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Full length Article

Wire tension control of an automatic motor winding machine—an iterative learning sliding mode control approach

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ABSTRACT

One of the most crucial factors that affects the winding quality in an automatic motor winding process is the regulation of wire tension. Most commercial automatic motor winding machines use passive devices such as a dancer arm or a hysteresis brake to adjust the wire tension. However, as the winding speed increases, these passive devices may not be able to react quickly enough to maintain constant wire tension and may cause the enameled wire to tremble. In order to cope with the aforementioned problems, this paper conducts an in-depth study on active wire tension control of automatic motor winding machines. In particular, an iterative learning sliding mode control scheme for wire tension control is developed in this paper, while a disturbance observer is employed to estimate the wire tension for the implementation of sensorless wire tension control. Moreover, due to the fact that the motion of the unwind roll is affected by the motion of the enameled wire, the estimated wire speed information is exploited in the design of the tension control scheme to lessen the lag phenomenon. Results of the winding experiments verify the effectiveness of the proposed wire tension control scheme.

1. Introduction

In a typical winding process of an automatic motor winding system, the enameled wire is driven by the rewind roll. Without proper control in wire tension, tidy winding of the enameled wire cannot be accomplished. In addition, one of the most important issues in automatic motor winding is the resistance of the enameled wire, whose value should not have any significant deviation before and after the winding process. That is, the wire tension should be controlled to stay around a constant level so that the cross section area of the enameled wire will not have significant variations during the winding process. In order to maintain constant wire resistance, an effective wire tension control scheme is essential. Without proper wire tension control during the winding process, the enameled wire could be overstretched so as to increase the wire resistance. In order to overcome the abovementioned difficulties, passive tension regulation devices such as a dancer arm or a hysteresis brake are commonly adopted in conventional automatic motor winding machines to regulate the wire tension. One of the drawbacks for using the passive devices is that the operators may have to spend considerable time in adjusting the proper wire tension. Moreover, as the winding speed increases and reaches a certain level, the passive device may not be able to react quickly enough to maintain wire tension around a constant level. Consequently, significant fluctuation in the wire tension will likely cause the enameled wire to tremble/vibrate. As a result, the winding quality will deteriorate considerably. In order to cope with the aforementioned problem, this paper employs a more subtle approach — active wire tension control. Namely, the wire tension is regulated by servomotors instead of passive devices. In particular, this paper focuses on observer-based sensorless wire tension estimation and tension control of the unwind roll so as to improve the performance of automatic motor winding machines.

The number of existing researches on wire tension control of an automatic motor winding machine is surprisingly few [1]. Nevertheless, that is not the case for the web tension control of roll-to-roll manufacturing. In particular, existing studies on web tension control of roll-to-roll processing [2-9] could shed some light on the wire tension control problem of automatic motor winding. In order to cope with the regulation problem of web tension/velocity, Zhou and Gao proposed an approach that considers issues such as friction compensation and disturbance rejection [2]. In addition, Lee et. al. proposed an on-line friction compensation scheme for the tension control problem of a continuous strip processing line [3]. By taking into account friction and inertial compensation, Lin et al. proposed a disturbance observer based approach for web tension control of roll-to-roll processing [4]. In order to enhance the disturbance rejection ability of a roll-to-roll system, Knittel et al. proposed an H_∞ based tension controller [5]. Wang et al. proposed a neural network based approach for coping with tension control problems [6]. Abjadi

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et al. developed a sliding-mode controller based approach for tension sensorless control of a web-winding system [7].

Without proper control actions, the performance of an automatic motor winding machine may deteriorate because of external disturbance. Furthermore, quite commonly the external disturbance encountered in an automatic motor winding process is periodic. In order to attain satisfactory control performance, the issue of suppressing external periodic disturbances should be considered in the design of the control scheme. Among the methods for dealing with periodic disturbances, Iterative Learning Control (ILC) is one of the most popular ones [10–13]. As a matter of fact, ILC has been applied to various kinds of control problems, e.g., robot manipulator [14–20], precision motion [21–23], and health care [24].

Generally speaking, the basic idea of ILC is to modify the control action or input command based on the error information obtained in the previous iteration [11,12]. Because of its periodic nature, ILC is particularly suitable for coping with control systems having periodic commands and/or disturbances. It is quite common that a typical ILC contains a filter and a learning function to filter out noise and also determine the learning speed and the way ILC learns through iterations. Different combinations of filters and learning functions lead to different types of ILC; e.g., PD type, plant inversion type, optimization type and adaptive type, etc. [11,25–27]. If the taxonomy is based on control structure, then the ILC can be divided into three architectures — parallel ILC, serial ILC and command based ILC. The control output of the parallel architecture ILC sent to the controlled plant in the current iteration is generated based on the error and control output in the previous iteration [11,18,21,28–31].

Several previous studies on tension control problems are based on ILC [32,33]. In particular, Garimella and Srinivasan employed a parallel architecture ILC to suppress the periodic disturbance due to friction in a roll-to-roll tension control problem [32]. Zhao and Rahn combined the PD feedback controller and the ILC feedforward controller to cope with the tension control problem [33]. Although the simulation results of [32] and [33] both confirm the effectiveness of ILC in tension control problems, there is a lack of practical implementations in both studies. Moreover, even though ILC is suitable for control problems with periodic disturbances, it does not necessarily mean that it works effectively for applications such as automatic motor winding, for which both nonlinearity and periodic disturbance coexist simultaneously [34].

