Adaptive Transition Disturbance Observer for Winding Machine

Jinwook Kim, Oh-Kyu Choi and Jin S. Lee

Department of Electrical Engineering, Pohang University of Science and Technology, Pohang, Korea
(Tel : +82-54-279-5574; E-mail: tw0822@postech.ac.kr, skaruwls@gmail.com, jsoo@postech.ac.kr)

Abstract: In this paper, we propose an adaptive transition disturbance observer for winding machine control. In winding machine control, keeping constant tension on the winding material is one of the most important control objectives. So the reduction of the internal and external disturbance that can cause tension error is important. The disturbance observer is then proposed to solve these problems. But the conventional disturbance observer cannot predict the tension error accurately, because the winder inertia changes according to the radius of the rewinding roll. By taking the change of the winder inertia into account, we develop an adaptive transition disturbance observer that makes the system robust against the disturbance. The validity of the scheme is tested through simulation.

Keywords: Winding machine, disturbance observer, tension control.

1. INTRODUCTION

A winding machine unwinds, rewinds and cuts several thin web materials, for example, the paper, plastic film, wire, textile, and so forth, according to its purpose. The performance of the winding machine can be evaluated by the quantity of handling web per unit hour, i.e., the working speed. In other words, the faster the working speed is, the better the performance of the winding machine is. But increasing the rewinding speed to improve the working speed also increases the instabilities of the winding machine, such as the splits, folds or transformations for the web materials, resulting in the qualitative degradation of products. Therefore, the development of control technique of the system is essential to raise the working speed as well as to manage the quality of the web material stably. The control objectives of the winding machine are representatively classified into three parts: the tension control acting on the winding material, the flat control of cutting plane and the edge position control for the side uniformity of the wound roll. Especially, the tension control is the most important because the web's right tension on the high speed winding machine is the core to determine the quality of the rolled web. Mostly, the tension control of winding machine aims to maintain the constant tension according to the constant reference value during the winding process.

Several papers have considered tension control of the winding machine [1]- [5]. T.Sakamoto [1] analyzed web tension control and presented a mathematical model that describes its control mechanism in 1997. K.Okada [2] proposed an adaptive control technique for web tension control, and B.Wang [3] applied it to web material packaging. Also, Hakan Koc [4] studied robust control of the winding machine, and M.Anibal Valenzuela [5] developed a sensorless control system using observer techniques with inertia compensation.

Main issue of uniform tension control is a disturbance elimination of the system, and estimating disturbance first is important to eliminate it. Ohnishi [6] proposed a disturbance estimation technique called a disturbance observer (DOB) in 1987 and applied it to Nakao and Ohnishi [7] in the multi-body robot manipulator. From then on, it was further improved by Umeno and Hori [8]. The DOB technique has been widely used in the several fields such as mechatronics, robotics and so on [9]- [13] because of its simple structure and robustness.

We classified the DOB into three structures: conventional DOB, adaptive DOB and adaptive transition DOB. A conventional DOB consists of a nominal plant inverse and a low-pass filter. An adaptive DOB is a conventional DOB equipped with an adaptive algorithm. The adaptive DOB supplements the weak point of the conventional DOB which is not readily applicable to the time-varying system [11]. In this paper, we present an adaptive transition DOB that is used to eliminate the disturbance of the tension the rewinder system. The adaptive transition DOB selects either a conventional DOB or an adaptive DOB by a transition criterion which is determined by the changing characteristics of the system.

In Section 2, we briefly introduce the winding machine and analyze the physical construction of its rewinder system for tension control. In Section 3, we present the background theories, structures and characteristics of the DOBs. In Section 4, we perform the computer simulation to evaluate the validity of the proposed DOB. In Section 5, we makes conclusions.

2. WINDING MACHINE

The winding machine consists of an unwinder system, a dancer roll unit and a rewinder system as shown in Fig. 1. The unwinder system unwinds the web materials continuously, the dancer roll unit transports and cuts them, and the rewinder system winds them again. Generally, the unwinder system feeds the web to the rewinder system at a constant speed, and all of the winding machine control unit except one concerned with cutting the web are performed in the rewinder system. The tension of the web is controlled at the rewinder system, too.

