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Robust tracking and vibration suppression for nonlinear two-inertia system via modified dynamic surface control with error constraint

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ABSTRACT

This paper proposes a modified dynamic surface control (DSC) for speed tracking and torsional vibration suppression for two-inertia systems with nonlinear friction. The proposed controller contains two parts: tracking controller and friction compensator. The tracking controller is designed by modifying dynamic surface control, which replaces the traditional first-order filter with a high-gain tracking differentiator (HGTD). Meanwhile, an improved prescribed performance function with error constraint is also presented and incorporated into DSC design. As for the friction compensator, the nonlinear nonsmooth friction is parameterized and then compensated using echo state neural networks (ESNs). The state observer with friction compensation is used to estimate unmeasurable load speed and torsional torque. The effectiveness of proposed control scheme is verified by simulation and experiment results.

1. Introduction

Electric actuators are widely used for the drive systems in various industrial applications, such as servo drive, robot-arm, crane system and automotive industry. The drive system is composed of a motor connected to a load through a stiffness shaft and flexible coupling, which can be modeled as a two-inertia system. This configuration may cause the torsional vibration and lead to the failure of the drive system in some cases. In order to achieve stable operation and reduce the speed vibration, it is necessary to eliminate the torsional vibration.

In order to achieve stable operation and reduce the speed vibration, many control algorithms have been proposed to damp the torsional vibration. Among them, a Proportional-Integral-Derivative (PID) control [1,2] is used for the speed control of a two-inertia system. Although this PID algorithm designed by using motor speed feedback is widely used in industry applications, it may cause decreased dynamic performance of drive system and may not be able to effectively suppress oscillations. To achieve highly precise control performance for a drive system, advanced control structures based on state feedbacks from state variables, such as motor speed, shaft torque, load speed and disturbance torque, are proposed in [3]. However, the state variables may not be used directly because these variables are difficult to measure in reality. Thus, the estimation and observation are needed to estimate these variables [4–9]. In many papers, Luenberger observers are applied to observe the unmeasured state variables for the linear system with small measurement noise and nonchangeable parameter [10]. However, the performance of Luenberger observer may be unsatisfactory due to the nonlinearity, measurement noise and uncertainty. In [7], the Kalman filter is proposed for a two-inertia system. It is utilized to estimate the shaft torque, load speed and load torque of the two-inertia system. A sliding-mode and optimized PID controller with a grey estimator is proposed, where the gray estimator is used to estimate torsional torque and load speed [11].

Furthermore, artificial intelligent techniques are also utilized to suppress torsional vibration of the two-inertia system [12–17]. A torsional vibration control approach is presented in [12], which is based on the additional feedback from the torsional torque and the load-side speed estimated by a neural network estimator. To estimate the motor-side speed for suppressing the torsional vibration, the neuro-fuzzy system is employed [13]. In [14], an adaptive sliding-mode neuro-fuzzy speed controller based on model reference adaptive structure is used to suppress torsional vibration. The modified fuzzy Luenberger observer based on the difference between the electromagnetic and estimated shaft torque [15] is reported.

The nonlinear nonsmooth friction should also be taken into account in the two-inertia system. To handle unknown nonlinearities, Recurrent Neural Networks (RNNs) and Fuzzy Logic systems (FLS) have been applied to approximate unknown nonlinearities owing to their nonlinear approximation and learning abilities [18–23]. Recently, an echo state networks (ESNs) is reported as a simplified RNNs in [24–26]. ESNs has the function approximation capability of RNNs, but

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requires simpler training than RNNs. Compared with RNNs, the ESNs can easily be trained without adjusting the weights between the input layer and the hidden layer, and the connection weights of the reservoir network are not altered during the training phase. However, it is noted that the transient convergence of aforementioned classical adaptive control schemes cannot be guaranteed (e.g., the overshoot, convergence rate cannot be quantitatively studied).

Recently, a new prescribed performance control (PPC) approach is proposed [27–30] to guarantee the convergence of output error to a predefined arbitrarily small region, where the convergence rate should be no less than a prespecified value. In [31], an improved prescribed performance function is proposed and incorporated into the controller design for the turntable servo system. An adaptive control with prescribed performance function is proposed for suspension systems to guarantee the error convergence rate, maximum overshoot and steady-state error within a predefined region [32]. However, to our best knowledge, the prescribed performance control has not yet been applied for the nonlinear two-inertia system.

In this paper, we propose a recursive feedback controller for the nonlinear two-inertia system with PPC. Inspired by [30], an improved prescribed performance function with error constraint is proposed and incorporated into the controller design. A recursive feedback controller is designed by modifying DSC technique from all state variables. In particular, the nonlinear friction of the two-inertia system is difficult to observe and compensate. A nonsmooth friction physics-model proposed in [33] is re-parameterized, which can capture the various friction dynamic effects such as Coulomb friction, Viscous friction, Static friction and Stribeck effect. Then, the unknown nonlinear nonsmooth friction force is approximated by ESNs, and compensated online. In order to obtain the state variables, the state observer with the estimated friction is employed to estimate the unmeasured load speed and torsional torque. Simulations and experiments based on a realistic test rig are utilized to validate the proposed control scheme. The main contributions of this paper can be summarized as follows.

