능동 장력 장치를 이용한 권취기의 연사 장력제어

Yarn Tension Control of Winding Machine Using Active Tensioner

울루구벡, 정 승 현, 한 창 욱, 박 정 일*
(Ulugbek R. Umirov, Seung Hyun Jung, Chang Wook Han, and Jung-Il Park)

Abstract : This paper is devoted to yarn tension control problem in winding machines. The passive take-up unit is replaced by active one with ADRC(Active Disturbance Rejection Control) and it was compared with the method using conventional PD(Proportional-Derivative) controller. The main part of ADRC is ESO(Extended State Observer) which continuously estimates nonlinearities of the system, such as intrinsic nonlinearity, external disturbance and sensor noise. Then the estimated nonlinearity is used to compensate the real one, thus making controlled system linear. A number of experiments have been conducted in order to verify the performance of the original winding system to the modified one. Experiments have shown improved efficiency of the system with adopting active yarn tension control. Experimental results show that the ADRC achieves a better tension response than PD controller and is robust to parameters variation.

Keywords : yarn tension control, active/passive tensioner, ADRC, ESO

I. Introduction

Yarns are fundamental for production of many consumer and industrial textiles. During their manufacture process, they are transported from package to bobbin in order to either improve their quality (evenness, texture, strength integrity), or to get new yarn by doubling together two or three yarns. It is required to provide predefined constant yarn tension during simple winding or doubling. Especially in case of yarns' doubling this problem becomes more important, as doubled yarn should be composed by yarns with the same tension, otherwise integrity of composed yarn cripples.

Main method of yarn transport is over-end unwinding, when yarn is pulled over the end of the package, as it provides the highest transport speed comparing to other methods. In winding machines tension-stabilizing devices are used, known as tensioners. Their function is to ensure that the tension of the yarn is maintained at a pre-set mean level, and that its dynamic component is reduced to certain limits. In the textile industry, use is mainly made of mechanical tensioners which can be adjusted to the required yarn tension, although it is desirable that the modern machines should be outfitted with active computer-controlled tensioners with the possibility of programming yarn tension at the desired level independently of the motion parameters of the yarn and its initial tension.

Due to importance of yarn tension problem, it is attracted attention of many researchers. First comprehensive investigation on dynamics of over-end unwinding process was reported by D.GPadfield [1] in 1958. Since then a theory was much improved, however there are not many reports about precise control of process, due to the limited capabilities of hardware computing power and a number of nonlinearities in the process model. In over-end unwinding process, the yarn tension depends on factors such as yarn material and its evenness, transport speed and unexpectedly it depends on size and shape of the package (especially in case of high transport speed). It is needs to develop control system (actuating device and algorithm) to deal with all those parameters to provide constant tension along the full length of yarn. Main goal is to make control system able to adjust yarn tension automatically even in case of large variations of parameters. Two methods were investigated, PD control[2] and Active Disturbance Rejection Control (ADRC)[3,4] as applied to yarn tension problem. As a result of experiments PD control has shown limited appliance, however, the ADRC method based on plant model estimation, has shown good results for all operating range.

In Section II textile manufacture process is reviewed and process of yarn winding is described. Section III is devoted to modifications made to winding system in order to make control possible. Section IV presents the disturbance compensation algorithms and followed by Section V describing experiments conducted under different circumstances on modified winding system. Finally this paper is enclosed by conclusion, where results of research are described.

II. Structure of Conventional Yarn Winding Machine

The purpose of winding is to produce a package of yarn that can be unwound later at downstream processing or the customer. There are different basic types of winder exist:

- Drive roll (friction drive) and traverse.
- Spindle drive and traverse
- Ring and traveler

In the Fig. 1, two types of winders are illustrated, and in our system friction drive winder is used, thus the yarn transport speed is constant.

General view of winding system is shown in Fig. 2. It consists of package spindle, guide-eye, tensioner and winder. As it can be seen from the figure, the yarn unwinds from package on spindle, passes through guide-eye, then through tensioner and finally winds up to bobbin by winder.

