} \tag{6}$$

Based on Eqs. (1), (2), and (6), it leads to

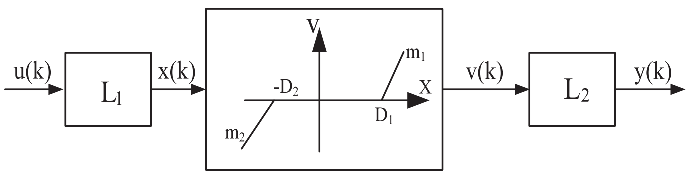

Fig. 1. The structure of the sandwich systems with dead zone.