MODELING AND TENSION CONTROL OF FILAMENT WINDING PROCESS

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Abstract: Currently, a variety of fiber materials are extensively used in a number of fields. Carbon fiber (CF), carbon-fiber reinforced plastics (CFRP), and their products are especially popular because they have a higher tensile strength than metal materials. CFRP are generally formed by a filament-winding (FW) method. The winding pitch and tension controls of this process are key factors in making sound products. The purpose of the present research is to establish an advanced filament-winding system with real-time control of the winding tension. First, modeling of the Hoop-winding tension process(pattern) is studied in terms of a system identification technique. Secondly, two-degree-of-freedom (2-DOF) PID control is applied to the winding process, with the controller having been designed to use the Genetic Algorithm (GA). Based on the above, a tuning method of control gain using GA is proposed herein. Finally, the effectiveness of the proposed approach is demonstrated via control experiments. Futhermore, the controller designed for Hoop-winding process has been applied to the Helical-winding process in a more general case. Important suggestion to be developed is given from the frequency analyse, although control experimental results did not satisfied our control performance.

Keywords: Carbon-fiber, Filament-winding, 2-DOF PID Tension control, Gain tuning, Genetic Algorithm, Helical-winding

1. INTRODUCTION

In recent years, the availability of lightweight and tough materials has caused several fiber materials to be used extensively for a variety of common uses. Carbon fiber (CF), for example, has approximately 10 times greater tensile strength than metal materials, and it can be used in many applications, including sports equipment, automobile bodies, building-reinforcement materials, and so on. Cylindrical-carbon fiber reinforced plastics (CFRP) are primarily used in pressure containers built for transferring and storing compressed natural gas (CNG), with this CFRP being made from CF via winding the CF onto a mandrel and subjecting it to a sintering process.

The filament-winding (FW) process is the usual method for forming or building up CFRP. FW forms a product by making the carbon-fiber tow
wind onto a mandrel, where "tow" refers to a string made of thousands of carbon fiber threads collected in a bundle. In order to make a sound CFRP, the winding pitch and winding-tension control in the winding process are of great importance. Although there have been some reports of the influence of winding pitch on final products (Hung and White, 1992a) (Hung and White, 1992b) (Oono, 1998) little research has been reported on the winding-tension control of FW systems, despite their importance (Kitaide et al., 1996). In the FW method, the winding-tension control during winding is presumed to be one of the key factors relating to the tensile strength of CFRP. However, there are few advanced FW machines able to measure and control the winding tension in real-time. In order to obtain CF of the appropriate strength, the winding-tension must be controlled at optimum values during the winding process. Moreover, there are some FW methods classified by the angle between the direction of the mandrel rotational axis and the direction in which CF tow is rolled during winding as illustrated in the Figure 1. When the angle is 90[deg], the method is called a Hoop-winding method, which is useful for reinforcing the tensile strength in the circumference direction of CFRP. In contrast, when the angle is from 30[deg] to 60[deg] (generally 30, 45 and 60[deg] are used), the method is called a Helical-winding method, which is useful for reinforcing the strength needed to protect against bending or twisting forces. However, as described above, Helical-winding includes Hoop-winding because the winding angle of Helical-winding is 90[deg]. The purpose of the present research is to establish an advanced FW system that employs the real-time sensing and control of the winding-tension.

We describe here first a model of winding tension constructed using the ARX (Auto-Regressive eXogenous) model via a system-identification technique. Secondly, a method of the winding-tension control using the ARX model and the Genetic Algorithm (GA) is proposed for the case of Hoop-winding. Finally, the winding-tension control performance using the proposed control method is evaluated based on experimental results obtained under several winding conditions. Furthermore, the controller obtained in the Hoop-winding is also applied to Helical-winding in a more general case. Based on the results of the control experiments and frequency analysis, we also provided some comments regarding improving the tension control of Helical-winding.

![Fig. 1. Examples of winding pattern](image)

2. EXPERIMENTAL APPARATUS

Figure 2 shows the filament-winding machine used in the present study, as described previously (Imamura et al., 1999). The system is comprised of the following elements: Mandrel, Traverse, and Nip-roll subsystems, and tension measuring subsystem. In the Mandrel subsystem, the large-diameter mandrel is driven by an AC servomotor with a belt-and-pulley system that winds the CF tow onto the mandrel. The Traverse subsystem makes the main body of the FW machine goes and returns in the traverse direction of the CF tow by the AC servomotor and the ball screw, as the position control of the CF tow is necessary to wind the CF tow onto the mandrel in the necessary order. All elements except the Mandrel subsystem are included in the main body part. The Nip-roll subsystem controls the feed rate of the CF tow by a pressed rubber-roll with an air cylinder and a drive shaft.