To provide doubling of yarn (winding together two or more

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* 책임저자(Corresponding Author)

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울루구벡, 정승현, 박정일 : 영남대학교 전자정보공학부
(ulugbek.umirov@gmail.com/bugman@ynu.ac.kr/jipark@yu.ac.kr)
한창욱 : 동의대학교 전기공학과(cwhan@deu.ac.kr)

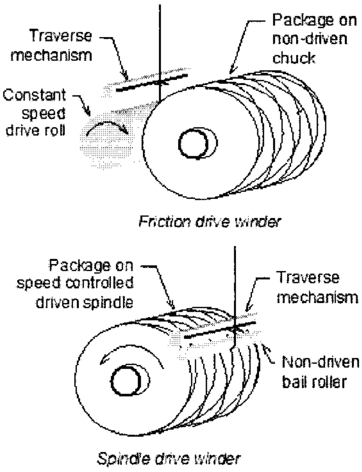

그림 1. 와인더 형태.
Fig. 1. Winder types.

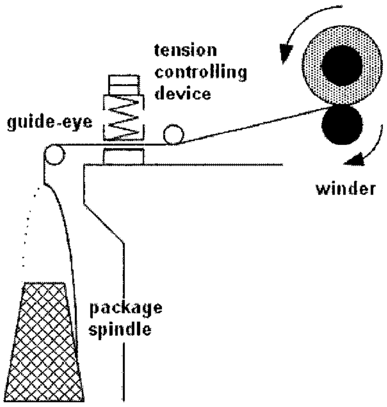

그림 2. 와인딩 시스템.
Fig. 2. Winding system.

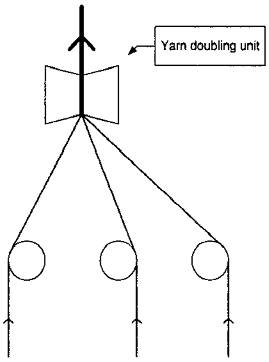

그림 3. 실 합사 장치.
Fig. 3. Yarn doubling unit.

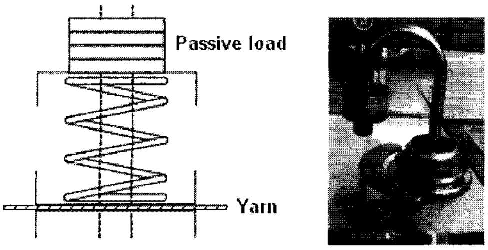

그림 4. 중력/스프링에 의한 장력조절기.
Fig. 4. Gravity/spring loaded tensioner.

yarns) there are several package spindles with separate tensioners for each one exist. Those yarns meet together at doubling unit located after tensioners as illustrated in Fig. 3.

In our original winding system, for the purpose of yarn tension control, the gravity/spring loaded tensioner, also known as additive tensioner, shown in Fig. 4 is used; we call it passive tensioner. It includes first and second plate members having adjacent inner faces positioned on opposite sides of the running yarn with one of the plate members being resiliently urged toward the other plate member and in engagement with one side of the running yarn to thereby apply tension to the running yarn passing therebetween. The inner faces of both plates are substantially smooth and flat. To achieve the desired tension, the operator should adjust the load on the top plate manually by adding/removing weights.

III. Yarn Tension Control Using Active Tensioner

In order to make yarn tension control possible, a number of modifications were made to the original winding system. As far as we cannot control speed of winder, the only thing to be modified is tensioner. In the following subsections tensioner modification, control board and general view of control system are presented.

