ISA Transactions ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

ISA Transactions

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

Research article

Wire rope tension control of hoisting systems using a robust nonlinear adaptive backstepping control scheme

Zhen-Cai Zhu [a,b], Xiang Li [a,b,*], Gang Shen [a,b], Wei-Dong Zhu [c]

[a] School of Mechatronic Engineering, China University of Mining and Technology, Xuzhou 221116, China
[b] Jiangsu Key Laboratory of Mine Mechanical and Electrical Equipment, China University of Mining and Technology, Xuzhou 221116, China
[c] Department of Mechanical Engineering, University of Maryland, Baltimore County, Baltimore, MD 21250, USA

ARTICLE INFO

Article history:
Received 15 March 2017
Received in revised form
2 October 2017
Accepted 13 November 2017

Keywords:
Double-rope winding hoisting system
Robust nonlinear adaptive backstepping controller
Disturbance observer
External disturbances
Parameter uncertainties

ABSTRACT

This paper concerns wire rope tension control of a double-rope winding hoisting system (DRWHS), which consists of a hoisting system employed to realize a transportation function and an electro-hydraulic servo system utilized to adjust wire rope tensions. A dynamic model of the DRWHS is developed in which parameter uncertainties and external disturbances are considered. A comparison between simulation results using the dynamic model and experimental results using a double-rope winding hoisting experimental system is given in order to demonstrate accuracy of the dynamic model. In order to improve the wire rope tension coordination control performance of the DRWHS, a robust nonlinear adaptive backstepping controller (RNABC) combined with a nonlinear disturbance observer (NDO) is proposed. Main features of the proposed combined controller are: (1) using the RNABC to adjust wire rope tensions with consideration of parameter uncertainties, whose parameters are designed online by adaptive laws derived from Lyapunov stability theory to guarantee the control performance and stability of the closed-loop system; and (2) introducing the NDO to deal with uncertain external disturbances. In order to demonstrate feasibility and effectiveness of the proposed controller, experimental studies have been conducted on the DRWHS controlled by an xPC rapid prototyping system. Experimental results verify that the proposed controller exhibits excellent performance on wire rope tension coordination control compared with a conventional proportional-integral (PI) controller and adaptive backstepping controller.

1. Introduction

Mine hoisting systems with a large capacity and velocity used for ultra-deep mines are widely required since exploration on ultra-deep ($>$ 1000 m) mines has been the development trend with increasing consumption of shallow (500–800 m) and deep (800–1000 m) coal resources [1]. However, conventional mine hoisting systems, including single-rope winding hoisting systems [2] and multi-rope friction hoisting systems [3], have significant limitations for ultra-deep coal mines. In order to realize ultra-deep mine hoisting, Blair multi-rope hoisting systems are employed in ultra-deep mines in South Africa [4]. Based on the multi-rope winding hoisting systems, a double-rope winding hoisting system (DRWHS) is presented [5]. A conveyance is hoisted by two wire ropes that are driven by a twin-drum to ensure that winding velocities of the two wire ropes are the same, which shows that the DRWHS can not only overcome the issue of decreasing hoisting capacity but also the problem that sizes of wire ropes and drums are overwhelmingly large [6,7].

With increasing numbers of wire ropes and winding drums, hoisting of two wire ropes would not be synchronous, with consideration of factors such as differences in features, dynamic deformations, and winding errors of wire ropes, which result in a sharp increase in tension difference. How to improve the tension coordination performance of a DRWHS has been of great interest in industry. The most widely used is a hydraulic automatic tension balance device, which contains two hydraulic cylinders fixed between two wire ropes and a conveyance. While there is difference in tensions of two wire ropes, high-pressure oil in corresponding hydraulic cylinders is squeezed into another hydraulic cylinder through connection pipes due to the theory of communicating vessels, which keeps a new balance of wire rope tensions [8]. However, the above-mentioned automatic tension balance device is passively regulated. What is worse is that the size and weight of the automatic tension balance device are huge when the capacity and velocity of a mining hoisting system are large, which reduces the hoisting capacity of the system. Moreover, hydraulic oil need

---

* Correspondence to: School of Mechatronic Engineering, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China.
E-mail address: lixiang_nn@126.com (X. Li).

https://doi.org/10.1016/j.isatra.2017.11.007

Please cite this article as: Zhu Z-C, et al. Wire rope tension control of hoisting systems using a robust nonlinear adaptive backstepping control scheme. ISA Transactions (2017), https://doi.org/10.1016/j.isatra.2017.11.007

to supplement on time to ensure effectiveness of the hydraulic automatic tension balance device due to leak of the two hydraulic cylinders, which is complicated and takes much working time.

In order to overcome issues with the hydraulic automatic tension balance device, a modified DRWHS, including two movable headgear sheaves and two hydraulic cylinders, is designed. Wire rope tensions can be proactively adjusted by the two movable headgear sheaves that are driven by the two hydraulic cylinders. Because the two hydraulic cylinders are between the headgear sheaves and head frame instead of two wire ropes and the conveyance, the hoisting capacity of the DRWHS would not be reduced due to increase of size and weight of the two hydraulic cylinders. Moreover, the two hydraulic cylinders are supplied oil by a hydraulic power pack and do not need to supplement on time. Therefore, critical problems to realize wire rope tension control of hoisting systems are to design displacements of the two hydraulic cylinders and guarantee tracking performance of the designed displacements.

