Control Engineering Practice 53 (2016) 1–13

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Proportional-integral based fuzzy sliding mode control of the milling head

Pengbing Zhao [a,*], Yaoyao Shi [b], Jin Huang [a]

[a] *The Key Laboratory of Electronic Equipment Structure Design, Ministry of Education, Xidian University, Xi'an, Shaanxi 710071, China*
[b] *The Key Laboratory of Contemporary Design and Integrated Manufacturing Technology Ministry of Education, Northwestern Polytechnical University, Xi'an, Shaanxi 710072, China*

ARTICLE INFO

Article history:
Received 24 November 2015
Received in revised form
19 April 2016
Accepted 19 April 2016
Available online 26 April 2016

Keywords:
A-axis
Positioning control
Parameters adaptation
Sliding mode control
Proportional-integral control

ABSTRACT

A-axis (that is, the milling head) is an essential assembly in the five-axis CNC machine tools, positioning precision of which directly affects the machining accuracy and surface qualities of the processed parts. Considering the influence of nonlinear friction and uncertain cutting force on the control precision of the *A*-axis, a novel fuzzy sliding mode control (FSMC) based on the proportional-integral (PI) control is designed according to the parameters adaptation. Main idea of the control scheme is employing the fuzzy systems to approximate the unknown nonlinear functions and adopting the PI control to eliminate the input chattering. Simulation analyses and experimental results illustrate that the designed control strategy is robust to the uncertain load and the parameters perturbation.

1. Introduction

The five-axis CNC machine tools are widely applied in manufacturing the parts of aeronautics and astronautics, the turbine wheels and some special molds which typically have the complicated geometries (Harik, Gong, & Bernard, 2013; Zhou, Chen, & Yang, 2015). As the essential component in five-axis CNC machine tools, the *A*-axis (that is, the milling head) has the characteristics of structural complexity, components diversity, transmission compactness and weak stiffness (Pengbing & Yaoyao, 2014). Research of the *A*-axis focuses on how to improve the tracking and positioning precision, increase the drive torque and enhance the system stiffness (Bi et al., 2015). Recently, all aspects of the system performance have been improved, but there are almost no cases that can take all the indicators into consideration, therefore, it is important to improve the positioning precision while enhance the driving torque of the existing *A*-axis (Zhao & Shi, 2014).

The *A*-axis researched in this paper is mainly based on the worm gear transmission. Compared with the rolling engagement of the ordinary gear transmission, engagement of the worm gear is pure sliding. Thus, sliding friction influences significantly on the positioning precision of the *A*-axis, generally, friction is considered to be a kind of interference for the control system. In addition, the uncertain cutting load during the machining process impacts the tracking precision, thus, surface qualities of the machined parts will be deteriorated. To maintain the perfect dynamic performance of the *A*-axis during the milling process, a controller that is robust to the nonlinear friction and external disturbance needs to be constructed.

The sliding mode control (SMC) has a complete self-adaptability to the uncertainties and external disturbances (Utkin, Guldner, Shi, & Mode, 2009), however, the input chattering of the SMC will undermine the control precision, increase the energy consumption, stimulate the unmodeled dynamics, deteriorate the system function and even damage the controller (Boiko, 2013; El-Sousy, 2013; Shtessel, Edwards, & Fridman, 2014). Therefore, the most important problem in designing SMC is how to eliminate the chattering, and the commonly used methods are the quasi-SMC and the approaching laws (Chakrabarty & Bandyopadhyay, 2015; Huang, Liao, Chen, & Yan, 2012; Wang, Jia, & Dong, 2013; Zhao, Qiao, & Wu, 2013). However, these methods can only reduce the input chattering to a certain extent, to further eliminate the chattering, many investigators introduce the artificial intelligence into the SMC. A fuzzy sliding mode control (FSMC) algorithm based on the boundary layer is presented in Saghafinia, Ping, and Uddin (2014), in which a fuzzy system is used to eliminate the chattering in spite of the system uncertainties. A SMC based on the adaptive neural network is designed in Zou and Lei (2015) to treat the model uncertainties and external disturbances of a stable inertial platform. A backstepping SMC is proposed in Dong and Tang (2014) to inhibit the vibration of a flexible ball screw drives induced by the time-varying parametric uncertainties and external

---

[*] Corresponding author.
E-mail address: zhpb83@163.com (P. Zhao).

http://dx.doi.org/10.1016/j.conengprac.2016.04.012
0967-0661/

disturbances. A novel adaptive backstepping SMC with fuzzy monitoring strategy is proposed in Song and Sun (2014) for the tracking control of the nonlinear mechanical system. An adaptive SMC with the recurrent radial basis function network (RRBFN) is proposed in El-Sousy (2013) for the indirect field orientation control of an induction motor and the RRBFN is employed as an uncertainty observer. In Hwang, Chiang, and Yeh (2014), trajectory tracking of the under-actuated nonlinear dynamic system with uncertainty is tackled by an adaptive fuzzy hierarchical SMC. An intelligent second-order SMC using a wavelet fuzzy neural network with an asymmetric membership function estimator is proposed in Lin, Hung, and Ruan (2014) to control a six-phase permanent magnet synchronous motor for an electric power steering system. An adaptive controller using a fuzzy compensator for MEMS triaxial gyroscope is presented in Fei and Zhou (2012), which can well compensate the model uncertainties and the external disturbances. An adaptive controller of MEMS gyroscope using global fast terminal SMC and fuzzy neural network is presented in Fei and Yan (2014). A robust adaptive SMC using the RBF neural network for a class of time varying system in the presence of model uncertainties and external disturbance is proposed in Fei and Ding (2012).

