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Research article

Adaptive super-twisting observer for fault reconstruction in electro-hydraulic systems

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A B S T R A C T

An adaptive-gain super-twisting sliding mode observer is proposed for fault reconstruction in electro-hydraulic servo systems (EHSS) receiving bounded perturbations with unknown bounds. The objective is to address challenging problems in classic sliding mode observers: chattering effect, conservatism of observer gains, strong condition on the distribution of faults and uncertainties. In this paper, the proposed super-twisting sliding mode observer relaxes the condition on the distribution of uncertainties and faults, and the gain adaptation law leads to eliminate observer gain overestimation and attenuate chattering effects. After using the equivalent output-error-injection feature of sliding mode techniques, a fault reconstruction strategy is proposed. The experimental results are presented, confirming the effectiveness of the proposed adaptive super-twisting observer for precise fault reconstruction in electro-hydraulic servo systems.

1. Introduction

Hydraulic systems are extensively used in industrial fields due to inherent advantages in power transmission through a pressurized fluid [1]. Their industrial applications include active suspension and force control [2–4], positioning [5–7], machine tools and manufacturing [8], excavating [9] and flight control [10]. The widespread applications and the importance of reliability and safety of hydraulic systems make the fault detection and diagnosis (FDD) an interesting field for control engineers.

The fault detection and diagnosis of electro-hydraulic servo systems (EHSS) is a generally challenging problem because of its highly uncertain nonlinear nature. This nonlinearity includes the dead-zone and hysteresis of control valves and the turbulent fluid flow equations governing the behavior of the overall system. Model uncertainties including parametric uncertainties and uncertain nonlinearities, matched/unmatched disturbances, and friction are among other types of obstacles in achieving of precise fault detection and diagnosis for hydraulic systems. Consequently, a suitable FDD algorithm needs to be proposed that takes into account model uncertainties and disturbances.

Certain efforts have been made in the literature in order to address the FDD of EHSS. These approaches include signal-based and model-based strategies [11]. Signal-based approaches including machine learning algorithms [12], the wavelet transformation [13,14] and the Hilbert-Huang transformation [15] have been studied to detect internal/external leakage. However, these strategies are not applicable in closed-loop tracking, mainly because closed-loop control creates correlation between plant inputs and outputs. Furthermore, signal-based approaches are dependent upon the plant receiving a specific type of input, which is not the case for a plant inside a control loop. Among model-based approaches, FDD using the adaptive threshold [16], unknown input observer [17], Extended Kalman Filter [18], adaptive and robust observer [2,19] and parameter estimation [20] methods have been studied. Nevertheless, these methods have the common disadvantage of sensitivity to unmodeled dynamics.

Over the past two decades, sliding mode observers for fault reconstruction based on the concept of the so-called equivalent output injection have been proposed [21–23]. In these studies, a linear/nonlinear system is transformed into a new form with two separate subsystems including the dynamics of unmeasurable and measurable states. After this transformation, a reduced-order Luen-

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berger observer is designed for the first subsystem (i.e. unmeasurable states) and sliding mode observer is proposed for observation of measurable states. Then, system faults associated with the second subsystem are reconstructed through the equivalent output injection. Nevertheless, in many practical applications this strategy suffers from the following:

- Chattering is a common problem in standard sliding mode observers/controllers that needs to be addressed.
- Bounds of the system uncertainties and faults need to be known for observer design.
- This method has a challenging problem to reconstruct faults on the first part i.e. unmeasurable states. This is due to the fact that, the mentioned method requires a strong condition on the distribution of system uncertainties and faults to hold.

This paper addresses these challenging problems. Using second-order sliding mode techniques is a well-known strategy to counteract the chattering effect. Nevertheless, these methods require the time derivative of the sliding variable for their realization. In contrast, the well-known super-twisting algorithm [24] can be realized using only the sliding variable itself. In order to establish the sliding motion, there is no need to know perturbation/fault bounds in the observer design. The gains of the super-twisting algorithm are chosen only in accordance with bounds on the gradient of the perturbation. In practical applications, this bound cannot be effortlessly estimated. As a result, the overestimation of perturbation bounds imposes a conservative choice for super-twisting observer gains and exacerbates the chattering.