1. Active tensioner

As it has been already discussed, for the yarn tension control in winding machines, the passive mechanical tensioner is usually used. However, it has some disadvantages, such as that load on the top plate should be adjusted manually. The main problem is that yarn tension depends not only on that load, but it depends on its type, moreover it depends on its transport speed. Also, the disk tensioners do not adequately stabilize yarn tension in winding, because if a thick place or knot in the yarn impacts upon on disk, tension in the yarn grows rapidly, while the vibration which is induced by the impact reduces yarn tension to nil, although a repeated contact of the yarn with a disk generates in it an additional dynamic component of tension. Hence, instead of being reduced, the dynamic component of tension is increased. Thus, the problem seemed to be simple in fact is quite complex and usually yarn tension is adjusted by trial-and-error or by using some predefined tables, what is quite inconvenient. Instead of manually adjusted load on top-plate, the MCU controlled load is used. For this purpose, the system composed of DC motor, gear and lead-screw was adapted. As it can be seen from the following figure, top plate is moved by lead-screw driven by the motor. We call such tensioner with motor-driven top plate as active tensioner as shown in Fig. 5.

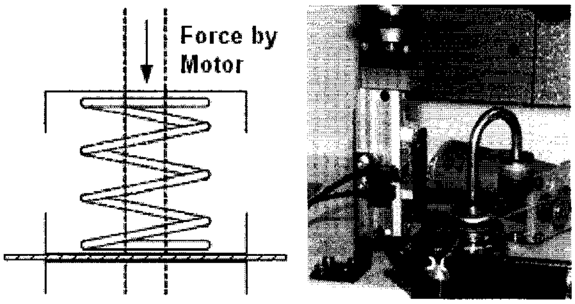

그림 5. 능동 장력조절기.
Fig. 5. Active tensioner.

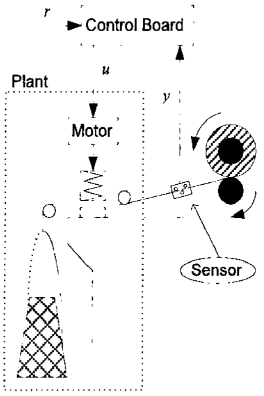

그림 6. 와인딩 시스템의 제어 개념도.
Fig. 6. Controlled winding system.

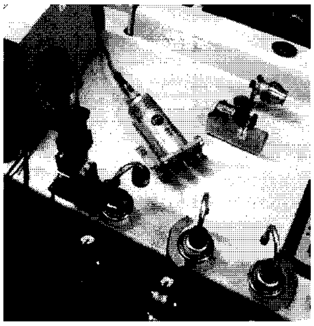

그림 7. 능동 장력조절기와 센서를 이용한 실험장치.
Fig. 7. Experimental setup: active tensioner and sensor.

Such modification to the tensioner provides us not a completely new system, but just helper to original passive tensioner, and thus active tensioner inherits all virtues and neglects shortcomings of original one.

2. Modeling of controlled winding system

So far the active tensioner and control board were described. The only missing part is tension sensor located right after tensioner. Altogether these three objects together provide control of yarn tension in winding system. Analogue signal from tension sensor is translated to digital form by ADC, then it is processed by microcontroller (PD control or ADRC control), and finally output signal in form of PWM (Pulse-Width-Modulation) signal is directed to DC motor of active tensioner. The scheme and photo of controlled winding system are shown in Figs. 6 and 7, respectively.

The plant model can be approximated as second-order system[3,4]:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f\left(t, x_1, x_2, w\right) + b_0 u \\ y = x_1 \end{cases} \tag{1}$$

where $f\,(t,x_1,x_2,w)$ is the uncertainty of the system. The uncertainty could be external and internal disturbances, such as measurement noise, sensor noise, frictions, backlash, and hysteresis, or the variation and uncertainties of the plant dynamics. The inputs of the system are w - disturbance, u - motor torque, the output is y - yarn tension, and b_0 is the known constant. r in Fig. 6 is reference tension.

IV. Control Algorithms

A lot of control methods are developed for different purposes. And some of them could be applied for yarn tension control. This section describes PID and ADRC methods, and NESO as base of ADRC.

1. Proportional Integral Derivative(PID) Controller

The PID controller is the most common form of feedback controllers. The control input by PID controller is described by:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt} \tag{2}$$

where $e(t)$ is the error, K_p is proportional gain, K_i is integral gain, and K_d is derivative gain. We can rewrite eq.(2) in s -domain:

$$\frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s \tag{3}$$

2. Active Disturbance Rejection Control(ADRC)

ADRC is based on ESO (Extended State Observer). The ESO is a nonlinear observer designed in state space for a class of uncertain systems, proposed by Han [5].