In the Resin-bath process of Fig. 2, resin to bind the tow is properly pasted on the surface of the CF tow, which is comprised of thousands of threads, when the tow is passed through the resin bath. The winding-tension sensor does its job by means of a load-cell and free rolls, and it is able to measure the winding-tension in the minimum sampling time: 8[msec]; the control sampling time is also set to 8[msec].

All subsystems are measured and controlled by control units using DSP and a host PC. AC servomotors used in each subsystem are able to control both the rotational speed and torque.

The object of our experiments was to control the winding tension at constant value during winding, and the performance specifications of the windings are given as follows. Namely, the reference input tension was primarily set at 10 [N] to 50[N], and the allowable range of tension fluctuation was less than 5[%] of its reference at the steady-state. When there was elasticity and viscosity in the mandrel body and the wound CF tows, there would be disturbances in the winding-tension control.
3. WINDING-TENSION CONTROL SYSTEM AND OVERVIEW OF PAST RESEARCH

The two AC servomotors used in the Mandrel and Nip-roll parts have two functions, as the velocity servo control or the torque servo control as an actuator for the winding-tension control. Thus, it is thought that tension control can be realized in several ways using the combination of torque control and velocity control in the AC servomotors.

We have previously proposed a winding-tension control method using the velocity control in each actuator (Imamura et al., 1999). In the method, the sending-out velocity of CF is controlled to generate the difference in velocities between the actuators of the Mandrel and Nip-roll subsystem based on the line speed, where the "line speed" refers to the transferring speed of the tow through the Nip-roll subsystem to the Mandrel subsystem in the process. As a result, the velocity difference between the two ends generates the winding tension for the CF tow.

The rotational velocity of the Mandrel subsystem is kept constant, and the difference between the rotational velocity of the Nip-roll subsystem that sends out CF and the rotational velocity of the Mandrel subsystem is treated as a control input variable. This method was implemented in the FW system using either a PID or I-PD control as a tension-control method using the difference in velocities. Regardless of the PID or I-PD control, this method using the difference in velocities showed good results in comparison with the method using mandrel torque.

However, an overshooting of the winding-tension does occur near the starting time of the winding control in order to achieve a faster rise time and a better steady-state response. This overshooting must be reduced, as this type of unexpected winding-tension causes damage to the CF tow. But, while reducing the control gain in order to reduce the overshoot of the winding tension, the steady-state response worsens.

In order to compensate for this deficiency and to improve both the transient and the steady-state response, the winding-tension controller was extended to a two-degree-of-freedom (2-DOF) PID controller shown in Eq. (1). Its performance is determined by two parameters, \( \alpha \) and \( \beta \), in addition to three parameters of \( P \), \( I \) and \( D \). The experimental results showed that the proposed 2-DOF PID controller had a good control response.

\[
U(s) = \frac{(1 - \alpha)K_p + K_i/s + (1 - \beta)K_ds}{s}E(s) + (\alpha K_p + \beta K_ds)Y(s)
\]  

(1)

where \( U(s) \) is Laplace transform of \( u(t) \), \( u(t) \) is a control input represented the difference of velocities between Mandrel and Nip and \( \alpha, \beta \) are 2-DOF parameter.

However, in previous work, control gain has been experimentally determined by a trial-and-error method. A systematic design method for controllers is therefore desirable, and a first step in realizing a reasonable design is to build a process model for the winding-tension process and to establish optimum parameters for controllers.

In what follows, modeling and control of the winding-tension process are described.

4. MODELING AND CONTROL OF THE WINDING-TENSION PROCESS: HOOP-WINDING PATTERN

4.1 System Identification

Although there are several kinds of methods in the tuning for PID control gain, it is difficult to tune the optimum control gains systematically satisfying several control specifications. In this report, we propose a control-gain tuning method using the Genetic Algorithm (GA) for the given control specification.

The winding-tension will be determined from the characteristics of the CF and the mechanical structures of the FW system, which primarily include a spring and friction element.

