Tension Control of the Let-off and Take-up System in the Weaving Process Based on Support Vector Regression

Dong Chang Han, Woon Jae Back , Sang Hwa Lee, Hyuk Jin Lee, Seok Hong Noh,
Han Kil Kim*, Jae Yong Park*, Suk Gyu Lee*, Du Hwan Chun**
Korea Textile Machinery Research Institute, Gyongsan, Korea
* Department of Electrical Engineering, ** Department of Textile Engineering Yeungnam University, Gyongsan, Korea
(Tel : +82-53-819-3141; E-mail: han1134@kotmi.re.kr)

Abstract: This paper proposes a robust tension control algorithm for the let-off and take-up system driven by servo motor which is robust to disturbance and tension variation by using SVR(Support Vector Regression). Quality of textile goods in fiber manufacturing process highly depends on control of let-off, take-up and tension which are essential for constant tension control of yarn and textile fabrics and correct length of them. The physical properties of textile fabrics are very sensitive to several factors(temperature, humidity, radius change of warp beam etc.) which result in tension change. Rapid development of fiber manufacture machine for higher productivity requires control system for let-off, take-up and tension for robustness to sharp tension-variation and quick response. The validity and the usefulness of the proposed algorithm are thoroughly verified through numerical simulation.

Keywords: Let-off, Take-up, Support Vector Regression, Servo Motor, Textile, Warp, Tension Control, Weaving Process.

1. INTRODUCTION

The production speed of textile machinery in all fields of textile has increased enormously over the past 40 years. High operating speeds in textiles usually result in deterioration of product quality unless more sophisticated control systems are employed. With the need for increased performance and productivity in the weaving machines, accurate modeling and effective controller design for weaving process control systems are essential for increasing the weaving speed and quality of the processed weaving. It is important to maintain warp tension within the desired limits under a wide range of dynamic conditions such as speed changes, variations in roll size and the physical properties of textile fabrics. Tension variations affect quality of textile goods and tend to cause yarn breakage and stop marks[1-3].

A let-off and take-up mechanism consists of two beams; one is a let-off beam, the other, a take-up beam. A let-off and take-up mechanism is also used as a feedback element in a number of tension control systems. Fig.1 shows schematic description of the weaving process.

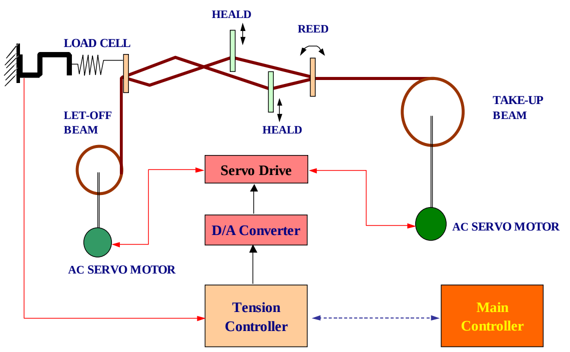

Fig. 1 Schematic description of the weaving process.

Various control algorithms and devices have been proposed for the tension of warp yarn control: PI controller using load cell signal, estimators using state equations, and so on[5]. However, load cell and supporting device require additional mounting space, reduce reliability in harsh environments and increase the cost of system.

This paper proposes a robust tension control algorithm of the let-off and take-up system driven by servo motor which is robust to disturbance and tension variation using SVR(Support Vector Regression). The validity and the usefulness of the proposed algorithm are thoroughly verified through numerical simulation.

2. MATHEMATICAL MODELING OF THE WARP TENSION

It is well known in the let-off and take-up system handling literature[1-4], where the tension dynamics of a general the let-off and take-up system shown in Fig. 2 is given by

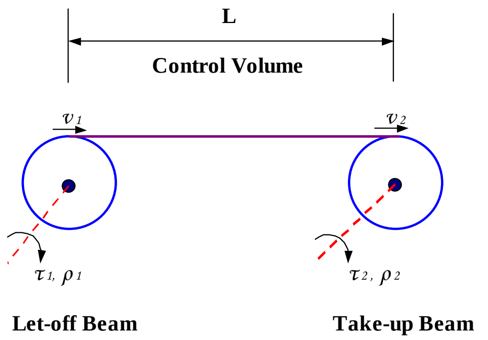

Fig. 2 Simplification of the let-off and take-up system in weaving process as a sheet transport system driven by two rollers.

$$L\frac{d\tau_2}{dt} = AE[v_2(t) - v_1(t)] + \tau_1(t)v_1(t) - \tau_2(t)v_2(t). \quad (1)$$

where $v_1(t)$: let-off velocity of the warp,

$v_2(t)$: take-up velocity of the fabric,

ρ_1 : linear density of the warp on warp beam,

ρ_2 : linear density of the warp on the section of weaving,

$\tau_1(t)$: tension of the warp on warp beam,

$\tau_2(t)$: tension of the warp on the section of weaving,
A : whole cross-section of warp on warp beam,
L : length of weaving zone and E is elastic modulus.