Fig. 2 represents the physical construction of the rewinder system. In this figure, F is the tension or force applied on the winding material, T the material thickness, W the roll width, r_1 the core radius and r_2 the roll radius.

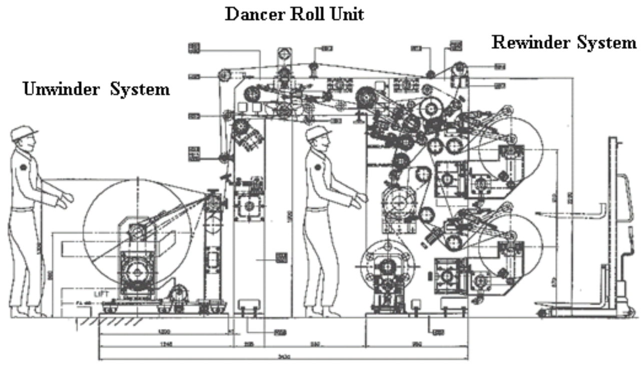

Fig. 1 Structure of the winding machine.

Most winding machines have a characteristic that F must be maintained at a constant tension value on the winding process. This is realized by controlling the torque of a DC-motor connected to the rewinder system's core.

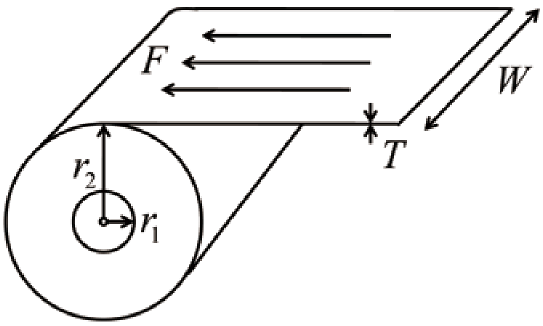

Fig. 2 Physical representation of the rewinder system.

For the torque control of the DC-motor, we need to analyze the dynamics of the rewinder system. The parameters concerned with the dynamics are as follows:

ρ: material density
w: angular speed of the rewinder system
S: surface speed of the winding material
L: wound material length
M: wound material mass
J_m: wound material inertia
J_c: core inertia of the rewinder system
J_t: total roll inertia of the rewinder system
B: rewinder viscous friction coefficient.

Other significant variables of the rewinder system are represented by the following equations:

$$S = w \times r_2,$$

$$L = \int S \, dt,$$

$$r_2 = \sqrt{\frac{L \times T}{\pi} + r_1^2},$$

$$M = \rho \times \pi \times W \times \left(r_2^2 - r_1^2\right),$$

$$J_m = \frac{1}{2} \cdot M \cdot (r_2^2 + r_1^2),$$

$$J_t = J_m + J_c,$$

and the motor drive electric torque T_e is calculated using the following differential equation.

$$T_e = J_t \cdot \frac{dw}{dt} + B \cdot w + T_l \tag{1}$$

where w is the angular speed of the rewinder system and T_l is the rewinder load torque. The relation between F and T_l is expressed as:

$$T_l = F \times r_2,$$

and F is calculated by the below equation

$$F = \frac{T_e - J_t \cdot \frac{dw}{dt} - B \cdot w}{r_2}.$$

The system (1) can be represented as the state equation form:

$$\dot{w} = \frac{B}{J_t} w + \frac{T_e - T_l}{J_t}, \tag{2}$$

$$y = w \tag{3}$$

where,

$$\begin{aligned} J_t &= J_m + J_c \\ &= \frac{1}{2} \cdot M \cdot (r_2^2 + r_1^2) + J_c \\ &= \frac{1}{2} \cdot \rho \cdot \pi \cdot W \cdot (r_2^4 - r_1^4) + J_c \end{aligned} \tag{4}$$

and T_l is treated as a second input. r_2 is expressed as

$$r_2 = r_1 + \frac{T}{2\pi} \cdot \theta,$$

where θ is the displacement angle of the rewinder system. Because θ is time-varying, r_2 and hence J_t is also time-varying. Therefore, we see that the rewinder system described by (2) and (3) is time-varying.