To build this tension model, the system-identification method is applied in terms of the Least-Square Method, in which the ARX (Auto-Regressive eXogenous) model represented by Eq. (2) is used.

\[
A(q)y(k) = B(q)u(k) + w(k)
\]

(2)

where \( A(q) = 1 + a_1q^{-1} + \cdots + a_nq^{-n} \), \( B(q) = b_0q^{-1} + \cdots + b_nq^{-n}g(k)/u(k) : \) output / input term, \( w(k) : \) white noise, \( q : \) shift parameter, \( k : \) discrete time. As the input of identification,
and output data of identification are shown in Figure 3. Before identification, the line speed is accelerated at a constant speed using conventional trapezoidal input, and then input data shown in Fig. 3 is applied to the system for system identification. Using the identification-of-tension model, the relationship between the variation of the model parameters built here and the winding conditions such as the thickness of CF tow, the winding line speed, and the mandrel diameter has been studied. In the present study, the tension model was constructed with respect to a variety of conditions, such as line speeds of 10, 20 and 30[m/min], both large \((r = 250[mm])\) and small \((r = 125[mm])\) mandrel diameters, and 6, 12 and 24[K] fibers in the CF. The System Identification Toolbox of MATLAB was used to identify the tension model.

As one of the identification results, Eq.(3) shows the transfer function of Eq.(2), where the experimental condition 12[K] as the CF tow, 10[m/min] as the line speed, with a large \((r = 250[mm])\) mandrel diameter were used. The results for the other conditions of CF tow, line speed and mandrel size are omitted due to space considerations but, Figure 4 shows the results regarding model validity. Based on these results, simulation results by ARX model agree well with the experimental results, thus confirming the model validity.

Moreover, we investigated a variation of process gain of the Bode diagram for the winding-tension model under various winding conditions. These results suggest that there is little relationship between the models and the changes in line speed and mandrel diameter, while there are some effects of the changes in the CF tow thickness on the mandrel. Because the number of filament threads in the CF tow is fixed for each product, it will be necessary to build specific models corresponding to the number of threads, e.g. 6[K], 12[K], and 24[K].

\[
y(k) = \frac{-0.00921z^3 - 0.170z^2 - 1.121z + 0.393}{z^3 - 0.977z^2} u(k) \tag{3}
\]

![Fig. 4. Validity of unidentified model for Hoop-winding pattern](image)

4.2 Gain Tuning of a 2-DOF PID Controller

In order to obtain optimum control gain, GA is applied to minimize the following criterion function represented by Eq. (4), where \(W_E, W_S, W_D, W_O,\) and \(W_I\) are the weights of each term in Eq. (4) and correspond with the characteristics of the control system, including the error \(e\) in the steady-state, the settling time \((T_s)\), the ease of start-up, and the restriction of input and output values. And, penalty functions of \(P_0\) and \(P_I\) are the restriction of overshoot-free and control input’s magnitude.

\[
\begin{align*}
\min J &= \left\{ \int_0^{T_f} e^2 dt - W_E \cdot T_s - W_S \right. \\
&+ \left. \int_0^{T_f} \left( \frac{dy}{dt} \right)^2 dt \cdot W_D + P_O(y) + P_I(u) \right\} \\
P_O &= \begin{cases} 0 & y \leq \text{Reference} \\ W_O & \text{Other} \end{cases} \\
P_I &= \begin{cases} 0 & -10 \leq u \leq 0 \\ W_I & \text{Other} \end{cases}
\end{align*}
\tag{4}
\]

![Flowchart of gain tuning method using GA](image)

4.3 Results of Tension Control for Hoop-winding pattern

To validate a gain tuning method of the proposed control gain, experiments of the winding-tension control using the tuned gain under the various conditions of CF tow were conducted. As the experimental condition, line speed and reference tension were fixed to each value such as 10[m/min] as line speed and 50[N] as tension. From the results in section 4.1, 2-PID control gains were tuned using the winding-tension model at the each conditions of 6, 12 and 24[K]. Figure 6 shows the winding-tension control results that each optimum control gain were applied to each conditions of CF tow.

This results show good performance of tension control after time \(T > 0.5\) as steady-state and...
also in the transient characteristics than previous tension control using try-and-error method as the gain tuning (Imamura et al., 1999), except for transient response in the case of 24[K]'s CF tow.

Fig. 6. Experimental results of tension control using optimized control gain for Hoop winding pattern

5. IMPLEMENTATION OF HELICAL WINDING PATTERN

As described in the previous sections, the Helical-winding method is a useful method for CFRP design, taking into consideration the distribution of strength. In this method, it is important to control the winding angle as well as the winding pitch before the tension-control system is created. To do so, a geometric analysis of the Helical-winding method was carried out in the present study.