Take-up velocity $v_2(t)$ of textile fabrics is decided by structure of loom and used machine material, drive motor and weaving condition. However, operation of main devices of loom depends on the speed of take-up motor. Therefore, let-off speed $v_1(t)$ can be described with Eq. (2).

$$v_1(t) \propto v_2(t) = \alpha v_2(t), \quad \alpha \le 1 \tag{2}$$

Eq. (1) can be further simplified by noting that tension of the warp on warp beam ($\tau_1(t) = \tau_{10}$: constant) and $v_1(t) = \alpha v_2(t)$ to obtain

$$L\frac{d\tau_2}{dt} + \tau_2(t)v_2(t) = AE[(1-\alpha) + \tau_1(t)v_1(t)]v_2(t) \cdot \tag{3}$$

The solution of Eq. (3) is given by

$$\tau_2(t) = D + (\tau_{20} - D)e^{-\int \frac{v_2(t)}{L}(t)}. \tag{4}$$

where $D = [A\,E(1-\alpha) + \tau_{10}]$, and τ_{20} is the initial tension.

1) For $D = \tau_{20}$: The warp tension $\tau_2(t)$ is always fixed regardless of take-up velocity $v_2(t)$

2) For $D \ne \tau_{20}$: The warp tension $\tau_2(t)$ changes according to take-up velocity $v_2(t)$.

In Eq. (4), it is difficult to measure D correctly. This paper proposes a new tension model which is robust to disturbance and tension variation.

In Eq. (3), the warp tension $\tau_2(t)$ can be described by

$$\tau_2(t) = [AE(1-\alpha) + \alpha\tau_{10}] - L\frac{d\tau_2(t)}{dt}\frac{1}{v_2(t)}. \tag{5}$$

Since it is not easy to calculate $L\frac{d\tau_2(t)}{dt}\frac{1}{v_2(t)}$ in Eq. (5), we propose a method to remove this term in this research. For constant $\tau_2(t)$ within one tension estimation cycle, the term $L\frac{d\tau_2(t)}{dt}\frac{1}{v_2(t)}$ vanishes. Then, Eq. (5) reduces to

$$\tau_2(t) \approx [AE(1-\alpha) + \alpha\tau_{10}]. \tag{6}$$

3. THE WARP TENSION ESTIMATION USING SVR

A regression method is an algorithm that estimates an unknown mapping between a system's input and outputs, from the available data or training data. Once such a dependency has been accurately estimated, it can be used to predict system outputs from the input values. The goal of regression is to select a function which guarantees optimal approximation of the system's response. A function approximation problem can be formulated to obtain a function f from a set of observations, $(y_1, x_1), \ldots, (y_N, x_N)$ with $x \in R^m$ and $y \in R$, where N, the number of training data, x, the input vector, and y, the output data respectively. The function in SVR has the form of

$$f(x, \omega) = \omega^T K(x) + b \,. \tag{7}$$

where $K(\cdot)$ is a mapping from R^m to so-called higher dimensional feature space $F, \omega \in F$ is a weight vector to be identified in the function, and b is a bias term. To calculate the parameter vector ω, the following cost function should be minimized [6]-[14]

$$\text{Min} \quad \frac{1}{2}\|\omega\|^2 + C\sum_{i=1}^{N}\left(\xi_i + \xi_i^*\right).$$

subject to

$$\begin{aligned} & y_i - \omega x_i - b \le \varepsilon + \xi_i, \\ & \omega x_i + b - y_i \le \varepsilon + \xi_i^*. \\ & \xi_i \xi_i^* \ge 0,\ C \succ 0,\ i = 1, \ldots, N \end{aligned} \tag{8}$$

where C is a pre-specified value that controls the cost incurred by training errors. The slack variables, $\xi_i \xi_i^*$ are introduced to accommodate error on the input training set.

With many reasonable choice of loss function, ξ, the solution will be characterized as the minimum of a convex function. The constraints also include a term, ε, which allows a margin of error without incurring any cost. The value of ε can affect the number of support vectors used to construct the regression function. The bigger ε is, the fewer support vectors are selected. Hence, ε -values affect model complexity.