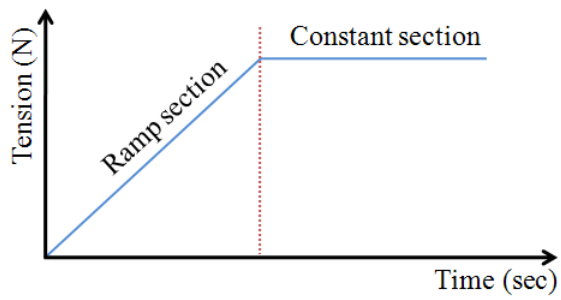

Fig. 3 Reference input.

The instabilities occurring on the tension control are classified into two: the overshoot caused by the transition of the reference input, and the arbitrary disturbances on the system. As mentioned above, the tension applied to the winding material must remain at a constant value during the winding process. Hence the reference input used for tension control must be constant, too. But actually the reference input is divided into the ramp reference input section and the constant reference input section (Fig. 3), because a ramp input is needed to ready the constant value. As the reference input transfers from the ramp to the constant, overshoot will be expected on the tension. The excessive overshoot on the tension can cause damages on the material. In order to guarantee the quality of products made with the winding material, we need to eliminate or to minimize the overshoot and the disturbances that can cause tension error.

3. DISTURBANCE OBSERVER

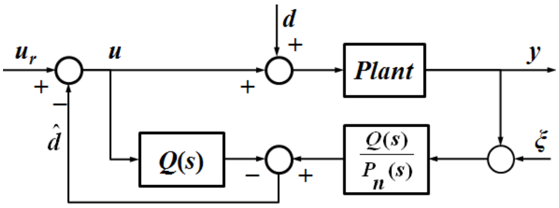

Fig. 4 Conventional Disturbance Observer.

A DOB is a useful approach for handling the uncertain disturbance in the mechanical system [6]- [13]. The conventional DOB consists of a nominal plant inverse and a low-pass filter called Q-filter. The diagram of a conventional DOB is shown in Fig. 4. u_r is the input reference, u is the input, d is the input disturbance, $\hat{d}$ is the disturbance estimate, y is the measurement and ξ is the measurement noise. The transfer function $P_n(s)$ and $Q(s)$ represent the nominal plant and the low-pass filter, respectively, and the *Plant* is a real system. Assuming that ξ is zero, the DOB is a series of process determining the estimate $\hat{d}$ from the measurement y. If we assume that the *Plant* is the same as $P_n(s)$, we can estimate disturbance $\hat{d}$ by passing y through $Q(s)/P_n(s)$ and subtracting $Q(s) \cdot u$.

Because the *Plant* is actually the rewinder in our system, the physical quantities of u_r, u, d and $\hat{d}$ are all tensions and y is the velocity. If the DOB is eliminated in Fig. 4, then u is represented as $T_e - T_l$ in (2). If we assume that J_t is constant, from (1), the transfer function $P(s)$ of the *Plant* becomes

$$P(s) = \frac{1}{J_t \cdot s + B}$$

and similarly, $P_n(s)$ can be defined as:

$$P_n(s) = \frac{1}{J_n \cdot s + B_n}$$

where J_n and B_n are the inertia and viscous friction of the nominal plant, respectively, and are fixed in the conventional DOB. Actually J_n is constant because J_m used for the conventional DOB is not updated. There are many candidates [14] that can be used for the low pass-filter $Q(s)$, but we choose to use:

$$Q(s) = \frac{g}{s + g}$$

where g is a cut-off frequency to suppress the high frequency noise.

As mentioned in Section 2, the rewinder system is time-varying, because the total roll inertia J_t increases as winding proceeds in the winding process. Because it is difficult in the time-varying system to obtain a fixed nominal model of the plant, the conventional DOB is not applicable to the rewinder system. To reflect the change of the total roll inertia, it makes sense to use an adaptive DOB [11] as in Fig. 5. The adaptive scheme updates

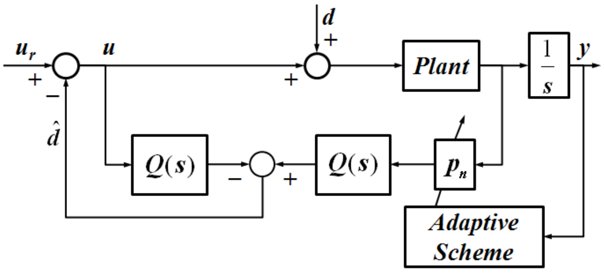

Fig. 5 Adaptive Disturbance Observer.