This paper presents a novel adaptive super-twisting (ASTW) observer for fault reconstruction (i.e. internal and external leakages), which takes into account the uncertainties and nonlinearities of the EHSS. Adaptive gains handle the perturbed EHSS with additive perturbations (uncertainties and faults) in which the perturbation bounds are unknown but bounded. These gains dynamically increase until the system states reach sliding motion and then start to reduce towards lower values. The mentioned procedure is repeated whenever the sliding variable or its derivative start to deviate from the sliding manifold. This strategy eliminates the gain overestimation as well as chattering. Furthermore, simultaneous state estimation and fault reconstruction for the EHSS is based on an extended form of previous works [21–23]. This consideration results in the constraint on the distribution of the perturbation of unmeasurable states being relaxed. In this case, both matched and unmatched disturbances/faults on the EHSS mechanical part can be reconstructed. Finally, the boundedness of adaptive gains has been proven and the finite convergence time is estimated. The stability proof is motivated by recently proposed Lyapunov function [25,26].

The rest of this paper is organized as follows: In Section 2, a detailed nonlinear mathematical model of the presented EHSS is described. Design of adaptive super-twisting observer (ASTW), the finite-time stability proof and the proof of the adaptive gains boundedness are presented in Section 3. Section 4 gives the fault reconstruction strategy. In Section 5, the experimental set-up and the implementation approach are described. The experimental results are also discussed and the efficacy of the proposed strategy is confirmed.

2. System modeling and problem statement

Consider the nonlinear dynamic model of the EHSS shown in Fig. 1. It is composed of a fixed-displacement hydraulic pump, a proportional relief valve (PRV), a proportional directional valve (PDV), and a double acting cylinder. The mathematical modeling of this system is presented as follows:

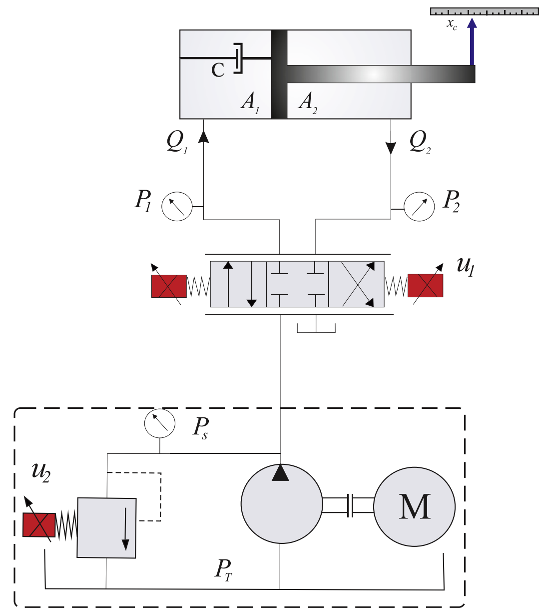

Fig. 1. Schematic diagram of the hydraulic system.

The proportional directional valve (PDV) model can be described as a first-order system given by:

$$\tau_v \dot{x}_v = -x_v + K_v u_1 \tag{1}$$

where x_v denotes the spool position, τ_v is the spool time constant, K_v and u_1 are the valve gain and the input voltage of the PDV, respectively.

The pressure dynamics of actuator chambers can be derived as follows [1]:

$$\dot{P}_1 = \frac{\beta}{V_{01} + A_1 x_c}(+Q_1 - A_1 \dot{x}_c + Q_{L1}) \tag{2}$$

$$\dot{P}_2 = \frac{\beta}{V_{02} - A_2 x_c}(-Q_2 + A_2 \dot{x}_c + Q_{L2}) \tag{3}$$

in which β is the fluid effective bulk modulus, $V_{01} + A_1 x_c$ and $V_{02} - A_2 x_c$ are the volumes of actuator chambers, x_c and $\dot{x}_c$ are the position and velocity of the actuator. Terms of Q_1 and Q_2 represent flow through PDV orifices, Q_{L1} and Q_{L2} represent actuator leakages which can be formulated as follows:

$$Q_1 = \begin{cases} C_d w x_v \sqrt{\frac{2}{\rho}(P_s - P_1)} & x_v \geq 0 \\ C_d w x_v \sqrt{\frac{2}{\rho}(P_1 - P_T)} & x_v < 0 \end{cases} \tag{4}$$

$$Q_2 = \begin{cases} C_d w x_v \sqrt{\frac{2}{\rho}(P_2 - P_T)} & x_v \geq 0 \\ C_d w x_v \sqrt{\frac{2}{\rho}(P_s - P_2)} & x_v < 0 \end{cases} \tag{5}$$

$$Q_{L1} = +C_i(P_2 - P_1) - C_{e1}(P_1 - P_T) \tag{6}$$

$$Q_{L2} = -C_i(P_2 - P_1) - C_{e2}(P_2 - P_T) \tag{7}$$

with C_d the discharge coefficient, w the valve orifice area gradient, ρ the fluid density, P_s the supply pressure, P_T the tank pressure, P_1, P_2 the piston and rod side pressures of the cylinder, respectively, C_i the

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