In order to reduce wire tension fluctuation so as to improve the winding quality of an automatic motor winding machine, this paper develops an Iterative Learning Sliding Mode Controller (ILSMC) that exploits the paradigm of iterative learning control [15] and sliding mode control [35–37]. In addition, several motor winding experiments have been conducted to validate the effectiveness of the proposed wire tension control scheme.

The rest of the paper is organized as follows. Section 2 briefly introduces the mathematical model of an automatic motor winding machine. Tension control of enameled wire during winding and the design of ILSMC for disturbance compensation are elaborated in Section 3. The issues concerning the disturbance observer based sensorless active wire tension control scheme are addressed in Section 4. Experimental results and conclusions are given in Sections 5 and 6, respectively.

2. Automatic motor winding machine and winding dynamics

Figs. 1 and 2 show a photograph and system model of the automatic motor winding machine employed in this paper, respectively. As shown in Figs. 1 and 2, the automatic motor winding machine employed in this paper has four axes that can move in the X-axis, Y-axis and Z-axis and U-axis directions. Based on Fig. 2, the block diagram of automatic motor winding with observer-based sensorless active tension control is depicted in Fig. 3. In particular, as shown in Fig. 3, the servomotors that actuate the motions on the X-axis, Y-axis and Z-axis are required to perform position control, while the servomotor that actuates the motions on the U-axis is responsible for wire tension control. Since this paper focuses on the control design problem of the U-axis, the motion control problems of the X-axis, Y-axis and Z-axis will not be considered here.

In order to achieve tidy winding of the enameled wire as shown in Fig. 2, the commonly used multi-loop control scheme is employed for the wire tension control of the U-axis that acts as the unwind roll of the automatic motor winding machine. In particular, as shown in Fig. 3, the multi-loop control scheme consists of two loops—the velocity loop is the inner loop, while the tension loop acts as the outer loop. That is, the velocity command for the U-axis's servomotor is provided by the outer tension loop. During the winding process, the line velocity of the enameled wire can be regarded as periodic external disturbance to the motion on the U-axis. Therefore, as the winding speed increases, the feedback controller may not be able to react quickly enough to effectively suppress external disturbance. As a result, the enameled wire may be overstretched or even broken. In order to overcome this difficulty, in this paper, a feedforward compensator that is designed based on the estimated line velocity of the enameled wire and a disturbance observer are exploited to cope with external disturbance. Moreover, an Iterative Learning Sliding Mode Controller (ILSMC) scheme for active tension control is proposed to suppress the periodic disturbance arising from the winding process so as to maintain the wire tension around a specified level and improve winding quality.

In this paper, during the winding process, the servo drive of the servomotor that actuates the unwind roll (i.e. U-axis) is set to the torque mode. The transfer function between the torque command τ_c and angular position θ_u for the unwind roll can be expressed as

$$\frac{\theta_u(s)}{\tau_c(s)} = \frac{1}{J_u s^2 + B_u s} \tag{1}$$

where J_u and B_u are the moment of inertia and viscous friction coefficient for the unwind roll.

Likewise, the transfer function between the external disturbance τ_d and θ_u for the unwind roll is described by

$$\frac{\theta_u(s)}{\tau_d(s)} = \frac{-1}{J_u s^2 + B_u s} \tag{2}$$

Since automatic motor winding is in general a periodic process, it is reasonable to assume that $\tau_d(t)$ is composed of a periodic external disturbance $d(t)$ and the Coulomb friction $F_c\text{sign}(x_2)$. Define the state vector $x=[x_1\ x_2]^T=[\theta_u\ \omega_u]^T$, where ω_u is the angular velocity of the unwind roll. According to (1) and (2), the state space model for describing the motion of the unwind roll can be expressed as:

$$\dot{x} = A_u x + B_u \tau \tag{3}$$

$$\omega_u = C_u x \tag{4}$$

where

$$A_u = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{B_u}{J_u} \end{bmatrix} \quad B_u = \begin{bmatrix} 0 \\ \frac{1}{J_u} \end{bmatrix} \quad C_u = \begin{bmatrix} 0 & 1 \end{bmatrix} \tag{5}$$

Note that in (3), $\tau = \tau_c - \tau_d \approx \tau_c - F_c\text{sign}(x_2) - d(t)$. In this paper, the identification method developed in [38] is used to identify the values of J_u and B_u, which are: $[J_u \quad B_u] = [\ 0.00042(Nm \cdot s^2/rad) \quad 0.002\ \ (Nm \cdot s/rad)]$.

Fig. 3 shows that the external disturbance $d(t)$ mainly results from the winding dynamics; that is, the wire tension during the winding process. By Hooke's law, the wire tension T is the product of the change in wire length Δ_l and stiffness K_f; i.e., $T=K_f\Delta_l$. Note that the total change Δ_l in wire length is the sum of change in the length of the rewind roll and change in the length of the unwind roll. By definition, the time derivative of the wire tension can be described as $\dot{T}(t) = K_f(\Delta_l/dt) = K_f\Delta_\omega$, where Δ_ω denotes the difference between the rewinding speed and unwinding speed. However, by accounting for other factors such as the modeling error Δ resulting from the simplification of the velocity loop of the servomotor of the unwind roll as well as the line velocity ω_{line}