Consider an n th-order nonlinear system described by

$$y^{(n)} = f(y, \dot{y}, \ldots, y^{(n-1)}, w(t)) + bu(t) \tag{4}$$

where $f\,(.)$ is an uncertain function, $w(t)$ is the unknown external disturbance, $u(t)$ is the known control input, and $y(t)$ is the measured output. The system is equivalent to

$$\begin{cases} \dot{x}_1 = x_2 \\ \ldots \\ \dot{x}_n = x_{n+1} + bu, \quad x_{n+1} \equiv f(t, x_1, \ldots, x_n, w) \\ \dot{x}_{n+1} = h(t) \\ y = x_1 \end{cases} \tag{5}$$

where $f\,(.)$ is augmented state and

$$h(t) = \sum_{i=1}^{n} \frac{\partial f}{\partial x_i} \dot{x}_i + \frac{\partial f}{\partial w} \dot{w}$$

Then the nonlinear continuous observer is designed for system eq.(4):

$$\begin{cases} e = z_1 - y(t) \\ \dot{z}_1 = z_2 - \beta_{01} g_1(e) \\ \ldots \\ \dot{z}_n = z_{n+1} - \beta_{0n} g_n(e) + bu \\ \dot{z}_{n+1} = -\beta_{0n+1} g_{n+1}(e) \end{cases} \tag{6}$$

when $t \to \infty$, $z_i(t) \to x_i(t)$, z_{n+1} is the estimate of the extended state f. The observer eq.(6) is the ESO for system eq.(4). The observer can be given as:

$$\begin{cases} \dot{z}_1 = z_2 - \beta_{01} f_{al}\left(z_1 - y(t), \alpha_1, \delta_1\right) \\ \ldots \\ \dot{z}_n = z_{n-1} - \beta_{0n} f_{al}\left(z_1 - y(t), \alpha_n, \delta_n\right) + b_0 u \\ \dot{z}_{n+1} = -\beta_{0n+1} f_{al}\left(z_1 - y(t), \alpha_{n+1}, \delta_{n+1}\right) \end{cases} \tag{7}$$

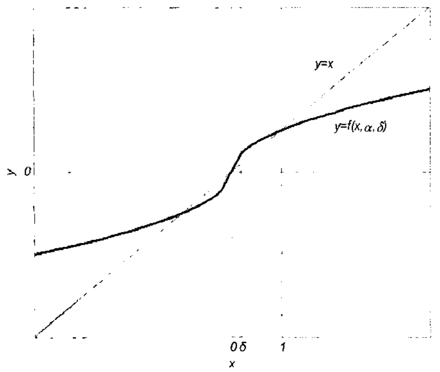

그림 8. 선형과 비선형 이득(α=0.5, δ=0.2)의 비교.

Fig. 8. Comparison of the linear and nonlinear gains (α=0.5, δ=0.2).

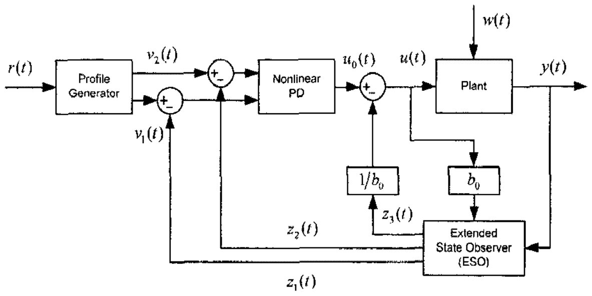

그림 9. ADRC의 구조.