As for the fuzzy system and the fuzzy control, an observer-based adaptive controller using a simplified type-II fuzzy neural network and a three dimensional type-II membership function is investigated in Mohammadzadeh and Hashemzadeh (2015). A novel fuzzy system based strategy for modeling both rate-independent and rate-dependent hysteresis in the piezoelectric actuator is proposed in Li, Yan, and Ge (2013). An adaptive fuzzy backstepping control and H_∞ performance analysis for a class of nonlinear systems with sampled and delayed measurements are investigated in Wang, Zhang, Qiu, and Gao (2015). A novel composite control based on fuzzy system and disturbance observer is proposed in Xu, Shi, and Yang (2015) for the uncertain nonlinear systems with actuator saturation and external disturbances. In Tong, Sui, and Li (2015), a tracking error constrained fuzzy output-feedback dynamic surface control scheme is proposed for a class of uncertain MIMO nonlinear systems. H_∞ controllers of interval type-II T–S fuzzy systems via dynamic output feedback control are designed in Zhao, Xiao, Sheng, and Wang (2015). In Wang, Wang, and Chai (2009), an adaptive fuzzy system is employed to approximate the nonlinear friction and estimation of the friction is applied in PD control to enhance the control performance.

Considering the nonlinear dynamics and the uncertain cutting load during the machining process of the *A*-axis, a novel FSMC based on PI control is proposed. Parameters uncertainty of the *A*-axis and external disturbance during the milling process is approximated by the fuzzy systems. By replacing the switching part of the traditional sliding mode control (TSMC) with the PI controller, input chattering of the TSMC is eliminated. Stability and convergence of the control system can be guaranteed by the Lyapunov theory and Barbalat Lemma.

Simulation analyses and experimental verifications illustrate that the designed control algorithm is robust to the uncertain external load and the system parameters perturbation. Compared with the conventional PID control, the designed FSMC can undermine the topping phenomenon and the deadzone in the displacement and speed tracking respectively, and compared with the TSMC, the FSMC based on the PI control not only can improve the positioning and tracking precision, but also can reduce the input chattering.

The rest of the paper is organized as follows: mechanical structure, control system and mathematical model of the *A*-axis are constructed in Section 2. In Section 3, basic principles of the FSMC based on PI control is elaborated. Simulation and experimental verification are carried out in Section 4. In Section 5, we draw the conclusions.

2. Mechanical structure, control system and mathematical model of the *A*-axis

The *A*-axis with high-power, high-torque and high stiffness used for processing the titanium alloy, superalloy and other difficult to machine materials is illustrated in Fig. 1. Backlash of the drive mechanism can be adjusted by the dual lead worm gear, and with a high-resolution encoder mounted on the right side of the shaft, the *A*-axis can be controlled in a closed-loop system. The hydraulic locking mechanism installed on the left side of the shaft can make the motorized spindle locked at any position within the angle range [−120°, 30°] (Pengbing & Yaoyao, 2014; Zhao & Shi, 2014).

Principle of the *A*-axis control system is shown in Fig. 2, and parameters of the AC servo motor, the motorized spindle and the angular encoder are illustrated in Tables 1–3 respectively.

As part of the control system, an industrial computer (ADVANTECH IPC-610-H) is used as the host computer which is utilized to edit and execute the control programs, achieve human–computer interaction and control various motions of the *A*-axis via the motion controller. PMAC2A PC-104 is adopted as the slave computer which is used to drive the AC motor to complete the desired motions and monitor the change of each state variable. Edit the control programs with the C++ language, which includes the traditional PID control, the TSMC and the FSMC, conversion programs of the A/D and D/A, the sampling program and

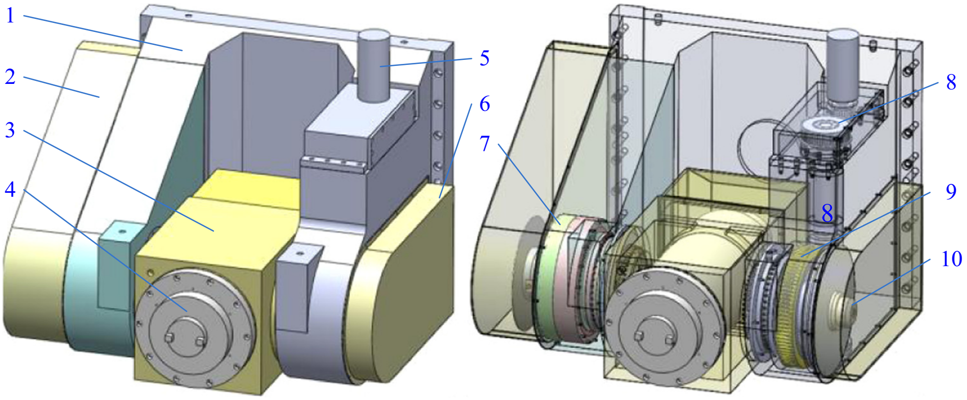

Fig. 1. Mechanical structure of the *A*-axis. 1- Support; 2-Left shield; 3-Spindle box; 4-Motorized spindle; 5-Servomotor; 6-Right shield; 7-Lockingmechanism; 8-Pulleys; 9-Wormgear; 10-Encoder.