1. An improved prescribed performance function is developed and incorporated into the control design of DSC for the nonlinear two-inertia system, and the tracking error is ensured within a prescribed region.
2. A new dynamic surface controller is designed by using the high-gain tracking differentiator (HGTD) to replace the first-order filter in virtual intermediate control signal. The use of HGTD can lead to better transient performance than first-order filter in the classical DSC.
3. The nonlinear nonsmooth friction model has been further parameterized, and then ESNs are used to successfully online approximate and compensate for these nonlinear nonsmooth dynamics.
4. The state observer with estimation of friction is designed to observe unmeasured load speed and torsional torque.

The rest of this paper is organized as follows. Section 2 provides a description of the nonlinear two-inertia system, the structure of ESNs, and an improved prescribed performance function. Section 3 designs a speed control by using the modified DSC and friction compensation. The stability of closed-loop system is given in Section 4. Section 5 presents simulation results. Section 6 is devoted to validate the proposed control scheme by experiments. Some conclusions are given in Section 7.

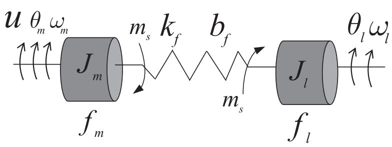

Fig. 1. Two-inertia system model (θ_m and θ_l are the motor position and the load position).

2. Problem formulation

2.1. Mathematical model of nonlinear two-inertia system

A typical two-inertia system is composed of a servo motor connected to a load through a stiffness shaft and flexible coupling (Fig. 1). The considered system could be described by the following state equation:

$$\frac{d}{dt}\begin{pmatrix}\omega_l\\ m_s\\ \omega_m\end{pmatrix}=\begin{pmatrix}\dfrac{-b_f}{J_l} & \dfrac{1}{J_l} & \dfrac{b_f}{J_m}\\ -k_f & 0 & k_f\\ \dfrac{b_f}{J_m} & \dfrac{1}{J_m} & \dfrac{-b_f}{J_m}\end{pmatrix}\begin{pmatrix}\omega_l\\ m_s\\ \omega_m\end{pmatrix}+\begin{pmatrix}0\\ 0\\ \frac{1}{J_m}\end{pmatrix}u$$
$$-\begin{pmatrix}\frac{f_l}{J_l}\\ 0\\ \frac{f_m}{J_m}\end{pmatrix}-\begin{pmatrix}\frac{\tau_l}{J_l}\\ 0\\ \frac{\tau_m}{J_m}\end{pmatrix}-\begin{pmatrix}\frac{\tilde{\Delta}_1(\omega_l)}{J_l}\\ 0\\ \frac{\tilde{\Delta}_2(\omega_m)}{J_m}\end{pmatrix} \qquad (1)$$

where ω_m and ω_l are the motor speed and load speed, J_m and J_l are the inertia of the motor and the load, f_m and f_l represent the nonlinear friction forces at the motor side and the load side, respectively. u is the motor electromagnetic torque, m_s is the shaft torque, k_f is the torsional stiffness coefficient, b_f is damping coefficient. τ_m and τ_l are the external disturbances of the motor side and the load side, $\tilde{\Delta}_1(\omega_l)$ and $\tilde{\Delta}_2(\omega_m)$ denote the parameters uncertainties.

Assumption 1. The reference input x_d, $\dot{x}_d$, and $\ddot{x}_d$, are continuous and bounded, that is, there exists a known compact set $\Omega_0=\{x_d,\dot{x}_d,\ddot{x}_d : x_d^2+\dot{x}_d^2+\ddot{x}_d^2\le\delta\}$, where δ is a positive constant.

Assumption 2. The disturbances τ_m, τ_l and parameters uncertainties $\tilde{\Delta}_1(\omega_l)$ and $\tilde{\Delta}_2(\omega_m)$ are bounded.

The control objective is to design a feedback control strategy which ensures: (i) the tracking error $e=X_d-WI$ converges to the prescribed performance boundary; (ii) vibration in the elastic shaft is damped; (iii) the friction is compensated; (iv) all signals in the closed-loop system are bounded.

2.2. Friction model structure

From Fig. 1, the two-inertia system mainly includes two friction forces: the motor side friction f_m and the load side friction f_l. Note that, the motor side friction force f_m is a function of the motor side velocity ω_m, while the load side friction f_l is a function of the load side velocity ω_l.

The combination of two-inertia system model (1) gives

$$J_m\dot{\omega}_m+J_l\dot{\omega}_l=u-f-d \qquad (2)$$

where $f=f_m+f_l$ defines the friction force of the two-inertia system, and $d=\tau_l+\tau_m+\tilde{\Delta}_1(\omega_l)+\tilde{\Delta}_2(\omega_m)$ denotes the external disturbance and uncertainties. Thus, they can be lumped as $F=-J_l\dot{\omega}_l+f+d$ and then referred to the uncertain dynamics to be compensated on the motor side [34].

Eq. (2) is used to show that the friction of two-inertia system can be lumped as an entire friction force. There are two reasons to model the entire friction force f as reflected on the motor side. First, it is not straightforward to compensate the friction separately on the load side. However, it is possible to compensate the effects of frictions entirely on the motor side. Second, from the