Fig. 9. Structure of ADRC.

where b_0 is the normal value of b, and $f_{al}(.)$ is defined as

$$f_{al}(\varepsilon,\alpha,\delta)=\begin{cases}|\varepsilon|^{\alpha}sign(\varepsilon), |\varepsilon|>\delta & \\ & \delta>0 \\ \dfrac{\varepsilon}{\delta^{1-\alpha}}, |\varepsilon|\le\delta & \end{cases} \tag{8}$$

The nonlinear function in eq.(8) is used to make the observer more efficient. Intuitively, it is a nonlinear gain function where small errors correspond to higher gains, and large errors correspond to smaller gains. When the error is small, it prevents excessive gain, which causes high frequency chattering in some simulation studies. Fig. 8 shows the difference between the linear and nonlinear gain.

If α_i is chosen as unity, then the observer is equal to the well-known Luenberger observer[6]. The ESO can reconstruct states reliably for nonlinear plants. Because it does not use a model, it is simpler and easier to construct, easier to implement due to its efficiency in many cases, and is not affected by model uncertainties such as parameter variations and external disturbances. Since Han's observer[5] uses nonlinear functions, it was named Nonlinear Extended State Observer (NESO).

ADRC is applied to counteract the uncertainty by the estimated signals. The structure of the controller is illustrated in Fig. 9.

ADRC mainly consists of three parts: the ESO, the Profile Generator, and the Nonlinear PD Controller. Let's rewrite eq.(1) as

$$\begin{cases}\dot{x}_1=x_2 \\ \dot{x}_2=x_3+bu, \qquad x_3(t)=f(t,x_1,x_2,w) \\ \dot{x}_3=h(t) \\ y=x_1\end{cases} \tag{9}$$

where $h(t)$ is the derivative of $f(t,x_1,x_2,w)$ and is unknown. Thus we have following structure of ESO

$$\begin{cases}\dot{z}_1=z_2-\beta_{01}f_{al}(z_1-y(t),\alpha_1,\delta_1) \\ \dot{z}_2=z_3-\beta_{02}f_{al}(z_1-y(t),\alpha_2,\delta_2)+b_0u \\ \dot{z}_3=-\beta_{03}f_{al}(z_1-y(t),\alpha_3,\delta_3)\end{cases} \tag{10}$$

where z_1, z_2, z_3 are the estimated x_1, x_2 and $f(t,x_1,x_2,w)$ respectively. The plant can now be dynamically compensated by

$$u(t)=u_0(t)-z_3(t)/b_0 \tag{11}$$

Combining eq.(1) with eq.(11), we get

$$\begin{cases}\dot{x}_1=x_2 \\ \dot{x}_2=b_0u_0 \\ y=x_1\end{cases} \tag{12}$$

The control problem of eq.(1) is now simplified to a double integrator control problem. Here the nonlinear combination takes the form:

$$u_0(t)=K_pf_{al}(\varepsilon_p,\alpha_p,\delta_p)+K_df_{al}(\varepsilon_d,\alpha_d,\delta_d) \tag{13}$$

where ε_p=v_1-z_1, ε_d=v_2-z_2 are error and its derivative, respectively. The controller gains are K_p and K_d. The nonlinear controller performs better than the linear controller, providing good gain scheduling and completely agreeing with the intuition obtained from working with practical problems. ADRC is defined as the control method where the value of $f(t,x_1,x_2,w)$ is estimated in real time and compensated by the use of the control signal u.

V. Experiments

For control purpose, such as DC motor control, tension measurement collecting, the board based on 8051 MCU was designed. MCS-51 architecture was chosen as it is well investigated core and there are a lot of resources dedicated to it. Particularly C8051F120 microcontroller with CIP-51 core by Silicon Laboratories is used, which main advantages over MCS-51 architecture for our problem are pipelined architecture, which greatly increases its instruction throughput, and internal ADC.