The tension difference between two wire ropes of the DRWHS can be partially reduce using a conventional proportional-integral (PI) controller [9] and backstepping controller [10]. However, the DWRHS is a complex nonlinear system with parameter uncertainties such as servo-valve and hydraulic actuator dynamics [11], stiffness and damping differences of wire ropes [12], and size differences between drums and sheaves [13]; and external disturbances such as friction among drums, sheaves [14] and wire ropes [15], and friction between rod and bore of hydraulic cylinders [16]. All these factors make it difficult to obtain satisfactory tension coordination performance with the conventional PI controller and backstepping controller because these two controllers cannot adjust their control parameters in consideration of parameter uncertainties and external disturbances of the DRWHS.

In order to reduce effects of above-mentioned parameter uncertainties and external disturbances of the DRWHS, many control approaches, including adaptive sliding mode control [17], adaptive backstepping control [18], and a nonlinear disturbance observer (NDO) [19], are introduced. A nonlinear adaptive backstepping controller was employed to improve the tension coordination performance, which estimates uncertain parameters through adaptive laws derived by guarantying stability of the DRWHS [20,21]. However, external disturbances that usually exist in nonlinear systems are not taken into account during the controllers' design process. To address these problems, a novel approach to design a robust adaptive backstepping excitation controller was employed to investigate external disturbances and parameter uncertainties, where external disturbances were dealt with by designing constant parameters [22]. Nevertheless, since the designed constant parameters in [22] were controlled by a sign function, which is obtained by a step function, there would be a chattering phenomenon when external disturbances were overwhelmingly large.

Thus, the NDO was utilized to weaken impacts of external disturbances by estimating unknown external disturbances [23]. Due to advantages of the NDO, several compound control methods combined with the adaptive backstepping controller and NDO have been proposed for nonlinear systems with consideration of parameter uncertainties and external disturbances. A novel adaptive backstepping controller combined with a NDO was presented to improve high precision of a servo manipulation, which effectively accommodated model uncertainties and external disturbances [24]. With consideration of parameter uncertainties, unmodeled dynamics, and environmental disturbances, a disturbance observer-based adaptive nonlinear controller was proposed that comprises a NDO and an adaptive backstepping controller [25].

The main contribution of this work is to design a combined controller that consists of a robust nonlinear adaptive backstepping controller (RNABC) and a NDO for wire rope tension coordination control of the DRWHS, and its implementation in a double-rope winding hoisting experimental system. The NDO composed of design parameters and state variables is employed to cope with uncertain external disturbances of the DRWHS. The RNABC combined with the designed NDO, which is composed of design parameters, estimated external disturbances, state variables, and time derivative of state variables are then employed to obtain desired displacements of the two hydraulic cylinders for wire rope tension coordination control and the control voltage for displacement tracking control, which accounts for parameter uncertainties and external disturbances. Stability analysis of the DRWHS with the proposed controller is proved based on Lyapunov function. To test the proposed compound control strategy, experiments are conducted on a double-rope winding hoisting experimental system. Experimental results show higher performance of the proposed controller in comparison with the conventional PI controller and adaptive backstepping controller.

This paper is organized as follows. Section 2 presents a setup of a nonlinear dynamic model of the DRWHS. The proposed controller design procedure and its theoretical results are described in Section 3. A double-rope winding hoisting experimental system is introduced in Section 4 and experimental results are conducted there on the double-rope winding hoisting experimental system, which demonstrates effectiveness of the proposed controller. Section 5 gives conclusions of the paper.

2. Dynamic model of the DRWHS

Fig. 1(a) shows constitution of the DRWHS with movable headgear sheaves, where two hydraulic cylinders are fixed under the movable headgear sheaves to adjust wire rope tensions by controlling displacements of the two hydraulic cylinders. Because the hydraulic cylinders are no longer attached between the wire ropes and conveyance, size of the hydraulic cylinders has little impact on hoisting capacity of the DRWHS. The schematic of the DRWHS is presented in Fig. 3(b), which can be divided into two parts: a hoisting system and an electro-hydraulic servo system.

2.1. Dynamic model of the hoisting system

Main parameters are described in Fig. 1(b), where $l_{ri}(i = 1, 2)$ are rotation lengths of the twin-drum, $l_{ci}(i = 1, 2)$ are lengths of two catenaries in the process of hoisting or lowering the conveyance, $l_{hi}(i = 1, 2)$ are lengths of two vertical hoisting wire ropes in the process of hoisting or lowering the conveyance, $u_i(i = 1, 2)$ are displacements of two movable headgear sheaves, φ- angle between two catenaries and the horizontal plane, $a_i(i = 1, 2)$ are horizontal distances between junctions of two wire ropes and the conveyance and the barycenter of the conveyance, $b_i(i = 1, 2)$ are longitudinal distances between top and bottom surfaces of the conveyance and the barycenter of the conveyance, $k_{si}(i = 1, 2, 3, 4)$ are lateral equivalent stiffness of four pairs of the spring-damper model, and $c_{si}(i = 1, 2, 3, 4)$ are lateral equivalent damping coefficients of four pairs of the spring-damper model.

In this work, the upward movement is regarded as the positive direction, the lengths of two vertical hoisting wire ropes in the process of hoisting or lowering the conveyance can be expressed as follows:

$$l_{h1} = l_{h10} - l_{r1} - u_1 \sin(\alpha) \tag{1}$$

$$l_{h2} = l_{h20} - l_{r2} - u_2 \sin(\alpha) \tag{2}$$

where l_{h10} and l_{h20} are initial lengths of two vertical hoisting wire ropes.

Please cite this article as: Zhu Z-C, et al. Wire rope tension control of hoisting systems using a robust nonlinear adaptive backstepping control scheme. ISA Transactions (2017), https://doi.org/10.1016/j.isatra.2017.11.007