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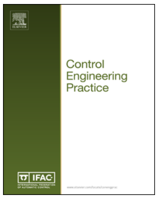

Modified dynamic surface approach with bias torque for multi-motor servomechanism

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ABSTRACT

This paper presents a modified neural dynamic surface control (DSC) with an adaptive bias torque for the multi-motor servomechanism (MMS) with backlash, friction and other disturbances. By introducing a continuous hybrid differentiator to replace the first-order filter in each step, a modified DSC is developed to improve the load tracking precision of MMS. However, when the MMS enters the backlash band, only DSC cannot guarantee the load tracking performance. Thus, an adaptive bias torque is firstly proposed based on the prescribed performance function technique to compensate the backlash nonlinearity and guarantee the load tracking performance of MMS. In addition, the unknown dynamics including the friction and other disturbances are approximated by using wavelet echo state networks where the weights are all updated online. By means of Lyapunov stability theory, the semi-globally uniformly ultimately bounded (SGUUB) property of all signals in the closed-loop system is proved. Finally, simulations and experimental results based on a four-motor servomechanism are presented to show the effectiveness of the proposed approach.

1. Introduction

Over the past decades, the multi-motor servomechanism (MMS) has been widely used as a result of an increasing requirement for the large inertia and power servo systems such as the radar antenna system and the naval gun control system. However, there are diverse nonlinearities such as backlash, friction and other disturbances which influence the motion accuracy of the MMS. Among these nonlinearities, the backlash appearing in the transmission device is the main factor which will degrade the MMS performance and even make the system chattering. To reduce the effects of backlash and achieve highly precise motion control, several compensation methods have been proposed, e.g., optimal control (Tao et al., 2001), switching control (Khan et al., 2010), liner feedback control (Huang and Cai, 2000) and redundancy control (Chang and Tsai, 1993).

The constant bias torque (Zhao et al., 2007; Zhao and Hu, 2005), a specific method for the redundancy control system, has been already proposed to compensate the backlash nonlinearity for the dual-motor servomechanism (DMS). This bias torque method can compensate the backlash nonlinearity by implementing two bias voltages which are equal in magnitude and opposite in direction on dual motors. With regards to the time varying bias torque, Gawronski et al. (2001) discussed the regulation strategy of the bias torque and further proposed a bias torque controller which was proportional to the load. Considering the relationship between the bias torque with the load velocity and acceleration, Liang and Fang (2010) designed a real-time bias torque compensation controller for the DMS to eliminate the backlash nonlinearity. Although the above-mentioned methods have achieved fair control results, the parameters selection of the bias torque was mainly based on the experimental trial-and-error rather than the theoretical analysis, and the energy consumption of the bias torque was rarely concerned.

Recently, to guarantee both the transient and steady-state performance of tracking error, a significant accomplishment named prescribed performance function (PPF) was put forward by Bechlioulis and Rovithakis (2008, 2009) where the key idea is to provide an error transformation capable of transforming the original “constrained” nonlinear system into an equivalent “unconstrained” one. Thus, the tracking error is contained within a prescribed error boundary, provided that the stability of the closed-loop system is guaranteed. Since the constraint technique proposed by Bechlioulis and Rovithakis (2008) had a singularity problem in the inverse transformation function, Han and Lee (2013a) presented a simpler and more efficient error transformation method to avoid this problem. In the application of this technique, Na et al. (2014) proposed an adaptive control for a class

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of nonlinear mechanisms with guaranteed transient and steady-state performances; Kostarigka et al. (2013) designed a full state feedback controller to achieve prescribed performance tracking for flexible joint robot systems without any approximator of nonlinearity. Inspired by the above results, the PPF technique will be used to design a novel bias torque controller to compensate the backlash nonlinearity in an efficient way.

Meanwhile, in order to achieve highly precise tracking control of motion systems, the backstepping methodology (Kanellakopoulos et al., 1990) has attracted a significant attention because of its recursive and systematic design procedure. However, with the increase of system order, the backstepping design procedure leads to an inevitable problem of “explosion of complexity” caused by the repeated differentiations of the virtual controller (Krstic et al., 1995). Fortunately, DSC was proposed by Swaroop et al. (2000) to handle this problem by introducing a first-order filter of the synthetic virtual control law at each step of the backstepping design procedure. Zhang et al. (2010) extended this DSC to handle the partially unknown states of the servo mechanisms. In Sung Jin et al. (2006), self-recurrent wavelet neural networks were incorporated into the adaptive DSC design to handle the model uncertainty of flexible-joint robots system. In Wu et al. (2014), a disturbance observer was further combined with a dynamic surface control algorithm to compensate for the friction and other uncertainties. In addition, Han and Lee (2013b) presented a dynamic surface sliding mode control using fuzzy wavelet echo state network for a class of strict feedback dynamic systems in the presence of the dead-zone and friction. As the filtering error was not considered in the aforementioned works, this paper will employ a continuous hybrid differentiator (CHD) to substitute the first-order filter of the DSC in each step to improve the tracking performance for MMS.