In order to make DC motor, stepping motor, 8-digit 7-segment LED, LCD control possible, technology of memory-mapped devices was used. Thus requests sent to address below 0x2000 are sent to internal RAM, and requests sent to address above the limit

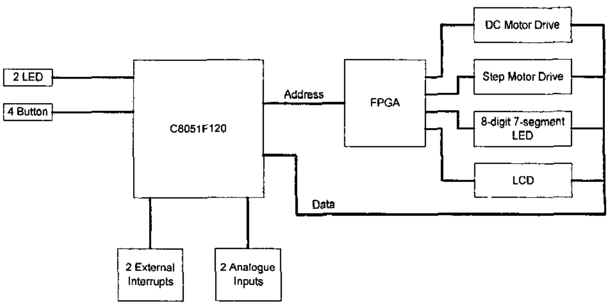

그림 10. 제어보드 블록도.

Fig. 10. Control board block diagram.

are sent to external devices. To enable this technology Altera EPM7064S FPGA chip is used as bridge, i.e. the chip accepts the address of device and generates CS(chip select) signal. Interaction with status LED, keypad, rotation sensors and tension sensors is made bypassing the bridge by mapping them to dedicated pins of MCU. Block diagram of control board is illustrated in Fig. 10.

The designed board has following specification:

- 2 analogue inputs: tension sensor output is analogue signal 0-5(V)
- 2 external interrupt inputs: bobbin and drive roll rotates count
- 2 outputs to DC motor: active tensioner control
- 1 output to step motor
- 8-digit 7-segment LED: display length, reference tension, current tension or tension error
- 1 graphic display
- 4-button keypad: start/stop control, adjust reference tension
- 2 LED indicators: indication of motor rotation direction

As operating system Real-Time Operating System RTX Tiny by Keil Software GmbH was used[7]. It has shown itself as stable and effective RTOS, also it has lightweight kernel (only 900 bytes). Operating frequency of OS is 4 kHz, it's enough for control purposes and all calculations could be finished within OS sampling time.

A number of experiments have been conducted to check performance of passive tensioner and active tensioners with PD and ADRC control.

For ADRC control profile generator should be used, which generates two profiles according to supplied reference tension r, one for profiled tension - v_1, and another one is for profiled tension derivative - v_2. Ramp profile for v_1 is used. Thus v_1 is linearly increasing from 0 to reference tension r during settling time T_{set}, then v_1 is set to r. According to such profile of v_1, profile of its derivative v_2 is defined as r/T_{set} during settling time, and then set to 0. Both profiles are illustrated in Fig. 11.

T_{set} is settling time for ADRC control defined in our algorithm as 2 seconds.

It is possible to define tension profile as step function, or to decrease settling time, but to provide smooth transition it was decided to make tension profile as explained. Thus, to compare performance of controllers, error in all experiments is calculated for the data measured after 2 seconds from starting, in other words we consider steady-state error.

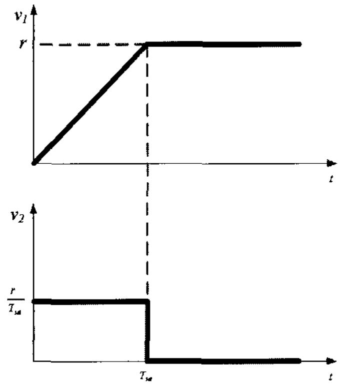

그림 11. ADRC를 위해서 사용한 장력과 미분 프로파일.

Fig. 11. Tension and its derivative profiles used for ADRC.

표 1. PD와 ADRC 제어기 파라미터.

Table 1. PD and ADRC controller parameters.

	Parameter	Value
PD	K_p	0.2
	K_d	2
ADRC	$\alpha_1, \alpha_2, \alpha_3$	0.5
	$\delta_1, \delta_2, \delta_3$	0.05, 0.2, 0.4
	$\beta_{01}, \beta_{02}, \beta_{03}$	30, 300, 1000
	b_0	20
	K_p, K_d	0.3, 1.5
	α_p, α_d	0.5
	δ_p, δ_d	0.2

PD control was used without integral component, as tension of yarn is characterized by very high order dynamics. Both ADRC and PD controller were implemented in digital form and operate at sampling frequency 100Hz. Data is transmitted to PC using serial cable 10 times a second. It's quite rough data to analyze, but still it gives us overall picture of system performance.