Our goal is to find function $f(x, \omega)$ that has at most ε deviation from the actually obtained targets y_i for all the training data, and at the same time, is as flat as possible for good generalization. In other words, we do not care about errors as long as they are less than ε, but will not accept any deviations larger than ε. This is equivalent to minimize an upper bound on the generalization error, rather than minimize training error.

The optimization problem in Eq. (8) can be transformed into the dual problem [11]-[13], and its solution is given by

$$\begin{aligned} & f(x) = \sum_{i=1}^{N}\left(\alpha_i - \alpha_i^*\right)\left(K(x_i) \cdot K(x)\right) + b \cdot \\ & s.t.\ 0 \le \alpha_i^* \le C,\ 0 \le \alpha_i \le C \end{aligned} \tag{9}$$

In Eq. (9), the inner product $(K(x_i) \cdot K(x))$ in the feature space is usually considered as a kernel function $K(x_i, x)$. Several choices for the kernel are possible to reflect special properties of approximating functions:

Linear kernel : $K(x_i, x) = x^T x_i$,

$$\text{RBF kernel : } K(x_i, x) = \exp(-\|x - x_i\|^2 / \sigma^2)\,. \tag{10}$$

The input data are projected to a higher dimensional feature space by mapping $K(\cdot)$.

In Eq. (6), target data and training data are defined as τ_{20} and $\{(1-\alpha), \alpha\}$ respectively. The basic idea is to minimize error between reference warp tension and calculate $\tau_2(t)$. Hence, robust warp yarn tension estimation under parameter AE, τ_{10}, and L variation circumstance is achieved. The warp yarn tension model is expressed as

$$y = \tau_{20}, \tag{11}$$

$$x = \{(1-\alpha), \alpha\}, \tag{12}$$

$$w = \{AE, \tau_{10}\}. \quad (13)$$

Where α is $v_1(t)/v_2(t)$.

Hence Eq. (7) can be depicted as

$$\hat{\tau}_2(t) = w_1^{T}(1-\alpha) + w^{T}2\alpha + b. \quad (14)$$

Fig.3 shows the structure of SVR warp tension estimator.

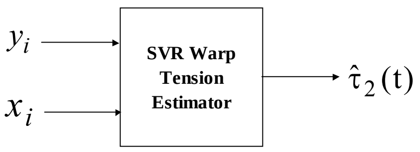

Fig. 3 Structure of the warp tension estimator using SVR.

4. SIMULATION RESULTS

The simulation has been performed for the verification of the proposed control algorithm. Table 1 shows the specifications of let-off and take-up system used in the simulation. As shown in Fig. 4, the proposed system mainly consists of an AC servo system with automatic speed regulator and automatic current regulator, the tension of SVR warp controller.

Table 1 Simulation conditions

Servo motor	Number of pole	8
	Rs	1.49 Ω
	Ls	9.53mH
	Moment of inertia	$3.0\times10^{-2}\,Kg-m^2$
	Back-EMF constant	0.25
	Nominal power	0.4Kw
SVR	α	63
	ε	0.001
Warp tension	$EA,\ L = L_{12}, \tau_{10}$	130, 2300mm, 1kgf
	Beam diameter	500mm

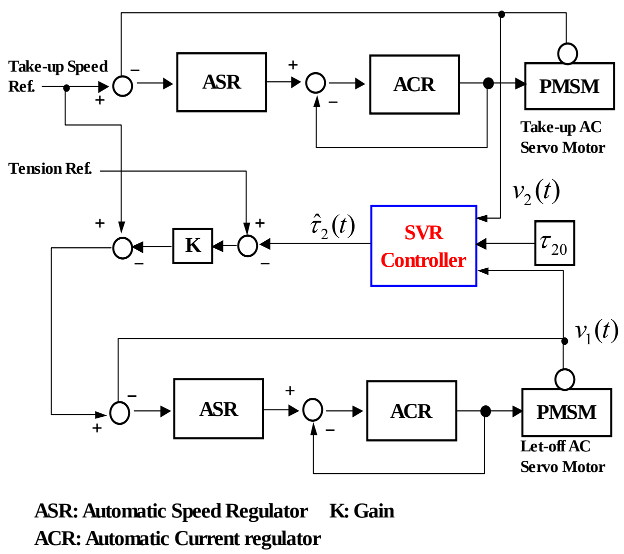

Fig. 4 Configuration of overall system

Stop marks caused by the irregularity of the weft density of woven fabrics mainly result from the variation of the warp yarn tension in the weaving process. In addition, the variation of the warp yarn tension depends on the difference between the let-off and take-up speed, and the physical properties of textile fabrics[3].