In this paper, a modified neural dynamic surface control with an adaptive bias torque is proposed to achieve the load tracking for the MMS with backlash, friction and other disturbances. With the unknown dynamics handled by wavelet echo state networks (WESNs), a modified DSC approach is realized by incorporating the CHD to guarantee the load tracking performance of MMS. However, when the MMS motion enters the backlash band, only DSC cannot guarantee the load tracking performance since the load has no contact with the motors. To overcome this problem, a PPF based bias torque is added to the DSC for compensating the backlash nonlinearity and further guaranteeing the load tracking performance of MMS. Comparative results revealed that the proposed method can not only eliminate the vibrations caused by the backlash nonlinearity but also achieve a better tracking performance than the other control techniques. The main contributions of this paper are listed as follows:

1. Different from the traditional backlash compensation methods, the PPF technique is utilized to transform the backlash compensation problem into an error stabilization problem. Then, the proposed bias torque controller is designed to stabilize the transformed error system, which can compensate the backlash nonlinearity and guarantee the load tracking performance.
2. To the best of our knowledge, this paper firstly proposes an adaptive bias torque design for backlash compensation rather than the traditional bias torque which was designed mainly based on the experimental trial-and-error method. As the proposed bias torque is a switching controller which only works in the backlash band, its energy consumption is largely reduced.
3. With the unknown friction and disturbance approximated by WESNs, a modified DSC approach is developed to obtain a superior tracking performance by incorporating the CHD which has a more precise virtual differentiable control signal than the widely used first-order filter.

This paper is organized as follows. Section 2 begins with a description of MMS with unknown nonlinearities. In Section 3, the modified DSC and the proposed bias torque are designed, where the closed-loop system stability is also analyzed. Section 4 presents the simulation and experimental results to validate the effectiveness of our control method. Finally, we give conclusions in Section 5.

2. Problem statement and preliminaries

This section begins with presenting the mathematic model of the MMS. Then, some preliminaries about the backlash model and WESN approximators are given. Finally, based on the continuously differential backlash model, the state space representation of MMS is deduced and its control objective is also established. In addition, to facilitate the system analysis, a four-motor servomechanism is adopted in the next subsection.

2.1. Multi-motor driving servomechanism

The experimental equipment of a four-motor servomechanism is shown in Fig. 1 with its transmission gears shown in Fig. 2.

The mechanical dynamics of the MMS is presented by

$$\begin{cases} J_i\ddot{\theta}_i + T_{fi} + T_{di} + T_i = u_i + \omega_i \\ J_m\ddot{\theta}_m + T_{fm} + T_{dm} = \sum\limits_{i=1}^{4} T_i \end{cases} \tag{1}$$

where θ_i and θ_m $(i = 1, 2, 3, 4)$ are the angular positions of the motors and the load respectively; J_i and J_m represent the inertias of the motors and the load respectively; u_i is the control input and ω_i is the bias torque; T_{fi} and T_{di} denote the friction and other disturbances in the motor side, respectively; T_{fm} and T_{dm} denote the friction and disturbances in the load side, respectively; T_i denotes the transmission torque between the motor and the load.

Affected by the backlash (Tao et al., 2001), the motor-load transmission torque T_i is expressed as

$$T_i = kf(z_i(t)) + cf(\dot{z}_i(t)) \tag{2}$$

where $k > 0$ is the stiffness coefficient, $c > 0$ is the damping coefficient and $f(z_i(t))$ is expressed by a dead-zone model as

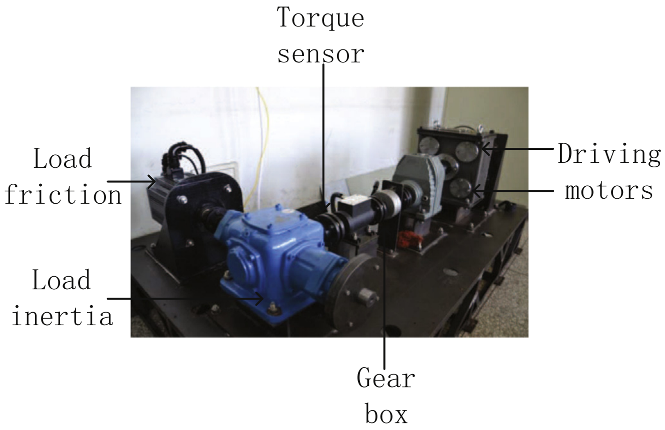

Fig. 1. Test rig of four-motor servomechanism.