Parameters, presented in Table 1, are used in experiments.

1. Thick cotton yarn with even surface

Initially experiments were conducted using thick cotton yarn with even surface. All gains of PD controller and ADRC controller have been tuned up basing on rough linear model data derived from the data gathered during process without control. For the following experiments gains were not changed, in order to compare performances of PD and ADRC controller in case of parameter variations. In this experiment reference tension r is set to 14cN. As far as we cannot tune passive tensioner precisely, we first conduct experiment with yarn using passive tensioner with some load, after that we find mean tension and define it as reference tension for experiments conducted using active tensioner.

Active tensioners with ADRC and PD controller have almost the same performance, however both of them outperforms passive tensioner by almost 100%. The measured tension root-mean-square errors are as follows:

- No control by passive tensioner:	1.86cN
- PD control:	1.08cN
- ADRC control:	0.94cN

2. Thick cotton yarn with rough surface

For this experiment the yarn with rough surface was used. It means bigger disturbances, and we would like to know how our active tensioner deals with them. This yarn breaking tension is 25cN, so we set reference tension r =14cN. The measured tension root-mean-square errors are as follows:

- No control by passive tensioner:	2.48cN
- PD control:	1.40cN
- ADRC control:	0.99cN

As expected, in case of passive tensioner the error is increased. Error in case of active tensioner with PD control is also increased. But error in case of ADRC control almost was not changed. As it can be seen, PD controlled unit outperforms passive one at least by

표 2. 실험에서 측정된 정상상태 오차(단위는 cN).

Table 2. Steady-state error measured during experiments (values in cN).

		Thick/Even	Thick/Rough	Thin/Even
Reference r		14	14	7
Error	Passive	1.86	2.48	1.65
	PD	1.08	1.40	1.18
	ADRC	0.94	0.99	0.70

50%, so does ADRC controlled unit comparative to PD controlled one.

3. Thin synthetic yarn with even surface

Third series of experiments were conducted using synthetic thin yarn with even surface. Control of thin yarns is usually more difficult, as in case of control error, probability to break the yarn is higher. And reference tension should not be set very high; otherwise, even in case of correct control, yarn will be broken. So for this type of yarn reference tension is defined as r =7cN. As before, this tension is acquired as result of experiment conducted with passive tensioner and then set for active one. The measured tension root-mean-square errors are as follows:

- No control	1.65cN
- PD control	1.18cN
- ADRC control	0.70cN

Again the best results are achieved by using active tensioner with ADRC control. As it could be seen, ADRC performs well under different conditions.

Results of experiments are represented in Table 2.

4. Mean tension inconstancy of passive tensioner

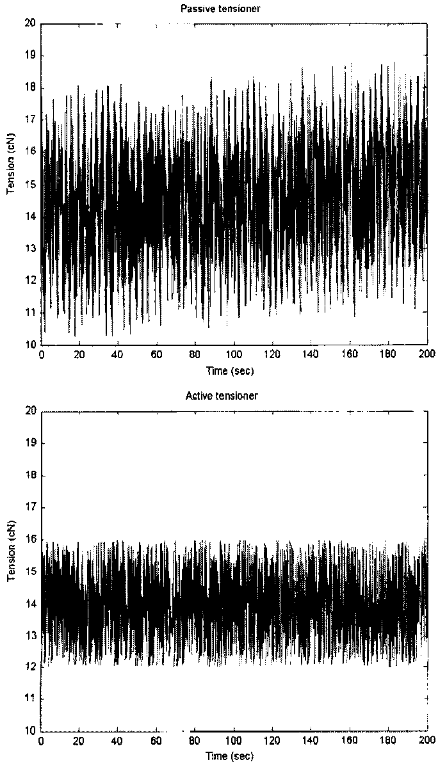

그림 12. 장시간 동안의 실 장력 동특성.

Fig. 12. Yarn tension dynamics over long-time process.

There is one more problem exists in system with passive tensioner used. During experiments it was noticed that even tension was adjusted correctly and mean tension in the beginning is equal to desired one, but during winding process yarn tension increases, as can be seen in the following figure.