The simulation was performed under the following conditions. 1) the take-up speed: 1500rpm(step and ramp), 2) the load torque: sine wave of 30rad/sec, 3) reference tension: 1kgf, and 4) kernel of SVR: linear. For the comparison with the conventional PI control algorithm, the simulation is performed under the same conditions.

Fig.5, Fig. 6 and Fig. 7 show the tension of warp yarn responses in case of considering the parameter variations with load. In Fig. 5(c), Fig. 6(a) and Fig. 7(c), we can know that the tension of warp yarn depends on the length of weaving zone L_{12} and the tension of warp on warp beam τ_{10}. Fig. 5(d), Fig. 6(b), and Fig. 7(d) show good characteristic of the tension of warp yarn regardless of variation of parameter for both transient and steady state. The simulation results are described in Table (2)-(7).

The simulation results show an improved and robust performance in the proposed tension of warp yarn control algorithm.

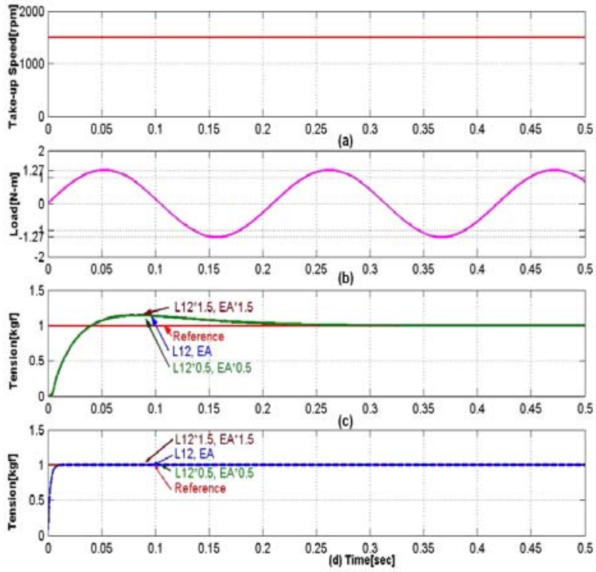

Fig. 5 The warp tension behavior at step input($\tau_{10} = 1$); (a) take-up speed, (b) with load torque(1.27[N-m]), (c) under PI control, (d) under SVR control.

Table 2 Simulation result of PI controller ($\tau_{10} = 1, step$)

	L, EA	L*1.5, EA*1.5	L*0.5, EA*0.5
Delay Time	0.0142 sec.	0.0143 sec.	0.0139 sec.
Rise Time	0.0406 sec.	0.0404 sec.	0.0411 sec.
Peak Time	0.0805 sec.	0.0821 sec.	0.0835 sec.
Settling Time	0.3333 sec.	0.5214 sec.	0.4456 sec.
Final Value	1.0001 sec.	1.0000 sec.	1.0000 sec.

Table 3 Simulation result of SVR controller ($\tau_{10} = 1, step$)

	L, EA	L*1.5, EA*1.5	L*0.5, EA*0.5
Delay Time	0.00148 sec.	0.00149 sec.	0.00148 sec.
Rise Time	0.01540 sec.	0.01550 sec.	0.01530 sec
Peak Time	0.01540 sec.	0.01550 sec.	0.01530 sec
Settling Time	0.01540 sec.	0.01550 sec.	0.01530 sec
Final Value	1.00000 sec.	1.00000 sec.	1.00000 sec.

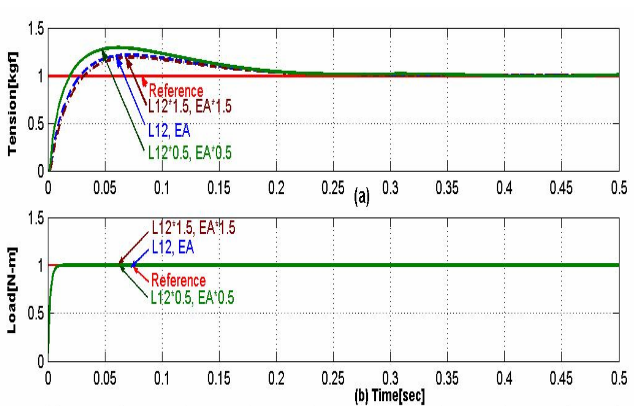

Fig. 6 The warp tension behavior at step inputs($\tau_{10} = 10$) ; (a) under PI control, (b) under SVR control.

Table 4 Simulation result of PI controller ($\tau_{10} = 10, step$)

	L, EA	L*1.5, EA*1.5	L*0.5, EA*0.5
Delay Time	0.00960 sec.	0.01160 sec.	0.00655 sec.
Rise Time	0.02890 sec.	0.03220 sec.	0.01950 sec.
Peak Time	0.07000 sec.	0.07330 sec.	0.06050 sec.
Settling Time	0.37500 sec.	0.42500 sec.	0.43200 sec.
Final Value	1.00000 sec.	1.00000 sec.	1.00000 sec.