First, the winding angle $\theta$ sent out from the Nip-roll was determined by $\tan \theta = V_M/V_T$, where $V_M$ is the mandrel velocity and $V_T$ the traverse velocity when $V_M = V \sin \theta$, $V_T = V \cos \theta$, and $V$ is the line speed. In order to obtain a reference value for the winding angle, reference value of $V_M$ and $V_T$ must be synchronized based on Eq.(5).

Secondly, so that the control winding pitch would not loosen the winding, Extra-winding was proposed. Extra-winding means the winding's operation conducted at both ends of the mandrel such that the additional winding of once or twice rotation is carried out at both ends of the mandrel. The main purpose is to prevent a loosening of the tow and therefore a collapse of the winding angle, and also to control the winding pitch. Moreover, to control the winding pitch, the winding length of Extra-winding is straightforwardly calculated by the winding pitch and Eq.(6).

$$V_T = V \cos \theta, V_M = V \sin \theta \quad (5)$$

$$l_1 = W \tan \theta, l_2 = \pi D - l_1 - l_3$$

$$l_3 = (W - p/\sin \theta) \tan \theta, l_4 = W - p/\sin \theta \quad (6)$$

6. CONTROL RESULTS AND ANALYSIS FOR HELICAL WINDING PATTERN

In the same way as in Hoop-winding, identification of the winding-tension model of Helical-winding was carried out. However, when the maximum-length linear shift register sequence was used as the identification input for Helical-winding, the referenced winding angle and pitch could not be obtained, because the random input of M-sequence disturbed the winding motion. Reasonable winding motion could not be carried out, and then the winding becomes failure.

It is therefore necessary to use another identification signal to obtain the winding-tension model. This problem did not occur in the simple case of Hoop-winding, as shown in the previous sections.

Hence, first, in order to check the relationship between the model fluctuation and the winding condition, and also to construct the winding-tension model using the controller built in the Hoop-winding pattern, the preliminary experiments of Helical-winding were carried out. The preliminary experiments under various conditions were done, where the conditions of 20, 30, 40, 60, and 80[deg] as the winding angle, 2, 5, 7, and 9[m/min] as the line speed, and 20[N] as the reference tension were used. Figure 8 shows the standard deviations of tension at the steady-state of these control experiments. From these results, it appears that the Helical-winding-tension model was varied in the case of a higher line speed and a lower winding angle, because control experimental results were worse under those conditions. It is thought that a higher line speed causes faster traverse motion, and a lower winding angle loosens for the CF tow. Owing to this reason, the winding will be worse under these conditions.

Therefore, to achieve good tension control for various conditions of Helical-winding, it is necessary to build a tension model for each winding conditions, including the winding angle and the line speed.

Using the above results, STFT (Short Time Fourier Transform) and FFT (Fast Fourier Transform) analysis were done to investigate the relationship between the winding condition and the controlled tension.

At first, to check the time-dependency of the tension characteristics, STFT analysis was carried out for the condition of the winding angles of 20, 45 and 80[deg] at a line speed of 2[m/min]. Figure 9 shows the case of 45[deg] as the winding

![Fig. 7. Schematic diagram of Helical winding](image)
angle. In the neighborhood of 50[Hz] and 10[Hz], there are some peaks of Power Spectrum, but time-dependency is not be found.

The target of analysis was the variation of tension model in Helical-winding, at the winding angle of 20, 45, 60, and 80[deg], line speeds of 2, 5, 7, and 9[m/min], and winding tension of 20[N]. Figure 10 shows the FFT results classified by the line speed for speeds of 2 and 9[m/min]. The results show that the amplitude near 10[Hz] becomes larger spectrum as the line speed increases, although the winding angle exerts little influence.

From these results, it appears that to construct tension model in Helical-winding, it is necessary to consider the influence of line speed and the winding angle. When using both input and output data obtained in control experiments of Figure 10, system identification will be able to be done, and it is now being prepared.

**7. CONCLUSION**

In this paper, modeling and control of the winding tension process in Hoop-winding pattern were described for a new filament-winding machine that could measure and control the winding tension in real-time. The identified ARX model was found to agree well with experimental results. Our finding showed that the optimum control gain of a 2-DOF PID controller satisfying several control specifications and constraints could be obtained by the Genetic Algorithm. The effectiveness of the proposed method was demonstrated via experiments. Furthermore, the present approach was applied to Helical-winding pattern in a more general case. A synchronous control of a mandrel and a traverse machine was realized through a geometric analysis of the FW machine. Through several control experiments, some comments to the winding-tension control in the case of Helical-winding case were suggested with regard to future work.

**REFERENCES**