the inertia J_n of nominal plant $P_n(s)$ when the radius r_2 increases. And J_n is obtained from (4)

$$J_n = \frac{1}{2} \cdot \rho \cdot \pi \cdot W \cdot (r_2^4 - r_1^4) + J_c \, .$$

In [11], the adaptive DOB is shown to perform much better than the conventional DOB for disturbance estimation in the time-varying situations. However, when the reference input transfers from the ramp to the constant, the adaptive DOB shows a big overshoot. To remedy this problem, we propose to use an adaptive transition DOB (Fig. 6) by combining the conventional DOB which comes with small overshoot with the adaptive DOB which is well suited to the time-varying disturbance. The transition scheme is separated into three

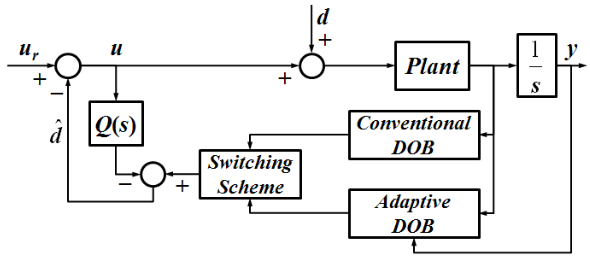

Fig. 6 Adaptive Transition Disturbance Observer.

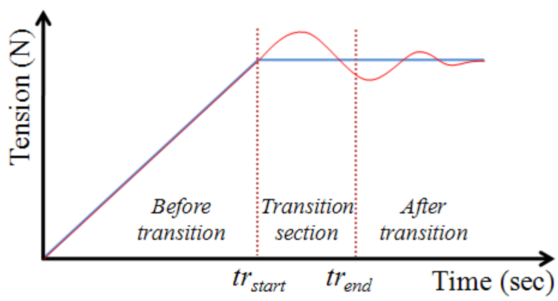

Fig. 7 Three regions as used in adaptive transition DOB.

regions (Fig. 7): before transition, during transition and after transition. Before transition, we adopt the conventional DOB. And after transition, we adopt the adaptive DOB. During transition, the conventional DOB is slowly changed to the adaptive DOB and its expression is described by using the parameters such as process time t, transition start time tr_{start}, transition end time tr_{end} and transition factor α where $0 \leq \alpha \leq 1$. tr_{start} is the time when the ramp and the constant reference intersect, and tr_{end} is determined from the experiments. The changing mechanism can be represented as follows:

$$J_{n3} = (1-\alpha) \cdot J_{n1} + \alpha \cdot J_{n2}$$

where J_{n1} is the nominal plant inertia when using the conventional DOB, J_{n2} when using the adaptive DOB and J_{n3} when using the adaptive transition DOB, and α is defined as

$$\alpha = \begin{cases} 0 & , \text{ for } t < tr_{start} \\ \frac{1}{tr_{end}-tr_{start}}(t - tr_{start}), & \text{for } tr_{start} \leq t < tr_{end} \\ 1 & , \text{ for } tr_{end} \leq t. \end{cases}$$

In the ramp reference input section, J_t and J_c are almost same, and hence we can use the conventional DOB.

4. SIMULATION

In this section, we test the winding machine using the adaptive transition DOB and compare its performance with those of the other DOBs. The surface speed of the winding material is 5 m/s. We use the PI control algorithm whose P and I gains are 10 and 20, respectively. The frequency of the external disturbance d is 60 Hz and its amplitude is 10 $N \cdot m$ peak to peak. The measurement noise ξ is zero and the cut-off frequency g is 5000 rad/s. That is,

$$Q(s) = \frac{5000}{s + 5000}.$$

The slope of ramp reference input is 25 N/s and the constant reference input is 300 N. Accordingly, the ramp reference input starts from 0 sec and continues up to 12 sec, and tr_{start} is 12sec. tr_{end} is 12.3 sec which is determined by the experiments.