Table 5 Simulation result of SVR controller ($\tau_{10} = 10, step$)

	L, EA	L*1.5, EA*1.5	L*0.5, EA*0.5
Delay Time	0.00148 sec.	0.00148 sec.	0.00148 sec.
Rise Time	0.01530 sec.	0.01531 sec.	0.01530 sec.
Peak Time	0.01530 sec.	0.01531 sec.	0.01530 sec.
Settling Time	0.01530 sec.	0.01531 sec.	0.01530 sec.
Final Value	1.00000 sec.	1.00000 sec.	1.00000 sec.

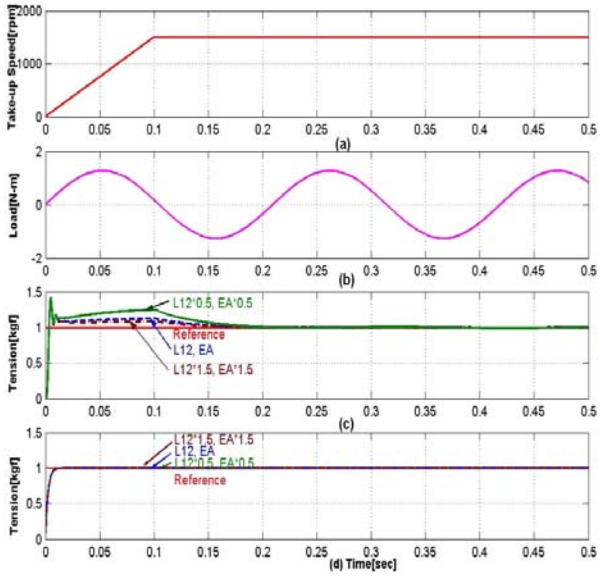

Fig. 7 The warp tension behavior at ramp inputs($\tau_{10} = 10$) ; (a) take-up speed, (b) with load torque(1.27[N-m]), (c) under PI control, (d) under SVR control

Table 6 Simulation result of PI controller ($\tau_{10} = 10, ramp$)

	L, EA	L*1.5, EA*1.5	L*0.5, EA*0.5
Delay Time	0.00259 sec.	0.00259 sec.	0.00258 sec.
Rise Time	0.00379 sec.	0.00348 sec.	0.00346 sec.
Peak Time	0.00480 sec.	0.00408 sec.	0.00479 sec.
Settling Time	0.21030 sec.	0.21380 sec.	0.21520 sec.
Final Value	1.00000 sec.	1.00020 sec.	1.00950 sec.

Table 7 Simulation result of SVR controller ($\tau_{10} = 10, ramp$)

	L, EA	L*1.5, EA*1.5	L*0.5, EA*0.5
Delay Time	0.00164 sec.	0.00164 sec.	0.00164 sec.
Rise Time	0.01640 sec.	0.01641 sec.	0.01640 sec.
Peak Time	0.01640 sec.	0.01641 sec.	0.01640 sec.
Settling Time	0.01640 sec.	0.01641 sec.	0.01640 sec.
Final Value	0.99999 sec.	0.99999 sec.	0.99999 sec.

5. CONCLUSIONS

Quality of textile goods in fiber manufacturing process highly depends on control of let-off, take-up and tension which are essential for constant tension control of yarn and textile fabrics and correct length of them. The physical properties of textile fabrics are very sensitive to several factors(temperature, humidity, radius change of warp beam etc.) which result in tension variation. The simulation result shows the validity and the usefulness of proposed algorithm with a better performance in the parameter variation comparing with the conventional algorithm.

From the simulation results, we got the followings.

1. A new tension model $\tau_2(t) \approx [AE(1-\alpha)+\alpha\tau_{10}]$ by eliminating the derivative term $\frac{d\tau_2(t)}{dt}$ in conventional model to avoid saturation of integral term and calculational difficulty is introduced.

2. A new tension estimation algorithm of the let-off and take-up system driven by servo motor $\hat{\tau}_2(t) = w_1{}^T(1-\alpha) + w_2{}^T\alpha + b$ which is robust to the physical properties of textile fabrics, weaving length and speed difference was proposed based on SVR.

3. The analysis of the transient state shows that the tension control based on the proposed algorithm was performed regardless of the speed profile of take –up process.

Practical implementation of the proposed algorithm is under way using prototype weaving system to show its applicability.

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