This problem becomes apparent because of gradual decreasing of package diameter, which invokes increasing of lift-off point angular velocity, thus increasing the initial yarn tension. As far as passive tensioner mostly provides only added tension, final tension increases too. But the system with active tensioner is eliminated of this effect.

VI. Conclusions

In this paper, the winding system using active tensioner to enhance yarn tension control is proposed. Two control methods such as Proportional-Derivative(PD) and Active Disturbance Rejection Control(ADRC) are investigated and implemented in the hardware of control system.

A number of experiments were conducted with original and modified winding systems, and it was approved experimentally that modified winding system outperforms original one. Moreover, comparison of two control methods of modified winding system is made, demonstrating that in accordance with theory ADRC works better than PD control, especially in the presence of some variations in plant model, such as yarn type, evenness, transport speed, etc.

The design procedure of PD controller is the most simple, unlikely design one of ADRC. But, even ADRC is much more complex technology than PD, due to presence of observer (ESO), it is worthy of notice, that correctly tuned ADRC controller is characterized by high robustness to plant parameters variations and can work within all operating range of the system.

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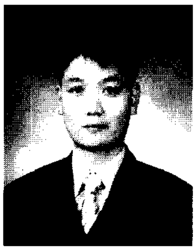
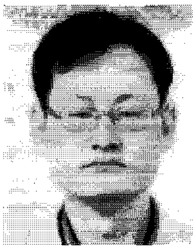
Ulugbek R. Umirov

He received the B.S. degree in Information Science and Technologies from Tashkent University of Information Technologies, Tashkent, Uzbekistan in 2003, and the M.S. degree in Electronic Engineering from Yeungnam University, Gyeongsan, Korea in 2006. He is currently Ph.D. degree student in Dept. of Electronic Engineering, Yeungnam University. His research interests are wireless network-based control, and neural-based intelligent control.



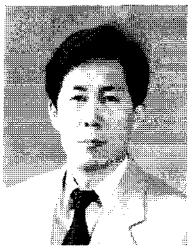
Chang Wook Han

He received the B.S., M.S., and Ph.D. degrees in Electronic Engineering from Yeungnam University, Gyongsan, Korea in 1994, 1996, and 2002, respectively. From 1996 to 1997, he worked as an engineer at Hyundai Heavy Industries Co., Ltd. During 2002~2003, he was a Post-doctoral Fellow in the Department of Electrical and Computer Engineering at the University of Alberta, Canada. From 2004 to 2007, he worked as a guest professor at School of Electrical Engineering and Computer Science, Yeungnam University, Korea. He joined the faculty of the Department of Electrical Engineering, Dong-Eui University, Busan, Korea in 2008, where he has been a full time lecturer. His research interests include fuzzy-neural networks, intelligent control, computational intelligence and its applications.



Seung Hyun Jung

He received B.S. and M.S. degrees in Electronic Engineering from Yeungnam University, Gyeongsan, Korea, in 1995 and 1998, respectively. He is currently Ph.D. degree student in Dept. of Electronic Engineering, Yeungnam University. From 2000 to 2002 he worked as a Assistant Engineer at LG Eelectronics. He is currently Automation Technology Senior Researcher of the Korea Textile Machinery Research Institute, Gyeongsan, Korea. His current research interests are high-precision motion control, nonlinear control, neurofuzzy control.



Jung-Il Park

He received the B.S. degree in Electronic Engineering from Kyoungbuk National University, Daegu, Korea in 1981, and the M.S. and Ph.D. degrees in Electronic Engineering from Seoul National University, Seoul, Korea, in 1983 and 1989, respectively. From 1989 to 1992 he worked as a Senior Engineer at Samsung Advanced Institute of Technology. He joined the faculty of the school of Electrical Engineering and Computer Science, Yeungnam University, Gyoungsan, Korea in 1992, where he has been a professor since 2003. His current research interests are neural-based intelligent control, high-precision motion control, networked control system.