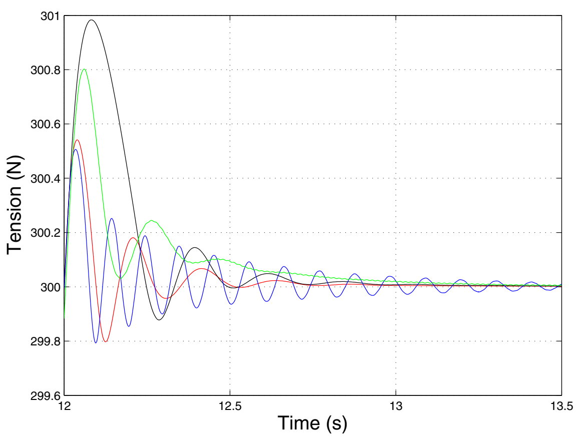

Fig. 8 Overshoots (red line: Adaptive Transition DOB, black line: Adaptive DOB, blue line: Conventional DOB, green line: no DOB).

In Fig. 8, note that the adaptive DOB shows a large overshoot (about 1 N). This is due to the fact that the adaptive DOB is over-fitted to the ramp reference input. It cannot be adapted to the change of the reference input. On the other hand, the conventional DOB shows small overshoot (about 0.5 N). But, it results in the big steady state error in Fig. 9 because it cannot eliminate the external disturbance efficiently in the rewinding system. In this figure, the adaptive DOB and the adaptive transition DOB show the smallest tension errors. It is mainly due to the fact that these DOBs can cope with the time-varying characteristics. In eliminating of the external disturbance, we see the adaptive DOB and the adaptive transition DOB are better in performance than the others.

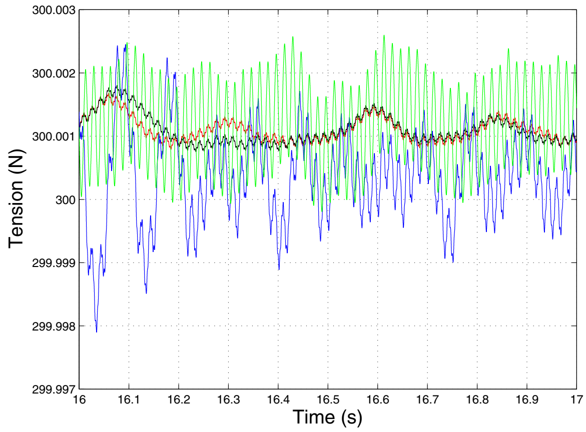

Fig. 9 Steady state (red line: Adaptive Transition DOB, black line: Adaptive DOB, blue line: Conventional DOB, green line: no DOB).

Consequently, the adaptive transition DOB shows relatively small overshoot but the small steady state error. And it shows the largest decrease in the following (the second, the third and so on) overshoots. As far as the overshoot is concerned, the adaptive transition DOB is best.

To evaluate the performance of DOBs numerically, the following error index is used:

$$(\text{Error index}) = \sum |\text{Target tension} - \text{System output}|.$$

Table 1 Average error of four methods (NODOB: no DOB, CDOB: conventional DOB, ADOB: adaptive DOB, ASDOB: adaptive transition DOB)

	NODOB	CDOB	ADOB	ASDOB
Error Index	0.0189	0.0125	0.0238	0.0094

In Table 1, the adaptive transition DOB shows the smallest error and the adaptive DOB shows the biggest error because of the big overshoot.

Fig. 8∼9 and Table 1 show that the adaptive transition DOB shows better performance over other DOBs in the time-varying system and the reference input variation situation.

5. CONCLUSIONS

In this paper, we proposed an adaptive transition DOB to estimate the internal and external disturbances in the winding machine. A DOB which consists of a nominal model inverse and a low-pass filter can estimate disturbances and the estimated one is used to eliminate the original one. Since the dynamics of winding machine is changing continuously, it is difficult to determine its nominal model in the conventional DOB. So we adopted an adaptive DOB which updates the nominal model continuously. To compensate for the weak point of the adaptive DOB, we used an adaptive transition DOB by combining the conventional DOB with the adaptive DOB. Simulation results show that the winding machine with the adaptive transition DOB is superior to those with other methods in the rewinder system.

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