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Research article

Decentralized coordinated control of elastic web winding systems without tension sensor

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ABSTRACT

In elastic web winding systems, precise regulation of web tension in each span is critical to ensure final product quality, and to achieve low cost by reducing the occurrence of web break or fold. Generally, web winding systems use load cells or swing rolls as tension sensors, which add cost, reduce system reliability and increase the difficulty of control. In this paper, a decentralized coordinated control scheme with tension observers is designed for a three-motor web-winding system. First, two tension observers are proposed to estimate the unwinding and winding tension. The designed observers consider the essential dynamic, radius, and inertial variation effects and only require the modest computational effort. Then, using the estimated tensions as feedback signals, a robust decentralized coordinated controller is adopted to reduce the interaction between subsystems. Asymptotic stabilities of the observer error dynamics and the closed-loop winding systems are demonstrated via Lyapunov stability theory. The observer gains and the controller gains can be obtained by solving matrix inequalities. Finally, some simulations and experiments are performed on a paper winding setup to test the performance of the designed observers and the observer-base DCC method, respectively.

1. Introduction

Systems transporting or processing paper, textile, films, strip or metal foils from one roll to another are very common in the industry. The main objective in industrial applications is to maintain the web tension in the entire processing line under expected web speeds. Otherwise, insufficient tension or excess tension may result in a web wrinkle or break, which directly affects final product quality and productivity. Traditionally, most tension control strategies are sensor-based control which depend on contact tension sensors such as load cells or swing rolls to measure web tensions [1]. However, such tension transducers not only require frequent maintenance and calibration, but also decrease system reliability and add complexity to web runs [1,2]. Tension observer provides a non-contacting effective solution to measure tension [1]. It relies on the dynamical model of a web-winding system and the commonly available measurements, e.g., winder radii, velocities, torques. Furthermore, the observer algorithms are typically implemented by control code, which make them more reliable than sensors and can be easily modified for different web materials or web winding systems. Therefore, observer is the natural option to replace the sensor.

An observer design is based on a mathematical model of the web winding system [3]. Hence, developing an accurate dynamics is critical to achieve good performance of an observer. Early studies about web-winding system modeling can be found in Ref. [4–8]. In Ref. [4], mathematical relationships between sheet tension and roll surface speed under the steady-state condition and transient condition are established. A mathematical model for a pliable material handling machine is developed in Ref. [5]; this model adopts a set of nonlinear ordinary differential equations to describe the dynamic behaviors of web tension and velocity, which forms the basis for the subsequent work on the winding system modeling. By neglecting the variations of rolls' radius and inertia, a model is built from the equations describing tension dynamics based on the fundamental of web behavior and the dynamics of drive machinery in Ref. [6]. In practice, the rolls' radii may vary greatly during the complete process. A distributed parameter model of the lateral dynamic behavior of a moving web is proposed in Ref. [7]. An overview of dynamic analysis and control of the lateral and longitudinal motions of a moving web are discussed in Ref. [8]. In Ref. [9], Given that the radius and inertia of each roll are slow time-varying, a linearized model is built using the model of the velocity of each roll and the equation of tension between two consecutive rolls. This model has been used as the basis for some controllers design, for e.g., a robust centralized H_∞ control [9], robust H_∞ control considering bounded

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parametric uncertainty [10], two-degrees-of-freedom (2DOF) H_∞ [11] and H_2 [12] controls, decentralized H_∞ control with or without integrators [13], decentralized robust control [14], overlapping decentralized control [15] and semi-decentralized control with or without overlapping [16]. Based on the model developed in Ref. [9] and assuming that there are no viscous damping terms in the rolls and motors, a robust load-sharing control scheme with application to a bridle roll system is discussed in Ref. [17]. A modified model considering the variations of radius and inertia is developed in Ref. [18], based on this model, some control schemes, such as decentralized control, output regulation control, sliding-mode control, adaptive PI control, adaptive H_∞ control are found in Ref. [18–22]. In Ref. [23], a mathematical model of a filament winding system is derived based on the dynamic equations of the driving motor and equations of the filament behaviors; a neural network controller is designed to minimize the interaction between the motor speed and the filament tension and to maximize the control precision of the overall system. A neuro-fuzzy control and a genetic fuzzy control for tandem rolling mills are proposed in Ref. [24]. A model for the looper and tension system is developed by considering the disturbances and unmodeled dynamics in Ref. [25]; based on the model, a disturbance decoupling (ADD) control method is studied.

Designs of observer and observer-based controller have been recognized as important research areas for web winding systems. Some relevant contributions have been published. In Ref. [26], an observer designed as a low-pass differentiator is proposed based on a linearized model of web machine. Effects of the variations in roll radii and inertias are not considered and friction is neglected. In Ref. [27], an observer-based decoupled state feedback controller is proposed for an aluminum strip processing line; a Luenberger observer is constructed to estimate both tension and velocity. In the case of the processing line with some parameters variation (e.g. radius and inertia of rolls, elasticity modulus), this observer cannot ensure good estimation accuracy. Since Kalman filter (KF) algorithm can ensure good estimation accuracy for nonlinear system with high measurement noises, it is introduced to estimate web tension in Refs. [28,29]. However, KF algorithm demands very high computational resources to process the related matrix math, resulting in long update times [3,30], which means that the KF algorithm is generally not acceptable for practical industrial applications. A first-order tension observer is designed for web winding system with air entrainment in Ref. [31]; the maximum observer error is derived in the general case, in the presence of time-varying radii and inertias of rolls, and motor parameter uncertainties. Based on the observer designed in Ref. [31], a robust control scheme are proposed in Ref. [32]. A sensorless sheet tension control for the dry end of a paper machine is presented and evaluated in Ref. [33]. This tension estimation algorithm only uses conventional motor and control signals, and does not include the inertial torque component. However, the estimation algorithm is valid only when the paper machine operates at essentially constant speed. To ensure good estimation accuracy even in the presence of rapid change in the speed and reel torque, an integrated sensorless tension control and sheet elasticity modulus estimation algorithm are developed in Ref. [34]. According to the expert reasoning strategy, a two-stage coupling intelligent tension observer is proposed in Ref. [35]. Based on the model developed in Refs. [9] and [18], respectively, two kind of nonlinear tension observers with similar structures are investigated in Refs. [1] and [20]; by appropriate choosing of observer gains, the observer error dynamics is globally exponentially stable. But it should be noted that the stable conditions given in this two literature are conservative, and the quantitative computation method of observer gains are also not given.

All the control methods mentioned above either are centralized control or are decentralized control. Generally, the centralized control is applied to the reduced-size winding systems containing no more than three motors [4,9,12], [31–34]. Since most industrial web-winding systems are generally large-scale systems, it is inconvenient to employ centralized control. Decentralized control method provides a simple means to control the entire systems by designing a controller for each subsystem without information exchange between subsystems [14,18–21,27]. However, ignoring the interactions between subsystems results in that decentralized control has poor ability to reject the disturbances introduced by the adjacent subsystems. Hence, some alternative solutions are provided in some literature. In Refs. [10,11,13,16], some semi-decentralized control strategies are proposed by splitting the whole system into several parts: each part contains a few motors (usually three motors) and is controlled independently by one controller. In Refs. [11,15,16], semi-decentralized control methods with overlapping are introduced to further improve system anti-interference capability.

In this paper, an observer-based DCC is designed for a three-motor web winding system, which can be scaled to web winding systems with an arbitrary number of motors. First, based on the dynamic model derived in Ref. [18], a nonlinear tension observer is introduced. A sufficient condition for asymptotic stability of the observer error dynamics is derived in terms of a bilinear matrix inequality (BMI). Compared with the tension observer presented in Refs. [1] and [20], the proposed observer has less conservativeness and higher estimation accuracy. Moreover, the observer gains can be calculated directly by solving BMI. Then, a variation dynamics at the forced equilibrium is presented. Based on the variation model and using the estimated tension as feedback signals, a DCC scheme is discussed. Within the limited increase the complexity of the decentralized controller, the proposed DCC can effectively reduce the coupling-disturbance between subsystems. General asymptotically stable condition of the closed-loop system with different DCC is given. Finally, the performances of the tension observer and the proposed observer-based DCC are evaluated by both simulation and experimental tests.

The remainder of the paper is organized as follows. Mathematical model of a web-winding system and some preliminaries are given in Section 2. In Section 3, the tension observer design are described. In Section 4, an observer-based DCC is introduced. Results of simulation and experiments are shown and discussed in Section 5. Section 6 gives the conclusions of this paper.

2. Model description and preliminaries

The system under study is shown in Fig. 1. It contains three active rolls, two infrared radius sensors, two load cell rolls and four guide rolls. Three active rolls are the unwind roll, master speed roll and rewind roll. Each roll is driven by a permanent magnet synchronous motor (PMSM) whose velocity is measured by an encoder. Two infrared sensors are equipped to detect the radii of the unwind and rewind rolls. The load cell roll is mounted on a pair of load cells on either side to measure the web tension.

It is common in the winding system modeling to assume that all the idlers such as load cell rolls and guide rolls do not contribute to web dynamics and the web does not slide on the rolls [1,18]. The

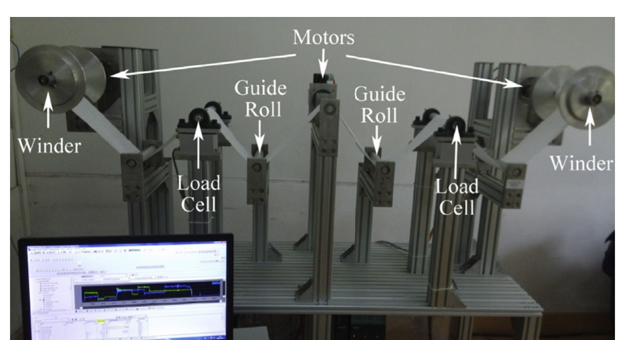

Fig. 1. Experimental web-winding system.